NOBEL LECTURES

PHYSICS

1901 - 1921

World Scientific

NOBEL LECTURES IN PHYSICS 1901-1921

NOBEL LECTURES

INCLUDING PRESENTATION SPEECHES AND LAUREATES BIOGRAPHIES

PHYSICS CHEMISTRY PHYSIOLOGY OR MEDICINE LITERATURE PEACE ECONOMIC SCIENCES

NOBEL LECTURES

Including Presentation Speeches And Laureates' Biographies

PHYSICS

1901-1921



Published for the Nobel Foundation in 1998 by

World Scientific Publishing Co. Pte. Ltd.
P 0 Box 128, Farrer Road, Singapore 912805
USA office: Suite IB, 1060 Main Street, River Edge, NJ 07661
UK office: 57 Shelton Street, Covent Garden, London WC2H 9HE

NOBEL LECTURES IN PHYSICS (1901-1921)

All rights reserved.

ISBN 981-02-3401-5

Printed in Singapore.

Foreword

Since 1901 the Nobel Foundation has published annually, *Les Prix Nobel* with reports from the Nobel award ceremonies in Stockholm and Oslo as well as the biographies and Nobel lectures of the Laureates. In order to make the lectures available to people with special interests in the different prize fields the Foundation gave Elsevier Publishing Company the right to publish in English the lectures for 1901-1970, which were published in 1964-1972 through the following volumes:

Physics 1901-1970	4 vols.
Chemistry 1901-1970	4 vols.
Physiology or Medicine 1901-1970	4 vols.
Literature 1901-1967	1 vol.
Peace 1901-1970	3 vols.

Since the Elsevier series has been out of print for many years the Nobel Foundation has given World Scientific Publishing Company the right to publish these Nobel lectures, biographies and presentation speeches. The Nobel Foundation is very pleased that the intellectual and spiritual message to the world laid down in the laureates' lectures will, thanks to the efforts of World Scientific, reach new readers all over the world.

Bengt Samuelsson Chairman of the Board Michael Sohlman Executive Director

Stockholm, March 1998

Contents

Foreword

1901	Wilhelm C onrad R ön t g e n	
	Motivation	1
	Presentation by C. T. Odhner	3
	Biography W. C. Röntgen	6
1902	2 HENDRIK ANTOON LORENTZ and PIETER ZEEMAN	
	Motivation	9
	Presentation by Hj. Thée1	11
	The theory of electrons and the propagation of light,	
	by H. A. Lorentz	14
	Biography H. A. Lorentz	30
	Light radiation in a magnetic field, by P. Zeeman	33
	Biography P. Zeeman	41
1903	3 ANTOINE HENRI BECQUEREL, PIERRE CURIE and	
	M ARIE SKLODOWSKA- CURIE	
	Motivation	45
	Presentation by H. R. Törnebladh	47
	On radioactivity, a new property of matter, by A. H. Becquerel	52
	Biography A. H. Becquerel	71
	Radioactive substances, especially radium, by P. Curie	73
	Biography P. Curie	79
	Biography M. Sklodowska-Curie	82
1904	LORD RAYLEIGH	
	(JOHN WILLIAM STRUTT)	
	Motivation	85
	Presentation by J. E. Cederblom	87

CONTENTS VIII The density of gases in the air and the discovery of argon, by Lord Rayleigh 90 **Biography Lord Rayleigh** 97 PHILIPP EDUARD A NTON VON LENARD 1905 Motivation 99 Presentation by A. Lindstedt 101 On cathode rays, by P. E. A. von Lenard 105 Biography P. E. A. von Lenard 135 **1906 JOSEPHJOHNTHOMSON** Motivation 139 Presentation by J. P. Klason 141 Carriers of negative electricity, by J. J. Thomson 145 Biography J. J. Thomson 154 A LBERT A BRAHAM M ICHELSON 1907 Motivation 157 Presentationby K. B. Hasselberg I59 Recent advances in spectroscopy, A. A. Michelson 166 Biography A. A. Michelson I79 1908 G ABRIEL LIPPMANN 181 Motivation Presentation by K. B. Hasselberg 183 Colour photography, by G. Lippmann 186 Biography G. Lippmann 189 GUGLIELMO M ARCONI a n d 1909 C ARL FERDINAND BRAUN Motivation 191 Presentation by H. Hildebrand 193 Wireless telegraphic communication, by G. Marconi 196 Biography G. Marconi 223 226 Electrical oscillations and wireless telegraphy, by C. F. Braun Biography C. F. Braun 246 1910 JOHANNES DIDERIKVAN DEB WAALS Motivation 249

	CONTENTS	IX
	Presentation by O. Montelius	25I
	The equation of state for gases and liquids,	
	by J. D. van der Waals	254
	Biography J. D. van der Waals	266
1911	W ILHELM W IEN	
	Motivation	269
	Presentation by E. W. Dahlgren	271
	On the laws of thermal radiation, by W. Wien	275
	Biography W. Wien	287
1912	N ILS G USTAF D A L É N	
	Motivation	291
	Presentation by H. G. Söderbaum	293
	Biography N. G. Dalén	298
1913	HEIKE KAMERLINGH ONNES	901
	Mouvalion Presentation by Th. Nordström	301 202
	Investigations into the properties of substances at law tempore	303
	tures which have led amongst other things to the proparation	
	of liquid holium by H Kamarlingh Oppos	306
	Riography H. Kamerlingh Onnes	300
	biography 11. Kameringh Onnes	337
1011	M ax von Laue	
1314	Motivation	341
	Presentation by G. Grangvist	343
	Concerning the detection of X-ray interferences,	
	by M. von Laue	347
	Biography M. von Laue	356
1915	W ILLIAM HENRY BRAGG and	
	W ILLIAM LAWRENCE BRAGG	
	Motivation	361
	Account of the Braggs' work by G. Granqvist	363
	Biography W. H. Bragg	368
	The diffraction of X-rays by crystals, by W. L. Bragg	370
	Biography W. L. Bragg	383

CONTENTS

1916 (Prize not awarded)	385
1917 CHARLES GLOVER BARKLA	
Motivation	387
Account of Barkla's work by G. Granqvist	389
Characteristic Röntgen radiation, by C. G. Barkla	392
Biography C. G. Barkla	400
1918 MAXPLANCK	
Motivation	403
Presentation by A. G. Ekstrand	405
The genesis and present state of development of the quantum	
theory, by M. Planck	407
Biography M. Planck	419
1919 JOHANNES STARK	
Motivation	421
Presentation by Å.G. Ekstrand	423
Structural and spectral changes of chemical atoms, by J. Stark	427
Biography J. Stark	436
1920 CHARLES- ÉDOUARD GUILLAUME	
Motivation	439
Presentation by Å. G. Ekstrand	441
Invar and elinvar, by CÉ. Guillaume	444
Biography CÉ. Guillaume	474
1921 ALBERTEINSTEIN	
Motivation	477
Presentation by S. Arrhenius	479
Fundamental ideas and problems of the theory of relativity,	
by A. Einstein	482
Biography A. Einstein	491
Name Index	493
Subject Index	499
Index of Biographies	500

X

Physics 1901

WILHELM CONRAD RÖNTGEN

<< recognition of the extraordinary services he has rendered by the discovery of the remarkable rays subsequently named after him >>

Physics 1901

Presentation Speech by the-former Rector of the National Archives C. T. Odhncr, President of the Royal Swedish Academy of Sciences

Your Royal Highnesses, Ladies and Gentlemen.

The Royal Swedish Academy of Sciences received from Alfred Nobel the privilege of awarding two of the great Prizes which he founded in his will - the Prizes in those branches of Science which lay nearest his heart - those in Physics and Chemistry. Now that the Royal Academy of Sciences has received from its Committees their expert opinion on the suggestions sent in, as well as their own suggestions, it has made its decision, and as current President 1 am here to make it known.

The Academy awarded the Nobel Prize in Physics to Wilhelm Conrad Röntgen, Professor in the University of Munich, for the discovery with which his name is linked for all time : the discovery of the so-called Röntgen rays or, as he himself called them, X-rays. These are, as we know, a new form of energy and have received the name <<rays>> on account of their property of propagating themselves in straight lines as light does. The actual constitution of this radiation of energy is still unknown. Several of its characteristic properties have, however, been discovered first by Röntgen himself and then by other physicists who have directed their researches into this field. And there is no doubt that much success will be gained in physical science when this strange energy form is sufficiently investigated and its wide field thoroughly explored. Let us remind ourselves of but one of the properties which have been found in Röntgen rays; that which is the basis of the extensive use of X-rays in medical practice. Many bodies, just as they allow light to pass through them in varying degrees, behave likewise with X-rays, but with the difference that some which are totally impenetrable to light can easily be penetrated by X-rays, while other bodies stop them completely. Thus, for example, metals are impenetrable to them; wood, leather, cardboard and other materials are penetrable and this is also the case with the muscular tissues of animal organisms. Now, when a foreign body impenetrable to X-rays, e.g. a bullet or a needle, has entered these tissues its location can be determined by illuminating the appropriate part of the body

PHYSICS 1901

with X-rays and taking a shadowgraph of it on a photographic plate, whereupon the impenetrable body is immediately detected. The importance of this for practical surgery, and how many operations have been made possible and facilitated by it is well known to all. If we add that in many cases severe skin diseases, e.g. lupus, have been successfully treated with Röntgen rays, we can say at once that Röntgen's discovery has already brought so much benefit to mankind that to reward it with the Nobel Prize fulfils the intention of the testator to a very high degree.

4

No Lecture was delivered by Professor W. Röntgen.

Biography

Wilhelm Conrad Röntgen was born on March 27, 1845, at Lennep in the Lower Rhine Province of Germany, as the only child of a merchant in, and manufacturer of, cloth. His mother was Charlotte Constanze Frowein of Amsterdam, a member of an old Lennep family which had settled in Amsterdam.

When he was three years old, his family moved to Apeldoorn in The Netherlands, where he went to the Institute of Martinus Herman van Doorn, a boarding school. He did not show any special aptitude, but showed a love of nature and was fond of roaming in the open country and forests. He was especially apt at making mechanical contrivances, a characteristic which remained with him also in later life. In 1862 he entered a technical school at Utrecht, where he was however unfairly expelled, accused of having produced a caricature of one of the teachers, which was in fact done by someone else.

He then entered the University of Utrecht in 1865 to study physics. Not having attained the credentials required for a regular student, and hearing that he could enter the Polytechnic at Zurich by passing its examination, he passed this and began studies there as a student of mechanical engineering. He attended the lectures given by Clausius and also worked in the laboratory of Kundt. Both Kundt and Clausius exerted great influence on his development. In 1869 he graduated Ph.D. at the University of Zurich, was appointed assistant to Kundt and went with him to Würzburg in the same year, and three years later to Strasbourg.

In 1874 he qualified as Lecturer at Strasbourg University and in 1875 he was appointed Professor in the Academy of Agriculture at Hohenheim in Würtemberg. In 1876 he returned to Strasbourg as Professor of Physics, but three years later he accepted the invitation to the Chair of Physics in the University of Giessen.

After having declined invitations to similar positions in the Universities of Jena(1886)andUtrecht(I888),h e accepted it from the University of Würzburg (1888), where he succeeded Kohlrausch und found among his collea-

BIOGRAPHY

gues Helmholtz and Lorenz. In 1899 he declined an offer to the Chair of Physics in the University of Leipzig, but in 1900 he accepted it in the University of Munich, by special request of the Bavarian government, as successor of E. Lommel. Here he remained for the rest of his life, although he was offered, but declined, the Presidency of the Physikalisch-Technische Reichsanstalt at Berlin and the Chair of Physics of the Berlin Academy.

Röntgen's first work was published in 1870, dealing with the specific heats of gases, followed a few years later by a paper on the thermal conductivity of crystals. Among other problems he studied were the electrical and other characteristics of quartz; the influence of pressure on the refractive indices of various fluids; the modification of the planes of polarised light by electromagnetic influences; the variations in the functions of the temperature and the compressibility of water and other fluids; the phenomena accompanying the spreading of oil drops on water.

Röntgen's name, however, is chiefly associated with his discovery of the rays that he called X-rays. In 1895 he was studying the phenomena accompanying the passage of an electric current through a gas of extremely low pressure. Previous work in this field had already been carried out by J. Plucker (1801-1868), J. W. Hittorf (1824-1914), C. F. Varley (1828-1883), E. Goldstein (1850-1931), Sir William Crookes (1832-1919), H. Hertz (1857-1894) and Ph. von Lenard (1862-1947), and by the work of these scientists the properties of cathode rays-the name given by Goldstein to the electric current established in highly rarefied gases by the very high tension electricity generated by Ruhmkorff's induction coil- had become well known. Röntgen's work on cathode rays led him, however, to the discovery of a new and different kind of rays.

On the evening of November 8, 1895, he found that, if the discharge tube is enclosed in *a* sealed, thick black carton to exclude all light, and if he worked in a dark room, a paper plate covered on one side with barium platinocyanide placed in the path of the rays became fluorescent even when it was as far as two metres from the discharge tube. During subsequent experiments he found that objects of different thicknesses interposed in the path of the rays showed variable transparency to them when recorded on a photographic plate. When he immobilised for some moments the hand of his wife in the path of the rays over a photographic plate, he observed after development of the plate an image of his wife's hand which showed the shadows thrown by the bones of her hand and that of a ring she was wearing, surrounded by the penumbra of the flesh, which was more permeable to the rays and there-

$1\ 9\ 0\ 1\ W$. C . R Ö N T G E N

fore threw a fainter shadow. This was the first <<rontgenogram>> ever taken.

In further experiments, Röntgen showed that the new rays are produced by the impact of cathode rays on a material object. Because their nature was then unknown, he gave them the name X-rays. Later, Max von Laue and his pupils showed that they are of the same electromagnetic nature as light, but differ from it only in the higher frequency of their vibration.

Numerous honours were showered upon him. In several cities, streets were named after him, and a complete list of Prizes, Medals, honorary doctorates, honorary and corresponding memberships of learned societies in Germany as well as abroad, and other honours would fill a whole page of this book. In spite of all this, Röntgen retained the characteristic of a strikingly modest and reticent man. Throughout his life he retained his love of nature and outdoor occupations. Many vacations were spent at his summer home at Weilheim, at the foot of the Bavarian Alps, where he entertained his friends and went on many expeditions into the mountains. He was a great mountaineer and more than once got into dangerous situations. Amiable and courteous by nature, he was always understanding the views and difficulties of others. He was always shy of having an assistant, and preferred to work alone. Much of the apparatus he used was built by himself with great ingenuity and experimental skill.

Röntgen married Anna Bertha Ludwig of Zurich, whom he had met in the cafe run by her father. She was a niece of the poet Otto Ludwig. They married in 1872 in Apeldoorn, The Netherlands. They had no children, but in 1887 adopted Josephine Bertha Ludwig, then aged 6, daughter of Mrs. Röntgen's only brother. Four years after his wife, Röntgen died at Munich on February 10, 1923, from carcinoma of the intestine. Physics 1902

HENDRIK ANTOON LORENTZ

PIETER ZEEMAN

<<in recognition of the extraordinary service they rendered by their researches into the influence of magnetism upon radiation phenomena >>

Physics 1902

Presentation Speech by Professor Hj. Théel, President of the Royal Swedish Academy of Sciences

Your Majesty, Your Royal Highnesses, Ladies and Gentlemen.

The Royal Swedish Academy of Sciences has decided to award this year's Nobel Prize for Physics to Professor Dr. Hendrik Antoon Lorentz of Leiden and Professor Dr. Pieter Zeeman of Amsterdam for their pioneering work on the connection between optical and electromagnetic phenomena.

Since the law of the conservation of energy was recognized as the first basic principle of modern physics, no realm of that science during the remarkable developments which have been based on this foundation has proved more fruitful than that which has had as its object the investigation of the connection between the phenomena of light and electricity.

Faraday, the great founder of the modern science of electricity, suspected this connection and devoted a great part of his experimental research to this very question. However, Maxwell was the first to take up Faraday's ideas again and develop them into a complete mathematical theory. According to this theory electrodynamic effects are transmitted through space at a finite speed and cause electrical currents, so-called displacement currents, even in non-conductors. Hence, every electrical current of periodically changing direction gives rise to an electrical wave motion, and light consists of just such a wave motion with an extremely short period.

This so-called electromagnetic theory of light of Maxwell's at first aroused comparatively little interest. Twenty years after its first appearance however it led to a scientific discovery which demonstrated its great significance in no uncertain manner. The German physicist Heinrich Hertz then succeeded in demonstrating that the electrical vibrations - which are generated under certain conditions when an electrically charged body is discharged are propagated through the surrounding space in the form of a wave motion, and that the wave motion spreads at the speed of light and also possesses its properties. This gave a firm experimental basis for the electromagnetic theory of light.

In certain respects however Maxwell's theory of light was inadequate, in that it left individual phenomena unexplained. The greatest credit for the

P H Y S I C S 1 9 0 2

further development of the electromagnetic theory of light is due to Professor Lorentz, whose theoretical work on this subject has borne the richest fruit. While Maxwell's theory is free from any assumptions of an atomistic nature, Lorentz starts from the hypothesis that in matter extremely small particles, called electrons, are the carriers of certain specific charges. These electrons move freely in so-called conductors and thus produce an electrical current, whereas in non-conductors their movement is apparent through electrical resistance. Starting from this simple hypothesis, Lorentz has been able not only to explain everything that the older theory explained but, in addition, to overcome some of its greatest shortcomings.

Alongside the theoretical development of the electromagnetic theory of light, experimental work also continued without interruption, and attempts were made to demonstrate in every detail the analogy between electrical wave motion and light. However, it was not sufficient to show a complete analogy between these phenomena; scientists wished far more to show that they were identical in nature, and to this end they attempted to demonstrate that magnetic forces act upon light in the same way as upon electric currents. It is this that Faraday was trying to prove, and the relevant experiments carried out by him led to the discovery of the rotation of the polarization plane of light by the effect of magnetic forces. His attempt to demonstrate the influence of magnetism on the radiation from a source of light - the last experiment with which Faraday was occupied -was, however, unsuccessful.

Professor Zeeman has recently succeeded in solving just this problem, which has up till now been the object of fruitless exertions on the part of many perspicacious research workers. Guided by the electromagnetic theory of light, Zeeman took up Faraday's last experiment, and, after many unsuccessful attempts, finally succeeded in demonstrating that the radiation from a source of light changes its nature under the influence of magnetic forces in such a way that the different spectral lines of which it consisted were resolved into several components. The consequences of this discovery give a magnificent example of the importance of theory to experimental research. Not only was Professor Lorentz, with the aid of his electron theory, able to explain satisfactorily the phenomena discovered by Professor Zeeman, but certain details which had hitherto escaped Professor Zeeman's attention could also be foreseen, and were afterwards confirmed by him. He showed, in fact, that the spectral lines which were split under the influence of magnetism consisted of polarized light, or in other words that the light vibrations are orientated in one particular way under the influence of the magnetic force, and in a way which varies according to the direction of the beam of light in relation to this force.

For the physicist this discovery - the Zeeman effect - represents one of the most important experimental advances that recent decades have to show. For, through the demonstration that light is affected by magnetism in accordance with the same laws as vibrating electrically charged particles, clearly not only has the strongest support been given to the electromagnetic theory of light, but the consequences of Zeeman's discovery promise to yield the most interesting contributions to our knowledge of the constitution of spectra and of the molecular structure of matter. For these reasons the Swedish Royal Academy of Sciences has come to the conclusion that the discovery outlined here is of such great importance for the understanding of the connection between the forces of Nature and for the development of physical science that its recognition by the award of the Nobel Prize for Physics is justified. The Academy also bore in mind the great part which Professor Lorentz has played in the following up of this discovery through his masterly theory of electrons, which is moreover of the greatest significance as a guiding principle in various other realms.

Since the discovery in physics which the Royal Academy of Sciences wishes to recognize on this occasion represents the result of the most perspicacious research, both theoretical and experimental, the Academy considers that a division of the Nobel Prize for Physics between the two outstanding research workers, Professor Lorentz and Professor Zeeman, for their work on the connection between light and magnetism, is not only justified, but just.

The theory of electrons and the propagation of light

Nobel Lecture, December 11, 1902

When Professor Zeeman and I received the news of the great honour of the high distinction awarded to us, we immediately began to consider how we could best divide our roles with respect to our addresses. Professor Zeeman was first to have described the phenomenon discovered by him, given the explanation of it, and given an outline of his later experimental work. My task should have been to consider rather more deeply our present-day knowledge of electricity, in particular the so-called electron theory.

I am more sorry than I can say that Professor Zeeman has been prevented by illness from undertaking the journey to Stockholm, and that therefore you will now only be able to hear the second half of our programme. I hope you will excuse me if under these circumstances I say only a little about the main theme, Zeeman's fine discovery. A short description of it, however, might well precede my further thoughts.

As is well known to you, Faraday even in his day discovered that magnetic forces can have an effect on the propagation of light. He showed in fact that in suitable conditions the vibrations of a beam of polarized light can be made to rotate by such forces. Many years later Kerr found that such a beam of light also undergoes similar changes when it is simply reflected from the polished pole of a magnet. However, it remained for Zeeman's talent to show that a magnetic field affects not only the propagation and reflection of light but also the processes in which the beam of light originates, that is to say that the rays emitted by a light source assume different properties if this source is placed in the gap between a magnetic north and south pole. The difference is shown in the spectral resolution of the light, when one is working with the type of light source whose spectrum consists of single bright lines

- that is, with a coloured flame, an electrical spark, or a Geissler tube. To have a specific case before your eyes, imagine that my hands are the two poles, only much closer together than I am holding them now, and that the light source is between these poles, that is to say in the space immediately in front of me. Now if the spectrum of the light which shines on a point directly opposite me is investigated, there can be observed, instead of a single spectral line such as can be seen under normal circumstances, a three-fold line, or triplet, whose components admittedly are separated from each other by a very small distance. Since each position in the spectrum corresponds to a specific frequency of light, we can also say that instead of light of one frequency the source is, under the influence of the magnetic field, emitting light of three different frequencies. If the spectrum consists of more than one line, then you can imagine that each line is resolved into a triplet. I must, however, add that the situation is not always as simple as this, and many spectral lines resolve into more than three components.

Before turning to the theory, I should like to remark that thanks to the speedy publication of research and the consequent lively exchange of views between scientists much progress must be considered as the result of a great deal of joint effort. Since it is expected of me, I am going to talk principally of my own ideas and the way in which I have come to them. I do beg of you, however, not to lose sight of the fact that many other physicists, not all of whom I can name in this short space of time, have arrived at the same or very similar conclusions.

The theory of which I am going to give an account represents the physical world as consisting of three separate things, composed of three types of building material: first ordinary tangible or ponderable matter, second electrons, and third ether. I shall have very little to say about ponderable matter, but so much the more about ether and electrons. I hope it will not be too much for your patience.

As far as the ether-that bearer of light which fills the whole universe - is concerned, after Faraday's discovery which I have already mentioned and also independently of it, many attempts were made to exploit the ether in the theory of electricity also. Edlund went so far as to identify the electric fluid with the ether, ascribing to a positively charged body an excess of ether and to a negatively charged one a deficiency of ether. He considered this medium as a liquid, subject to the Archimedean principle, and in this way succeeded in imputing all electrostatic effects to the mutual repulsion of particles of ether.

There was also a place in his theory for the electrodynamic attraction and repulsion between two metallic wires with electrical current flowing in them. Indeed, he formed a most remarkable conception of these effects. He explained them by the condition that the mutual repulsion of two particles of ether needs a certain time to be propagated from the one to the other; it was in fact an axiom with him that everything which occurs in Nature takes a

1902 H.A. LORENTZ

certain length of time, however short this may be. This idea, which has been fully developed in our present-day views, is found also in the work of other older physicists. I need only mention Gauss, of whom we know that he did not follow this up only because he lacked a clear picture of the propagation. Such a picture, he wrote to Wilhelm Weber, would be the virtual keystone of a theory of electrodynamics.

The way pioneered by Edlund, in which the distinction between ether and electricity was completely swept aside, was incapable of leading to a satisfactory synthesis of optical and electrical phenomena. Lorenz at Copenhagen came nearer the goal. You know, however, that the true founders of our present views on this subject were Clerk Maxwell and Hertz. In that Maxwell developed further and constructed a basis for the ideas put forward by Faraday, he was the creator of the electromagnetic theory of light, which is undoubtedly well known to you in its broad outline. He taught us that light vibrations are changes of state of the same nature as electric currents. We can also say that electrical forces which change direction extremely rapidly - many billions of times a second - are present in every beam of light. If you imagine a tiny particle in the path of a sunbeam, something like the familiar dust motes in the air, only considerably smaller, and if you also imagine that this particle is electrically charged, then you must also suppose that it is set into a rapid quivering movement by the light vibrations.

Immediately after Maxwell I named Hertz, that great German physicist, who, if he had not been snatched from us too soon, would certainly have been among the very first of those whom your Academy would have considered in fulfilling your annual task. Who does not know the brilliant experiments by which he confirmed the conclusions that Maxwell had drawn from his equations? Whoever has once seen these and learnt to understand and admire them can no longer be in any doubt that the features of the electromagnetic waves to be observed in them differ from light beams only in their greater wavelength.

The result of these and other investigations into the waves propagated in the ether culminate in the realization that there exists in Nature a whole range of electromagnetic waves, which, however different their wavelengths may be, are basically all of the same nature. Beginning with Hertz's <<rays of electrical force >>, we next come to the shortest waves caused by electromagnetic apparatus and then, after jumping a gap, to the dark thermal rays. We traverse the spectrum far into the ultraviolet range, come across another gap, and may then put X-rays, as extremely short violent electromagnetic disturbances of the ether, at the end of the range. At the beginning of the range, even before the Hertzian waves, belong the waves used in wireless telegraphy, whose propagation was established last summer from the southwest tip of England to as far as the Gulf of Finland.

Although it was principally Hertz's experiments that turned the basic idea of Maxwell's theory into the common property of all scientists, it had been possible to start earlier with some optimism on the task of applying this theory to special problems in optics. We will begin with the simple phenomenon of the refraction of light. It has been known since the time of Huygens that this is connected with the unequal rate of propagation of the beams of light in different substances. How does it come about, however, that the speed of light in solid, liquid, and gaseous substances differs from its speed in the ether of empty space, so that it has its own value for each of these ponderable substances; and how can it be explained that these values, and hence also the refractive index, vary from one colour to another?

In dealing with these questions it appeared once more, as in many other cases, that much can be retained even from a theory which has had to be abandoned. In the older theory of undulation, which considered the ether as an elastic medium, there was already talk of tiny particles contained in ponderable substances which could be set in motion by light vibrations. The explanation of the chemical and heating action of light was sought in this transmission of motion, and a theory of colour dispersion had been based on the hypothesis that transparent substances, such as glass and water, also contained particles which were set into co-vibration under the influence of a beam of light. A successor to Maxwell now has merely to translate this conception of co-vibrating particles into the language of the electromagnetic theory of light.

Now what must these particles be like if they can be moved by the pulsating *electrical* forces of a beam of light? The simplest and most obvious answer was: they must be electrically charged. Then they will behave in exactly the same way as the tiny charged dust motes that we spoke of before, except that the particles in glass and water must be represented, not as floating freely, but as being bound to certain equilibrium positions, about which they can vibrate.

This idea of small charged particles was otherwise by no means new; as long as 25 years ago the phenomena of electrolysis were being explained by ascribing positive charges to the metallic atoms in a solution of a salt, and negative charges to the other components of the salt molecule. This laid the foundation of modern electrochemistry, which was to develop so rapidly once Prof. Arrhenius had expressed the bold idea of progressive dissociation of the electrolyte with increasing dilution.

We will return to the propagation of light in ponderable matter. The covibrating particles must, we concluded, be electrically charged; so we can conveniently call them <<electrons>>), the name that was introduced later by Johnstone Stoney. The exact manner in which this co-vibration takes place, and what reaction it has on the processes in the ether, could be investigated with the aid of the well-known laws of electromagnetism. The result consisted of formulae for the velocity of propagation and the refractive indices, in their dependence on the one hand on the vibration period-i.e. on the colour of the light - and on the other hand on the nature and number of the electrons.

You will forgive me if I do not quote the rather complicated equations, and only give some account of their significance. In the first place, as regards the dependence of the refractive index on vibration period - that is, colour dispersion: in the prismatic spectrum and in rainbows we see a demonstration of the fact that the electrons in glass and water possess a certain mass; consequently they do not follow the vibrations of light of different colours with the same readiness.

Secondly, if attention is focussed on the influence of the greater or smaller number of particles in a certain space an equation can be found which puts us in a position to give the approximate change in the refractive index with increasing or decreasing density of the body - thus, for example, it is possible to calculate the refractive index of water vapour from that of water. This equation agrees fairly well with the results of experiments.

When I drew up these formulae I did not know that Lorenz at Copenhagen had already arrived at exactly the same result, even though he started from different viewpoints, independent of the electromagnetic theory of light. The equation has therefore often been referred to as the formula of Lorenz and Lorentz.

This formula is accompanied by another which makes it possible to deduce the refractive index of a chemical compound from its composition, admittedly only in rough approximation as was possible earlier with the aid of certain empirical formulae.

The fact that such a connection between the refraction of light and the chemical composition does exist at all is of great importance in the electromagnetic theory of light. It shows us that the power of refraction is not one of those properties of matter which are completely transformed by the action of chemical combination. The relative positions of, and type of bond between, the atoms are not of primary importance as concerns the speed of propagation in a compound. Only the number of atoms of carbon, hydrogen, etc. is of importance; each atom plays its part in the refraction of light, unaffected by the behaviour of the others. In the face of these results we find it hard to imagine that the forces which bind an electron to its equilibrium position and on the intensity of which depends the velocity of light are generated by a certain number of neighbouring atoms. We conclude rather that the electron, together with whatever it is bound to, has its place within a single atom; hence, electrons are smaller than atoms.

Permit me now to draw your attention to the ether. Since we learnt to consider this as the transmitter not only of optical but also of electromagnetic phenomena, the problem of its nature became more pressing than ever. Must we imagine the ether as an elastic medium of very low density, composed of atoms which are very small compared with ordinary ones? IS it perhaps an incompressible, frictionless fluid, which moves in accordance with the equations of hydrodynamics, and in which therefore there may be various turbulent motions? Or must we think of it as a kind of jelly, half liquid, half solid ?

Clearly, we should be nearer the answers to these questions if it were possible to experiment on the ether in the same way as on liquid or gaseous matter. If we could enclose a certain quantity of this medium in a vessel and compress it by the action of a piston, or let it flow into another vessel, we should already have achieved a great deal. That would mean displacing the ether by means of a body set in motion. Unfortunately, all the experiments undertaken on these lines have been unsuccessful; the ether always slips through our fingers. Imagine an ordinary barometer, which we tilt so that the mercury rises to the top, filling the tube completely. The ether which was originally above the mercury must be somewhere; it must have either passed through the glass or been absorbed into the metal, and that without any force that we can measure having acted upon it. Experiments of this type show that bodies of normal dimensions, as far as we can tell, are completely permeable to the ether. Does this apply equally to much larger bodies, or could we hope to displace the ether by means of some sort of very-large, very-fast moving piston? Fortunately, Nature performs this experiment on a large scale. After all, in its annual journey round the sun the earth travels through space at a speed more than a thousand times greater

1902 H.A. LORENTZ

than that of an express train. We might expect that in these circumstances there would be an end to the immobility of the ether; the earth would push it away in front of itself, and the ether would flow to the rear of the planet, either along its surface or at a certain distance from it, so as to occupy the space which the earth has just vacated. Astronomical observation of the positions of the heavenly bodies gives a sharp means of determining whether this is in fact the case; movements of the ether would assuredly influence the course of the beams of light in some way.

Once again we get a negative answer to our question whether the ether moves. The direction in which we observe a star certainly differs from the true direction as a result of the movement of the earth - this is the so-called aberration of light. However, by far the simplest explanation of this phenomenon is to assume that the whole earth is completely permeable to the ether and can move through it without dragging it at all. This hypothesis was first expressed by Fresnel and can hardly be contested at present.

If we wish to give an account of the significance of this result, we have one more thing to consider. Thanks to the investigations of Van der Waals and other physicists, we know fairly accurately how great a part of the space occupied by a body is in fact filled by its molecules. In fairly dense substances this fraction is so large that we have difficulty in imagining the earth to be of such loose molecular structure that the ether can flow almost completely freely through the spaces between the molecules. Rather are we constrained to take the view that each individual molecule is permeable. The simplest thing is to suggest further that the same is true of each atom, and this leads us to the idea that an atom is in the last resort some sort of local modification of the omnipresent ether, a modification which can shift from place to place without the medium itself altering its position. Having reached this point, we can consider the ether as a substance of a completely distinctive nature, completely different from all ponderable matter. With regard to its inner constitution, in the present state of our knowledge it is very difficult for us to give an adequate picture of it.

I hardly need to mention that, quite apart from this question of constitution, it will always be important to come to a closer understanding of the transmission of apparent distant actions through the ether by demonstrating how a liquid, for example, can produce similar effects. Here I am thinking in particular of the experiments of Prof.Bjerknes in Christiania*

* Now Oslo.

on transmitted hydrodynamic forces and of his imitation of electrical phenomena with pulsating spheres.

I come now to an important question which is very closely connected with the immobility of the ether. You know that in the determination of the velocity of sound in the open air, the effect of the wind makes itself felt. If this is blowing towards the observer, the required quantity will increase with the wind speed, and with the wind in the opposite direction the figure will be reduced by the same amount. If, then, a moving transparent body, such as flowing water, carries along with it in its entirety the ether it contains, then optical phenomena should behave in much the same way as the acoustical phenomena in these experiments. Consider for example the case in which water is flowing along a tube and a beam of light is propagated within this water in the direction of flow. If everything that is involved in the light vibrations is subject to the flowing movement, then the propagation of light in the flowing water will in relation to the latter behave in exactly the same way as in still water. The velocity of propagation relative to the wall of the tube can be found by adding the velocity of propagation in the water to the rate of flow of the water, just as, if a ball is rolling along the deck of a ship in the direction in which it is travelling, the ball moves relative to an observer on the shore at the sum of two speeds - the speed of the ship and the speed at which the ball is rolling on it. According to this hypothesis the water would drag the light waves at the full rate of its own flow.

We come to a quite different conclusion if we assume, as we now must, that the ether contained in the flowing water is itself stationary. As the light is partly propagated through this ether, it is easy to see that the propagation of the light beams, for example to the right, must take place more slowly than it would if the ether itself were moving to the right. The waves are certainly carried along by the water, but only at a certain fraction of its rate of flow. Fresnel has already demonstrated the size of this fraction; it depends on the refractive index of the substance - the value for water, for example, being 0.44. By accepting this figure it is possible to explain various phenomena connected with aberration. Moreover, Fresnel deduced it from a theoretical standpoint which, however ingenious it may be, we can now no longer accept as valid.

In 1851 Fizeau settled the question by his famous experiment in which he compared the propagation of light in water flowing in the direction of the beam of light with its propagation in water flowing in the opposite direction. The result of these experiments, afterwards repeated with the same

1902 H.A.LORENTZ

result by Michelson and Morley, was in complete agreement with the values assumed by Fresnel for the drag coefficient.

There now arose the question of whether it is possible to deduce this value from the new theory of light. To this end it was necessary first of all to develop a theory of electromagnetic phenomena in moving substances, with the assumption that the ether does not partake of their motion. To find a starting-point for such a theory, I once again had recourse to electrons. I was of the opinion that these must be permeable to the ether and that each must be the centre of an electric and also, when in motion, of a magnetic field. For conditions in the ether I introduced the equations which have been generally accepted since the work of Hertz and Heaviside. Finally I added certain assumptions about the force acting on an electron, as follows: this force is always due to the ether in the immediate vicinity of the electron and is therefore affected *directly* by the state of this ether and *indirectly* by the charge and velocity of the other electrons which have brought about this state. Furthermore, the force depends on the charge and speed of the particle which is being acted upon; these values determine as it were the sensitivity of the electron to the action due to the ether. In working out these ideas I used methods deriving from Maxwell and partly also relied on the work of Hertz. Thus I arrived at the drag coefficient accepted by Fresnel, and was able to explain in a fairly simple way most of the optical phenomena in moving bodies.

At the same time, a start was made on a general theory which ascribed all electromagnetic processes taking place in ponderable substances to electrons. In this theory an electrical charge is conceived as being a surplus of positive or negative electrons, but a current in a metallic wire is considered to be a genuine progression of these particles, to which is ascribed a certain mobility in conductors, whereas in non-conductors they are bound to certain equilibrium positions, about which, as has already been said, they can vibrate. In a certain sense this theory represents a return to the earlier idea that we were dealing with two electrical substances, except that now, in accordance with Maxwell's ideas, we have to do with actions which are transmitted through ether and are propagated from point to point at the velocity of light. Since the nature and manner of this transmission can be followed up in all its details, the demand that Gauss made for a theory of electrodynamics is fulfilled. I cannot spend any more time on these matters, but would like to mention that Wiechert at Göttingen and Larmor at Cambridge have produced very similar results, and that Prof.Poincart has also contributed much to the development and evaluation of the theory.

I must also pass over many phenomena investigated in recent years, in which the concept of electrons has proved a useful guide, in order not to stray too far from the theory of the Zeeman effect.

When Prof. Zeeman made his discovery, the electron theory was complete in its main features and in a position to interpret the new phenomenon. A man who has peopled the whole world with electrons and made them covibrate with light will not scruple to assume that it is also electrons which vibrate within the particles of an incandescent substance and bring about the emission of light. An oscillating electron constitutes, as it were, a minute Hertzian vibrator; its effect on the surrounding ether is much the same as the effect we have when we take hold of the end of a stretched cord and set up the familiar motion waves in the rope by moving it to and fro. As for the force which causes a change in the vibrations in a magnetic field, this is basically the force, the manifestations of which were first observed by Oersted, when he discovered the effect of a current on a compass needle.

I will leave the explanation of triplets to Prof. Zeeman. I will confine myself to remarking that it is the negative electrons which oscillate, and that from the distance between the components into which the spectral line is resolved the ratio between the numerical value of the charge and the mass of these particles can be deduced. The results are in gratifying agreement with those which have been found in other contexts. The same or similar values for the ratio mentioned above have been found for the negative particles with which we are concerned in cathode rays.

A noteworthy aspect is the enormous size of the charge of these particles compared with their mass. A numerical example will give you some idea of this. Imagine that we had two iron spheres, each with a radius of one metre, situated ten metres apart, and that we gave each of them a surplus of our negative electrons of such a size that the mass of this surplus *was* the millionth part of a milligram. The spheres would then repel each other with a force equivalent to a weight of more than 80,000 kilograms and would therefore be able to reach a speed of many metres per second. I need hardly say that we are far from being able to make an experiment on this scale; we are not in a position to bring such a large number of electrons of one certain kind together on one body. If it were possible, we could carry out many interesting experiments which we can now only imagine. For instance, we could demonstrate the Zeeman effect on a simple pendulum. This can easily be made to swing in a circle, and if the bob is given an electrical charge the vertical component of the earth's magnetic field somewhat alters the period

1902 H.A.LORENTZ

of rotation, which is increased in one direction and reduced in the other. With the charges which we have at our disposal this difference is completely imperceptible, and Prof.Zeeman himself would be unable to observe the Zeeman effect on a pendulum.

Let us now turn from the relative sizes of charge and mass to their absolute values. We can at least give an estimate of these. If we combine the results to which Zeeman's experiments lead with those which can be deduced from the colour dispersion of gases, on the hypothesis that it is the same type of electrons which is under consideration in both cases, we come to the conclusion that the charge of an electron is of the same order of size as the charge of an electrolytic ion. The mass, however, is much smaller about one eight-hundredth part of that of a hydrogen atom. J. J. Thomson at Cambridge has confirmed this result by a completely different method. At present we are not concerned with the exact value; the principal thing is that, as we have remarked before, the electron is very small compared with the atom. The latter is a composite structure, which can contain many electrons, some mobile, some fixed ; perhaps it bears electrical charges which are not concentrated at single points but distributed in some other way.

Of the other magneto-optical phenomena I will only describe one in any greater detail. Soon after Zeeman had published his discovery the Russian physicists Egorov and Georgievsky found that a sodium flame situated between the poles of an electromagnet emitted partially polarized light - i.e., in its beams vibrations in a certain direction were present with a greater intensity than vibrations in the direction perpendicular to this. To describe this phenomena to you more exactly and at the same time to make clear how it is to be explained, I ask you to imagine once more that my hands are opposing magnetic poles and that the sodium flame is placed between them. Now if you were exactly opposite me, you would observe that the vertical electrical vibrations have a greater intensity than the horizontal ones.

This is connected with the fact that the flame has a certain thickness and that the beams emitted by the back half are partly swallowed up again as they pass through the front half. In accordance with a familiar rule, this absorption effect is strongest when all the incandescent particles in the flame are vibrating with the same period. It diminishes, and the flame therefore becomes brighter, as soon as this uniformity of the period of vibration is disturbed in any way. Now the magnetic field does this, in that instead of one common period of vibration it causes several to come into play. However, the increase in illuminating power brought about in this way is restricted to the vertical vibrations in the flame that we are imagining. The horizontal vibrations of the electrons, from right to left and back again, are - it follows from the principles of the theory - not at all influenced by the magnetic field.

The conclusion therefore is that of the vibrations emitted only the vertical ones and not the horizontal ones are reinforced, which is the cause of the phenomenon we have observed.

I may add that this phenomenon is one of those magneto-optical effects which are most easily observed. The explanation given can also be put to the proof by the use of two flames instead of one, and an investigation of the absorption to which the light of the rear one is subject in the front one which has been situated between the magnetic poles.

Now that I have come to absorption, I must also consider the masterly and important theoretical considerations to which Prof. Voigt at Göttingen has been led by Zeeman's discovery. His theory differs from mine in that he always has in mind, not the emission of light, but its absorption. He explains the so-called *inverse* Zeeman effect-that is, the phenomenon that, when a strong white light is transmitted through the flame situated between the poles, instead of an absorption stripe we get a triplet of dark lines. On the basis of the parallelism between absorption and emission, it is possible to work back from this inverse phenomenon to the direct one.

Voigt does not refer to vibrating electrons ; he is content to add appropriately chosen new terms to the equations which represent propagation in *an* absorbent medium. This method throws into relief the connection between the Zeeman effect and the rotation of the direction of vibration which was discovered by Faraday, and has other advantages, namely when vapours of rather high density, with correspondingly wider spectral lines, are concerned. Professor Zeeman will be able to give you an example of the effects of Voigt's theory.

However, any one who sets himself the task of drawing conclusions about the nature of the vibrations of electrons from these observations will, I think, prefer to choose the emission from very rarefied gases as an object of study. Here the radiation from the single molecules or atoms, undimmed by their effects on each other, *is* mirrored by the sharp lines in the spectrum. I followed this course in my later research, but came across considerable difficulties due to the fact that although the simple triplet frequently appears, in many cases there is resolution into more than three lines. This is a stumblingblock in the way of the theory. At all events it is easy to draw some general

1902 H.A.LORENTZ

rules about the state of polarization of the light beams corresponding to the different components - i.e., the shape and direction of their vibrations, but unfortunately I have hardly got any further.

As long as we have to deal only with resolution into three components, it is sufficient explanation to assume that each incandescent atom contains a single electron which can vibrate round its equilibrium position in all directions in the same way. This simple theory however leaves us high and dry as soon as the spectral lines split into more than three components in the magnetic field. It is obvious then that we must imagine atoms of more complicated structure, which are provided with electrical charges, and the parts of which are capable of making small vibrations, rather like the parts of an elastic resonant body. When I investigated the theory of such movements, which can be done without much difficulty, it became evident that such an arbitrary system would in general show no Zeeman effect at all.

However, no mathematical theory is necessary to perceive this and to find the condition necessary to bring about such an effect. Imagine a light source which shows a Zeeman triplet under the influence of a magnetic field. The three lines naturally cannot appear unless three types of vibration with slightly d&rent periods are present in the particles of the light source. These periods however can only be different if the directions of movement or the shapes of the path in the three cases are not the same. We will say in short that we are dealing with three different *vibration patterns*, each with its own frequency, in the light source.

We will now gradually reduce the intensity of the magnetic field and finally let it disappear. As long as even a weak field is present, the three lines persist, only they draw nearer each other; the three vibration patterns thus always exist, but their frequencies approach a common limiting value, the frequency of the unresolved spectral line. In this way we come to suppose that even when we observe the latter, the three patterns of movement still exist, though without distinguishing themselves from each other by their frequency as is the case in a magnetic field. It can be expressed thus: the spectral line is already three-fold before the magnetic force comes into play, and this force has nothing else to do except, as it were, to push apart the three lines which originally coincided.

The same applies to a four-, five- or six-fold line, and you may rest assured that a spectral line will never resolve into six components unless, before the magnetic field is set up, each incandescent particle can vibrate in six different ways, that is, with exactly the same frequency. Herein lies one necessary condition which is not quite so easy to fulfil. I could add a second condition for the appearance of clear-cut components of the spectral lines, but the one I have described should suffice to show that in the further development of the theory we cannot give free rein to our imagination. Instead, we are fairly limited in the choice of hypotheses. A suitable model of a vibrating atom would be an elastic spherical shell with a uniformly distributed electrical charge, whose surface is divided by nodal lines into a greater or lesser number of fields vibrating in different directions. However, I will not linger over the phenomena which appear in such models, for I fear I might wander too far from reality along these paths.

I have tried to delineate in broad outline how much - or it would be better to say, how little - the electron theory has achieved in the explanation of the new magneto-optical phenomena. If I were now to give an account of the experimental work, it would become clear that the experiments have made more considerable advances. The research workers have already made a start on comparing the different spectral lines of a chemical element with each other, with respect to their magnetic resolution, and on investigating the connection between this resolution and the regular relationships existing in spectra.

In this country, where the father of my worthy colleague Angstrom, and Prof. Thalén have worked, and where Prof. Hasselberg continued his observations and measurements with indefatigable diligence, I hardly need to say how wonderful and rich a world these investigations into spectra have opened up to us. A world whose laws we are beginning to understand. It has become apparent that many line spectra are constructed according to a definite type; the lines are arranged in certain series, and in such a way that each series consists of lines which are distributed over the spectrum in accordance with a fairly simple law, and moreover there are relationships between the one series and the next. These relationships, in the clarification of which Prof. Rydberg and the German physicists Kayser and Runge have been particularly prominent, suggest a connection between the magnetic resolution of lines belonging to the same series. Such a connection has now in fact been confirmed. Runge and Paschen have found, in their investigation of the Zeeman effect in mercury, that all the lines of one series are resolved in exactly the same way.

I am convinced that the theory will only make significant progress when it also turns its attention not simply to one single spectral line but to all the lines of a chemical element. When once we succeed in building a theoretical

1902 H.A.LORENTZ

foundation for the structure of spectra, then and not before then will we be able to grasp successfully the more complicated forms of the Zeeman effect. It would be better to say: in the future, research into the regular relationships in the spectra and into the Zeeman effect must go hand in hand; thus they will be able to lead some day to a theory of light emission, the achievement of which is one of the greatest aims of present-day physics.

The electron theory also presents an enormous field of study outside the realm of magneto-optical phenomena. For one thing, the free-moving electrons, with which we are concerned in cathode rays and in some types of Becquerel rays, give rise to many interesting problems. I will single out only the important question of the so-called apparent mass of these particles. A definite magnetic field in the surrounding ether - and hence also a certain amount of energy in this medium - are inextricably connected with every movement of an electron; we can therefore never set an electron in motion without simultaneously imparting energy to the ether. To do this a great amount of work is necessary, and we must employ a greater force than if it were not necessary to set up this magnetic field. Calculation shows that the force required is the same as would be needed if the mass were somewhat greater than it is in reality. In other words, if we determine the mass in the usual way from the phenomena, we get the true mass increased by an amount which we can call the apparent, or electromagnetic, mass. The two together form the effective mass which determines the phenomena.

Now the investigations published by Kaufmann and Abraham in the past year have shown that the apparent mass is by no means to be discounted. It certainly forms a considerable part of the effective mass, and there is a possibility that in the end we shall have to ascribe apparent mass only and never true mass at all to electrons.

The peculiar thing about this apparent mass is, moreover, that it is not constant, but depends on the velocity; consequently the study of the motion of the electron differs in many ways from ordinary dynamics.

It is hard to say if it will ever be possible to examine further with any success the question of the nature of an electron, which the research I have mentioned has already touched on. Meanwhile, even without ascertaining this, we can continue to test the basic assumptions of the theory in practice, and to draw from the properties of ponderable matter conclusions about the electrons it contains. The conductivity of electricity and heat by metals, thermoelectricity, permanent and temporary magnets, heat radiation and absorption, the optical, electrical and magnetic properties of crystals - all
these aspects promise us a rich harvest. And even farther fields are opening up to our view. If it is true, as had been concluded from optical experiments, that the dimensions of a ponderable body undergo a slight alteration as soon as it moves through the motionless ether, we must conclude that molecular forces are transmitted through the ether in a way similar to electrical effects, and that leads to the idea that these forces are basically of an electromagnetic nature and the material particles among which they exist are composed of electrons - or, at least, the electrical charges of these particles are not something accidental but something very significant, also where molecular forces are concerned.

Thus we hope that the electron hypothesis, as it is being taken up in widely different sectors of physics, will lead to a general theory embracing many aspects of physics and also of chemistry. Perhaps it will be itself completely transformed on the long journey; however, there can hardly be any doubt that our hypotheses about the connection of widely differing phenomena with electromagnetism will prove correct, and that hence, in so far as it relates to the nature of ponderable matter, that general theory will be an electrochemical one, as Berzelius already dimly foresaw and as he tried to demonstrate with the resources at his disposal.

This is admittedly a prospect of the distant future, and the individual scientist can scarcely hope to make any significant contribution to its achievement. As far as I am concerned, I would count myself fortunate if it fell to me, encouraged and spurred on as I am by the high distinction awarded to me by your Academy, to play a modest part in the solution of the problems which next present themselves to us.

I close with the warmest thanks for the attention with which you have listened to me.

Biography

Hendrik Antoon Lorentz was born at Arnhem, The Netherlands, on July 18, 1853, as the son of nursery-owner Gerrit Frederik Lorentz and his wife née Geertruida van Ginkel. When he was four years old, his mother died, and in 1862 his father married Luberta Hupkes. In those days the grade school did not only have school hours in the morning and in the afternoon, but also in the evening, when teaching was more free (in a sense resembling the Dalton method). In this way, when in 1866 the first highschool (H.B.S.) at Arnhem was opened, Hendrik Lorentz, as a gifted pupil, was ready to be placed in the 3rd form. After the 5th form and a year of study of the classics, he entered the University of Leyden in 1870, obtained his B.Sc. degree in mathematics and physics in 1871, and returned to Arnhem in 1872 to become a nightschool teacher, at the same time preparing for his doctoral thesis on the reflection and refraction of light. In 1875, at the early age of 22, he obtained his doctor's degree, and only three years later he was appointed to the Chair of Theoretical Physics at Leyden, newly created for him. In spite of many invitations to chairs abroad, he always remained faithful to his Alma Mater. From 1912 onward, when he accepted a double function at Haarlem as Curator of Teyler's Physical Cabinet and Secretary of the <<Hollandsche Maatschappij der Wetenschappen>> (Dutch Society of Sciences), he continued at Leyden as Extraordinary Professor, delivering his famous Monday morning lectures for the rest of his life. The far-seeing directors of Teyler's Foundation thus enabled his unique mind to be freed from routine academic obligations, permitting him to spread his wings still further in the highest secluded realms of science, which are attainable by so few.

From the start of his scientific work, Lorentz took it as his task to extend James Clerk Maxwell's theory of electricity and of light. Already in his doctor's thesis, he treated the reflection and refraction phenomena of light from this standpoint which was then quite new. His fundamental work in the fields of optics and electricity has revolutionized contemporary conceptions of the nature of matter.

In 1878, he published an essay on the relation between the velocity of light

BIOGRAPHY

in a medium and the density and composition thereof. The resulting formula, proposed almost simultaneously by the Danish physicist Lorenz, has become known as the Lorenz-Lorentz formula.

Lorentz also made fundamental contributions to the study of the phenomena of moving bodies. In an extensive treatise on the aberration of light and the problems arising in connection with it, he followed A. J. Fresnel's hypothesis of the existence of an immovable ether, which freely penetrates all bodies. This assumption formed the basis of a general theory of the electrical and optical phenomena of moving bodies.

From Lorentz stems the conception of the electron; his view that his minute, electrically charged particle plays a rôle during electromagnetic phenomena in ponderable matter made it possible to apply the molecular theory to the theory of electricity, and to explain the behaviour of light waves passing through moving, transparent bodies.

The so-called Lorentz transformation (1904) was based on the fact that electromagnetic forces between charges are subject to slight alterations due to their motion, resulting in a minute contraction in the size of moving bodies. It not only adequately explains the apparent absence of the relative motion of the Earth with respect to the ether, as indicated by the experiments of Michelson and Morley, but also paved the way for Einstein's special theory of relativity.

It may well be said that Lorentz was regarded by all theoretical physicists as the world's leading spirit, who completed what was left unfinished by his predecessors and prepared the ground for the fruitful reception of the new ideas based on the quantum theory.

In 1919, he was appointed Chairman of the Committee whose task it was to study the movements of sea water which could be expected during and after the reclamation of the Zuyderzee in The Netherlands, one of the greatest works of all times in hydraulic engineering. His theoretical calculations, the result of eight years of pioneering work, have been confirmed in actual practice in the most striking manner, and have ever since been of permanent value to the science of hydraulics.

An overwhelming number of honours and distinctions from all over the world were bestowed on Lorentz. International gatherings were presided over by him with exceptional skill, both on account of his amiable and judicious personality and his masterly command of languages. Until his death he was Chairman of all Solvay Congresses, and in 1923 he was elected to the membership of the <<International Committee of Intellectual Coopera-

tion>> of the League of Nations. Of this Committee, consisting of only seven of the world's most eminent scholars, he became the President in 1925.

Through his great prestige in governmental circles in his own country, Lorentz was able to convince them of the importance of science for national production. He thus initiated the steps which finally led to the creation of the organisation now generally known under the initials T.N.O. (Dutch for Applied Scientific Research).

Lorentz was a man of immense personal charm. The very picture of unselfishness, full of genuine interest in whoever had the privilege of crossing his path, he endeared himself both to the leaders of his age and to the ordinary citizen.

In 1881 Lorentz married Aletta Catharina Kaiser, whose father, J. W. Kaiser, Professor at the Academy of Fine Arts, was the Director of the Museum which later became the well-known Rijksmuseum (National Gallery) of Amsterdam, and the designer of the first postage stamps of The Netherlands. There were two daughters and one son from this marriage. The eldest daughter Dr. Geertruida Luberta Lorentz is a physicist in her own right and married Professor W. J. de Haas, Director of the Cryogenic Laboratory (Kamerlingh Onnes Laboratory) of the University of Leyden.

Lorentz died at Haarlem on February 4, 1928.

PIETER ZEEMAN

Light radiation in a magnetic field

Nobel Lecture, May 2, 1903

As Professor Lorentz told you last December, immediately after hearing of the great and very honourable distinction awarded to us, we set to work to see how best to co-ordinate our two lectures. To my great regret I was unable to be present here for Professor Lorentz's lecture, but he was able to report to you on present electron theory from his viewpoint, only briefly touching on the experimental investigations which have occupied me in recent years. I hope that you will allow me therefore to emphasize these experimental investigations. Two fields of physics, light and magnetism, are combined in the subject of today's lecture, whose history dates only from the days of Michael Faraday. The wonderful discovery of the connection between light and magnetism, which he made in 1845, was the reward for an investigation carried out with indefatigable patience and tenacity. Today we call this connection the magnetic rotation of the polarization plane. Faraday succeeded in showing that the plane in which light oscillations take place, is rotated as soon as light passes through special magnetizable bodies along the lines of force. Faraday himself called his discovery the magnetization of light and the illumination of magnetic lines of force. His contempories did not understand this name, which perhaps corresponded more to what he was searching for than to what he found. Throughout his life his hopes, desires and yearnings led him to make repeated investigations into the connection between light, magnetism, and electricity.

The last experiment recorded in Faraday's laboratory notebook and ostensibly the last in his life, gives an indication of the extent to which his spirit was still occupied with the boundary region of possible phenomena.

It was on March 12, 1862, in the laboratory of the Royal Institution that Faraday carried out this experiment. The notes in his notebook, although not quite clear, leave no doubt that he was attempting to demonstrate by means of a spectroscope that magnetism has a direct effect on a light source. The result was however absolutely negative, and Faraday writes in his notebook <<not the slightest effect demonstrable either with polarized or unpolarized light>>.

1902 P.ZEEMAN

Perhaps it was because of this observation that Maxwell, at a meeting of the British Association in Liverpool on September 15, 1870, said of the light-radiating particles in a flame <<that no force in nature can alter even very slightly either their mass or their period of oscillation>>, a statement which, coming from the mouth of the founder of the electromagnetic light theory and spoken with such intensity, must really surprise present-day physicists.

It was not simply out of a spirit of contradiction that I exposed a light source to magnetic forces. The idea came to me during an investigation of the effect discovered by Kerr on light reflected by magnetic mirrors.

When it is a question of splitting up the light of a luminous gas into very fine detail, the simple glass prism of Newton and Frauenhofer is of no use, and the physicist has recourse to the excellent aid which we owe to Row-land: the concave grating. Most physics institutes possess this polished metal mirror with a very large number of grooves, say 50,000 over a width of 10 cm scratched on by means of a diamond. A beam of compound light is no longer reflected by the lined surface in the ordinary way; instead each special kind of light follows its own path.

Of course the light source must be very restricted for the large number of beams corresponding to the various kinds of light to appear separately. This is ensured by placing the light source behind an opaque screen with a linear slit. The spectral image produced can be observed, and from the location and intensity of the linear-slit images we can determine how the different kinds of light in the light being studied are distributed on the basis of the period of oscillation and intensity. A further main advantage of Rowland's grating is that it is now no longer scratched on plane surfaces, but on spherical concave surfaces with a radius of say 3 metres, so that real images are produced of luminous lines without the need for the insertion of lenses. Moreover, photography has made it possible to fix these images and now provides us with a permanent record of each observed spectrum, which can be measured out at any time.

When we study the well-known Bunsen sodium flame by means of Rowland's grating, we see a spectrum consisting mainly of two separate sharp yellow lines, which in our grating lie about 1mm from each other. We see that sodium radiation consists of two kinds of light, the periods of oscillation of which differ only very slightly (1 in 1000) from each other. We confined our attention exclusively to one of these two lines.

I must ask you now to go with me into the Physics Institute of Leiden University. In August, 1896, I exposed the sodium flame to large magnetic forces by placing it between the poles of a strong electromagnet. Again I studied the radiation of the flame by means of Rowland's mirror, the observations being made in the direction perpendicular to the lines of force. Each line, which in the absence of the effect of the magnetic forces was very sharply defined, was now broadened. This indicated that not only the original oscillations, but also others with greater and again others with smaller periods of oscillation were being radiated by the flame. The change was however very small. In an easily produced magnetic field it corresponded to a thirtieth of the distance between the two sodium lines, say two tenths of an Angstrom, a unit of measure whose name will always recall to physicists the meritorious work done by the father of my esteemed colleague.

Had we really succeeded therefore in altering the period of vibration, which Maxwell, as I have just noted, held to be impossible? Or was there some disturbing circumstances from one or more factors which distorted the result? Several of such might be mentioned.

We doubted the result. We studied the light source in the direction of the magnetic force, we perforated the poles of the magnet; but even in the direction of the magnetic lines of force we found that our result was confirmed. We also studied the reverse phenomenon, the absorption of light in sodium vapour, and this too satisfied our expectations. We then asked, do different substances behave in different ways? What happens when the magnetic force is raised to the maximum attainable values? How do different lines of the same substance behave? But before these questions could be answered, theory took over.

I was in fact able to verify experimentally some conclusions which followed from the theory of optical and electrical phenomena of my esteemed teacher and friend Professor Lorentz. This theory assumes that all bodies contain small electrically charged mass particles, <<electrons>>, and that all electrical and optical processes are based on the position and motion of these <<electrons>>.Light oscillations result from the vibration of the<<electrons>>. On the basis of Lorentz's theory, if we limit ourselves to a single spectral line, it suffices to assume that each atom (or molecule) contains a single moving electron.

Now if this electron is displaced from its equilibrium position, a force that is directly proportional to the displacement restores it like a pendulum to its position of rest. In this model the electrons are represented by the red balls and the direction of the magnetic force by the arrows. Now all oscillatory movements of such an electron can be conceived of as being split up into

1902 P.ZEEMAN

force, and two circular oscillations perpendicular to this direction rotating in opposite directions. In the absence of a magnetic field the period of all these oscillations is the same. But as soon as the electron is exposed to the effect of a magnetic field, its motion changes. According to well-known electrodynamic laws, an electron moving in a magnetic field is acted upon by a force which runs perpendicular to the direction of motion of the electron and to the direction of the magnetic field, and whose magnitude is easily determined. Here the rectilinear oscillation is not changed by the magnetic field, the period remains the same; on the other hand the two circular oscillations are subjected to new forces which, running parallel with the radius, either increase or decrease the original central force. In the first case the period of oscillation is reduced, in the second it is increased.

Now it is easy to determine the light motion to which this type of motion of the electrons will lead.

Let us consider first what happens in a direction running *perpendicular to the lines* of force. To the three electron motions there correspond three electrical oscillations, or in terms of the electromagnetic light theory three light oscillations of different periods. Thus the light source will emit three-colour light instead of the original one-colour light. Therefore, instead of the single non-polarized spectral line we shall see three separate lines when we place the light source in a magnetic field. The different directions of oscillation of the electrons affect the polarization state of the emitted light. The light of the middle component oscillates in parallel with, and that of the outer components perpendicular to the lines of force.

I will presently show you as an illustration a line which actually displays this behaviour postulated by Prof. Lorentz's theory.

But let us first consider the rays which run *parallel with the lines of force.* For this purpose I will rotate the model so that the arrow points in your direction. The opposite circular oscillations of the electrons excite two circularly polarized rays rotating in opposite directions, one having a longer and the other a shorter period of oscillation than the original spectral line. The original spectral line splits up under the action of the magnetic field into two components which are circularly polarized in opposite directions. The light source emits two-colour light.

I would now like to project for you two enlargements of photographs taken with the aid of Rowland's grating.* The lines are cadmium lines. In the first half of the picture you can see the unchanged line, and in the second * A number of lantern slides were projected in the course of the lecture.

rectilinear oscillations occurring in the direction of the magnetic lines of half the line changed by magnetic forces, the so-called triplet, which we see in the direction perpendicular to the lines of force.

Secondly I will project for you a cadmium line observed in the direction of the lines of force. The first half of the picture shows the unchanged line, and the second half the double line or doublet produced by the magnetic forces.

You see how beautifully the consequences following from Prof. Lorentz's theory were confirmed by observation in these cases. I should point out, however, that at first some difficulty was experienced in observing the phenomena predicted by the theory, owing to the extreme smallness of the variations in the period of oscillation.

I have just said that the change was extremely small; but it could be said that it was unexpectedly large. The magnetic cleavage of the spectral lines is dependent on the size of the charge of the electron, or, more accurately, on the ratio between the mass and the charge of the electron. Let us see what the observations teach us. When Prof. Lorentz published his theory in 1895, no data were available from which to estimate the ratio between the mass and the charge of the light-exciting particles, and in this theory the ratio was left undefined. We can now calculate this ratio from the magnitude of the magnetic splitting of the spectral lines: it is 10⁷ c.g.s. units per gram, a colossal number even for the physicist, since it is 1,000 times as great as the similar number which was known from electrolysis phenomena in the case of hydrogen atoms. This makes it most probable for the physicist that in the luminous particles only ca.1/1000th of the atom oscillates, and that the main mass of the atom remains virtually stationary. The oscillating electrons and the electrolysis ions were found to be not identical with each other; if they had been, the splitting of the spectral lines would have been only one thousandth of that observed, and then I should not have had the honour of addressing you in Stockholm today.

A further question must also be answered here and now, namely, are the oscillating particles positively or negatively charged?

We observed the doublet in the direction of the magnetic lines of force and studied the sign of the polarization. Then I suddenly resolved the problem: the oscillating electrons are *negatively* charged. We now know that cathode rays, which can occur in tubes filled with highly rarefied gases, are negative particles with the same high charge/mass ratio. We can conclude that that which vibrates in the light source is the same as that which travels in cathode rays.

1902 P.ZEEMAN

We can hardly avoid recalling the two titles of Faraday's basic work: <<Magnetization of light>>, <<Illumination of lines of force>> They appear to us to be almost prophesies, because we have now seen that light can in fact be magnetized, and according to Prof. Arrhenius's theory we have in nature itself, in the northern lights, an example of illumination of the magnetic lines of force of the Earth by the electrons escaping from the sun.

Nature gives us all, including Prof. Lorentz, surprises. It was very quickly found that there are many exceptions to the rule of splitting of the lines only into triplets. The French physicist Cornu was perhaps the first to observe that, contrary to the elementary theory, in some cases splitting into four lines, a quadruplet, occurs. In other cases splitting into five, six or even nine lines can be observed. In the line-rich spectrum of iron we find a whole selection of different forms. Very soon a number of physicists were working in the extended field; I need only name Becquerel, Cotton, Michelson, Preston, Righi, Runge, and Paschen. If I had more time at my disposal, I would gladly deal in greater detail with the work of the last-mentioned investigators. For the present, however, I must confine myself to projecting a cadmium line for you, which is split up into four lines, and negatives of a mercury line which has split up into nine components, and for which I am grateful to Prof. Runge. But despite this very complicated splitting-up, even when larger aids are used, the division into three groups of oscillations, two perpendicular to and one parallel with the lines of force, assumed in Lorentz's elementary theory, remains valid, as this photograph of the nonet shows.

It was natural that, soon after I had succeeded in splitting up lines, I should also study how the different lines behave in this respect. I was soon able to show by investigating the zinc lines that there are great differences in the splitting-up of different lines of a substance. Particularly great differences were found in lines belonging to different series, the discovery of which we owe to the lucid investigations of your countryman Prof. Rydberg, and in particular Professors Kayser and Runge.

I found very great differences in the lines of the different series, and it appeared that the splitting-up, contrary to the postulations of the elementary theory, expressed in the scale of oscillation frequencies, is *not* the same for all lines in the same magnetic field. We can conclude from this on the basis of Lorentz's theory that the charge/mass ratio is not the same for all electrons.

I would now like to talk about three separate phenomena, first a phenomenon which I have not been able to observe, secondly phenomena which I have hardly been able to verify, and thirdly a surprising phenomenon. All the results which have been discussed so far have related to line spectra; but in the case of many bodies we also know of the existence of band spectra. Here a difference is found : the band spectrum displayed by iodine vapour or bromine vapour as an absorption medium at low temperatures, remains unchanged in a magnetic field; I personally have been unable to bring about any change in the extremely accurate images which Prof.Hasselberg has given us of the absorption spectra of bromine and iodine vapour, even with the strongest magnetic fields.

We are indebted to Prof.Voigt in Göttingen for a comprehensive theory of magneto-optical phenomena. The triplet you have seen today was absolutely symmetrical, as postulated in the elementary theory. Now on the basis of his theory Prof. Voigt was able to predict that as a result of the action of *weak* magnetic forces asymmetry should occur. According to him, the two external components should have different light intensities and be at different distances from the centre line. In the case of iron, zinc, and cadmium lines I was able to observe both asymmetries; because of their extreme smallness, however, I cannot demonstrate the phenomena in the projector.

However, another phenomenon, which will give you some idea of the scope of Voigt's theory, is more striking. In this phenomenon Faraday's magnetic rotation of the polarization plane and the magnetic splitting of the spectral lines, are intimately connected with each other.

The rotation of the polarization plane is extraordinarily small in all gases, thus also in sodium vapour. As Macaluso and Corbino found, it is only in the case of those colours which lie close to an absorption band of the vapour that the rotation is very great, of the order of 180° , and the rotation takes place in the *positive* direction, the direction of the current exciting the magnet.

What about the rotation inside the absorption band?

Prof.Voigt was able to predict that in the case of highly rarefied vapours the rotation must be negative in the zone between the two components of the doublet, i.e. opposite in direction to that outside the band, and also very great. I had the pleasure of confirming this theoretical finding in experiments on sodium vapour. Provided that the vapour is highly rarefied, the rotation in very strong fields between the lines of the doublet can rise to - 400°.

To give you some idea of the distribution of the rotations, I will show you two negatives connected with this investigation.

The magnetic field is not set up.

The two dark vertical lines are the absorption lines of sodium vapour, the well-known D-lines. The reason why they are so broad is that the vapour

1902 P.ZEEMAN

was very dense. The horizontal bands are interference bands, which were produced by means of a special device. They indicate the points where the direction of oscillation is the same. The directions of oscillation in each of the successive bands differ by 180°.

Now as soon as the magnetic field is set up we get the image now being projected. On each side of each of the D-lines the bands bend *upwards*, the more so the smaller the distance, because the rotation in the vicinity of the bands grows very rapidly and reaches almost 180° in the immediate neighbourhood of the bands. Within the bands a blurred band only is visible.

The phenomenon becomes far clearer once the vapour is highly rarefied. The bands bounding the components rise as before. At the same time, however, the inner band becomes detached; it has fallen, the rotation is negative. In our third image the rotation in the case of one of the D-lines is about -90° , in the other everything is more blurred, the rotation is about -180° .

Summarizing briefly the results of the tests described in the light of Lorentz's theory, it can be stated that firm support has been found for the assertion that electricity occurs at thousands of points where we at most conjectured that it was present. Innumerable electrical particles oscillate in every flame and light source. We can in fact assume that every heat source is filled with electrons which will continue to oscillate ceaselessly and indefinitely.

All these electrons leave their impression on the emitted rays. We can hope that experimental study of the radiation phenomena, which are exposed to various influences, but in particular to the effect of magnetism, will provide us with useful data concerning a new field, that of atomistic astronomy, as Lodge called it, populated with atoms and electrons instead of planets and worlds.

I count myself fortunate to be able to contribute to this work; and the great interest which the Royal Swedish Academy of Sciences has shown in my work and the recognition that it has paid to my past successes, convince me that I am not on the wrong track.

Biography

Pieter Zeeman was born on May 25, 1865, at Zonnemaire, a small village in the isle of Schouwen. Zeeland, The Netherlands, as the son of the local clergymen Catharinus Forandinus Zeeman and his wife, née Wilhelmina Worst. After having finished his secondary school education at Zierikzee, the main town of the island, he went to Delft for two years to receive tuition in the classical languages, an adequate knowledge of which was required at that time for entrance to the university. Taking up his abode at the house of Dr. J. W. Lely, conrector of the Gymnasium and brother of Dr. C. Lely (Minister of Public Works and known for initiating and developing the work for reclamation of the Zuyderzee), Zeeman came into an environment which was beneficial for the development of his scientific talents. It was here also that he came into contact with Kamerlingh Onnes (Nobel Prize in Physics for 1913), who was twelve years his senior. Zeeman's wide reading, which included a proper mastery of works such as Maxwell's Heat, and his passion for performing experiments amazed Kamerlingh Onnes in no small degree, and formed the basis for a fruitful friendship between the two scientists.

Zeeman entered Leyden University in 1855 and became mainly a pupil of Kamerlingh Ormes (mechanics) and Lorentz (experimental physics) : the latter was later to share the Nobel Prize with him. An early reward came in 1890 when he was appointed assistant to Lorentz, enabling him to participate in an extensive research programme which included the study of the Kerr effect-an important foundation for his future great work. He obtained his doctor's degree in 1893, after which he left for F. Kohhausch's institute at Strasbourg, where for one semester he carried out work under E. Cohn. He returned to Leyden in 1894 and became <<pre>privaat-docent>> (extra-mural lecturer) from 1895 to 1897.

In 1897, the year following his great discovery of the magnetic splitting of spectral lines, he was called to a lectureship at the University of Amsterdam; in 1900 came his appointment as Extraordinary Professor. In 1908 Van der Waals (Nobel Prize in Physics for 1910) reached the retiring age of 70 and Zeeman was chosen as his successor, at the same time functioning as Director of the Physics Laboratory. In 1923 a new laboratory, specially erected for

1902 P.ZEEMAN

him, was put at his disposal, a prominent feature being a concrete block weighing a quarter of a million kilograms, erected free from the floor, as a suitable platform for vibration-free experiments. The institute is now known as the Zeeman Laboratory of Amsterdam University. Many world-famous scientists have visited Zeeman there or worked with him for some time. He remained in this dual function for 35 years - on numerous occasions refusing an invitation to occupy a Chair abroad -until in 1935 he had to resign on account of his pensionable age. An accomplished teacher and of kind disposition he was much loved by his pupils. One of these was C. J. Bakker, who was from 1955 until his untimely death in an aircraft accident in 1960 the General Director of the Centre Européen des Recherches Nucléaires (CERN) at Geneva. Another worker in his laboratory was S. Goudsmit, who in 1925 with G. E. Uhlenbeck originated the concept of electron spin.

Zeeman's talent for natural science first became apparent in 1883, when, while still attending the secondary school, he gave an apt description and drawing of an aurora borealis - then clearly to be observed in his country - which was published in *Nature.* (The Editor praised the meticulous observations of <<Professor Zeeman in his observatory at Zonnemaire>>!)

Zeeman's main theme of investigation has always concerned optical phenomena. His first treatise Mesures relatives du phénoméne de Kerr, written in 1892, was rewarded with a Gold Medal from the Dutch Society of Sciences at Haarlem; his doctor's thesis dealt with the same subject. In Strasbourg he studied the propagation and absorption of electrical waves in fluids. His principal work, however, was the study of the influence of magnetism on the nature of light radiation, started by him in the summer of 1896, which formed a logical continuation of his investigation into the Kerr effect. The discovery of the so-called Zeeman effect, for which he has been awarded the Nobel Prize, was communicated to the Royal Academy of Sciences in Amsterdam -through H. Kamerlingh Onnes (1896) and J. D. van der Waals (1897) -in the form of papers entitled Over den Invloed eener Magnetisatie op den Aard van het door een Stof uitgexonden Licht (On the influence of a magnetization on the nature of light emitted by a substance) and Over Doubletten en Tripletten in het Spectrum teweeggebracht door Uitwendige Magnetische Krachten (On doublets and triplets in the spectrum caused by external magnetic forces) I, II and III. (The English translations of these papers appeared in The Philosophical Magazine; of the first paper a French version appeared in Archives Néerlandaises des Sciences Exactes et Naturelles, and in a short form in German in Verhandlungen der Physikalischen Gesellschaj zu Berlin.)

BIOGRAPHY

The importance of the discovery can at once be judged by the fact that at one stroke the phenomenon not only confirmed Lorentz' theoretical conclusions with regard to the state of polarization of the light emitted by flames, but also demonstrated the negative nature of the oscillating particles, as well as the unexpectedly high ratio of their charge and mass (e/m). Thus, when in the following year the discovery of the existence of free electrons in the form of cathode rays was established by J. J. Thomson, the identity of electrons and the oscillating light particles could be established from the negative nature and the e/m ratio of the particles. The growing number of observations made by other investigators on studying the effects of using various substances as light emitters-not all of them explicable by Lorentz' original theory (the so-called << anomalous Zeeman effect>> could only adequately be explained at a later date, with the advent of Bohr's atomic theory, quantum wave mechanics, and the concept of the electron spin) -was assembled by him in his book Researches in Magneto-Optics (London 1913, German translation in 1914). Not only has the Zeeman effect thrown much light on the mechanism of light radiation and on the nature of matter and electricity, but its immense importance lies in the fact that even to this day it offers the ultimate means for revealing the intimate structure of the atom and the nature and behaviour of its components. It still serves as the final test in any new theory of the atom.

Already in his second communication Zeeman expressed the opinion that the accepted existence of strong magnetic fields on the surface of the sun could be verified, since these should alter spectral lines derived from the celestial body. (It is typical of Zeeman to extend physical concepts into the realm of celestial phenomena.) In a letter to him (1908) the astronomer G. E. Hale, Director of Mount Wilson Observatory, corroborated this opinion by means of photographs which indicated that in solar vortices the spectral lines indeed appeared to be affected by magnetic fields. Even the theoretical prediction concerning the probable interrelationship between the directions of polarization and those of the magnetic fields was subsequently confirmed by Hale.

With regard to Zeeman's activities outside the field of the magnetic splitting of spectral lines, mention should first be made of his work on the Doppler effect in optics and in canal rays (laboratory tests). A second field of study was that on the propagation of light in moving media (justification of the existence of the Lorentz-term in the Fresnel drag coefficient). Other investigations were those into the influence of the magnetic moment of the nucleus on the hyperfine structure of spectral lines. He also succeeded, with

1902 P.ZEEMAN

J. de Gier, in discovering a number of new isotopes (³⁸Ar, ⁶⁴Ni, amongst others) by means of Thomson's parabola mass spectrograph. Zeeman's predilection for testing fundamental laws also found expression in his verification - carried out with an accuracy of $< 1 : 10^7$ - of the equality of heavy and inert masses.

Zeeman was Honorary Doctor of the Universities of Göttingen, Oxford, Philadelphia, Strasbourg, Liege, Ghent, Glasgow, Brussels and Paris. He was also a member or honorary member of numerous learned academies, including the very rare distinction of Associé Etranger of the Académie des Sciences of Paris. He was also member and Chairman of the Commission Internationale des Poids et Mesures, Paris. Appointed member of the Royal Academy of Sciences of Amsterdam in 1898, he served as the Secretary of the Mathematical-physical Section from 1912 to 1920. Among the other distinctions may be mentioned the Rumford Medal of the Royal Society of London, the Prix Wilde of the Académie des Sciences of Paris, the Baumgartner-Preis of the Akadémie der Wissenschaften of Vienna, the Matteucci Medal of the Italian Society of Sciences, the Franklin Medal of the Franklin Institute of Philadelphia, the Henry Draper Medal of the National Academy of Sciences of Washington. He was also made a Knight of the Order of Orange-Nassau and Commander of the Order of the Netherlands Lion.

Outside his field of study Zeeman showed much interest in literature and the stage. An entertaining host, he loved to invite his collaborators and pupils to dine with him at his home, an event preceded by a learned talk in his study and followed by a gathering in the family circle.

Zeeman married Johanna Elisabeth Lebret in 1895 ; they had one son and three daughters, During the last year of his professorship he suffered from ill-health. He died after a short illness on October 9,1943.

44

Physics 1903

ANTOINE HENRI BECQUEREL

<<in recognition of the extraordinary services he has rendered by his discovery of spontaneous radioactivity >>

PIERRE CURIE

MARIE SKLODOWSKA-CURIE

<<in recognition of the extraordinary services they have rendered by their joint researches on the radiation phenomena discovered by Professor Henri Becquerel>>

Physics 1903

Presentation Speech by Dr. H. R. Törnebladh, President of the Royal Swedish Academy of Sciences

Your Majesty, Your Royal Highnesses, Ladies and Gentlemen.

The last decade's record of development in the physical sciences is outstanding for the discoveries, as unexpected as they are impressive, that have been made. The Royal Academy of Sciences has been accorded the task of beginning to carry out the noble intentions expressed by Alfred Nobel in his will dating from this fruitful period for the physical sciences. The great discovery, to which the Academy of Sciences resolved to award the Nobel Prize of 1903 for Physics, marks a stage in this brilliant expansion, while it is at the same time strictly linked to the discovery which won the very first Nobel Prize for Physics.

Further to the discovery of Röntgen rays, the question was raised whether they could not also be produced in other conditions than those in which they had been first observed. During the course of experiments in this field, Professor Henri Becquerel achieved results that not only contained an answer to this question, but led to a new discovery of the first order.

When electricity is discharged through a tube filled with highly rarefied gas, the phenomenon of radiation occurs in this tube. This has been called cathode radiation, which when it meets an object in its turn produces the rays discovered by Röntgen. It often happens that these cathode rays also give rise to phenomena of light, called fluorescence and phosphorescence, in objects they encounter. Now it is this circumstance which occasioned Becquerel's experiments. He asked himself if the bodies whence the phosphorescent rays emanate, after having been subjected for a longer or lesser time to the action of ordinary light, would not likewise emit Röntgen rays. To solve this problem, Becquerel made use of the well-known property of Röntgen rays to affect a photographic plate. Having placed aluminium foil upon a sensitive plate, he laid glass laminae on it with the phosphorescent materials that were under study, contending that if the photographic plate was affected through the aluminium foil, this could only take place by means of rays which like those of Röntgen had the property of passing through metals. Carrying his research further, Becquerel found that the sensitive

PHYSICS 1903

plate bore images from certain substances, in particular from all the salts of uranium. He thus demonstrated that these substances emit rays of a special nature, distinct from ordinary light. Tests continued and he established an even more extraordinary fact, namely that this radiation is not in direct relation to the phenomenon of phosphorescence, that phosphorescent materials as well as those which are not can give rise to this radiation, that previous lighting is never necessary for the phenomenon to occur, and lastly that the radiation in question continues with invariable force to all appearances without its origin being traced to any of the known sources of energy. This was how Becquerel made the discovery of spontaneous radioactivity and the rays that bear his name. This discovery revealed a new property of matter and a new source of energy, the latter of puzzling origin. It goes without saying that a discovery such as this was bound to excite the liveliest interest in the scientific world and give birth to a whole host of new investigations with the aim of making a thorough study of the nature of the Becquerel rays and determining their origin. It was at this point that M.and Mme. Curie undertook the most comprehensive and systematic research into this topic, examining the majority of simple substances and a large number of minerals to find if possible new substances with the remarkable properties of uranium. The first discovery in this field was made at approximately the same time by the German Schmidt and by Mme. Curie, both of whom found that thorium possesses radioactive properties to about the same degree as uranium.

During research, scientists have made full use of the property of the Becquerel rays, to make conductors of electricity out of bodies that are not so in normal circumstances. As a result, if rays of this kind fall on an electroscope charged with electricity, it will discharge more or less quickly, according to the greater or lesser activity of these rays which make the air round the electroscope a conductor. The electroscope has thus to some extent played the same part in respect of radioactive materials as the spectroscope in the search for new elements. M. and Mme. Curie, having thus found with the aid of the electroscope that the radioactive properties of the mineral pitchblende were more marked than those of uranium, came to the conclusion that pitchblende must contain one or more new radioactive substances. By breaking up pitchblende into its chemical components and examining, again with the aid of the electroscope, the radioactivity of the products that were obtained, they at last managed by means of a series of solutions and precipitates to isolate the materials that were distinguished by radioactivity of extraordinary intensity. Some idea of the prodigious work these results entail

PRESENTATION

may be formed from the fact that it takes 1,000 kg of raw material to produce a few decigrams of these active substances. Of these, *polonium* was discovered by M. and Mme. Curie, *radium* was also discovered by them in collaboration with Bémont, and *actinium* by Debierne. Of all these materials, at least radium has been shown to be a simple substance.

Becquerel had already shown by the study of radiation in uranium some of the most important properties of these rays. It was however only by means of the highly radioactive substances we have just mentioned that it became possible to carry out more comprehensive research into the Becquerel rays and in certain respects to amend findings on them. Foremost among scientists who carried out this programme, we find both Becquerel and also M. and Mme. Curie.

Becquerel radiation resembles light in several respects. Propagation is rectilinear. Like certain light wavelengths, it has a strong photochemical action, causes phosphorescence, etc. Yet it differs from light in certain essentials, for example by its property to pass through metals and many other opaque bodies, by the intensity with which it brings about the discharge of bodies charged with electricity, and lastly by the absence of phenomena of reflection, interference and refraction, characteristic of light. In this the Becquerel rays are exactly similar to Röntgen rays and cathode rays. It has been found all the same that Becquerel radiation is not homogeneous, but is composed of different kinds of rays, some of which like those of Röntgen are not deflected by magnetic or electric forces, while others are, like cathode rays or Goldstein rays. Like Röntgen rays, Becquerel rays have a very strong physiological effect; thus, for example, they attack the skin, affect the eye, etc.

Lastly, certain of the radioactive substances have a special property which bears no direct relation to their beams. This is to make temporarily radioactive all the bodies in their neighbourhood, by producing a radioactive emanation which communicates the radioactive property to the surroundings.

It is thus beyond doubt that Becquerel rays are in strict relation to Röntgen rays and cathode rays. The modem theory of electrons, which is used to explain this last form of radiation, has also been applied with the greatest success to explain the Becquerel rays.

We could close our account of the discoveries of Becquerel and the Curies at this point, as what we have covered is the main result of research they undertook early in 1903 and which is consequently to be considered in de-

PHYSICS 1903

ciding the award of the Nobel Prize for 1903. Surely the discoveries we have outlined are important enough to deserve such a prize. These discoveries have taught us that special forms of radiation that were only known hitherto by electric discharges through rarefied gas are natural phenomena of wide occurrence. We have gained knowledge of a property of matter quite new to us, the capability of emitting, spontaneously as it seems, these marvellous rays. We have gained new methods, infinitely superior in subtlety to any we had in this sphere, to examine under certain conditions the existence of matter in nature. Finally we have found a new source of energy, for which the full explanation is not yet forthcoming. It will evidently give rise to new research of the very highest value in physics and in chemistry.

The discoveries of Becquerel and the Curies in their own right herald a new era in the history of the physical sciences. Now we can only touch on the magnificent experiments carried out in this domain last year by Curie who discovered in radium the great spontaneous development of heat, together with the findings of Rutherford and Ramsay on the release of helium by radium, discoveries that are bound to be of great importance for the physicist and for the chemist alike. The promise for the future stemming from Becquerel's discovery seems near full realization.

The discoveries and research of Becquerel and of M. and Mme. Curie are closely bound up with each other; the latter were of course co-workers. The Royal Academy of Sciences did not think it right to distinguish between these eminent scientists, when it came to awarding the discovery of spontaneous radioactivity a Nobel Prize. The Academy thus deemed it equitable to share the Nobel Physics Prize for 1903 by awarding one half to Professor Henri Becquerel for the discovery of *spontaneous radioactivity*, and the other half to Professor and Madame Curie for great merit, of which they have given proof in work on rays first discovered by Henri Becquerel.

Professor Becquerel. The brilliant discovery of radioactivity shows us human knowledge in triumph, exploring Nature by undeflected rays of genius that pass through the vastness of space. Your victory serves as a shining refutation of the ancient dictum, *ignoramus - ignorabimus, we* do not know and we shall never know. It breeds the hope that scientific toil will succeed in conquering new territories and this is mankind's vital hope.

The great success of Professor and Madame Curie is the best illustration of the old proverb, coniuncta' *valent*, union is strength. This makes us look at

PRESENTATION

God's word in an entirely new light : <<It is not good that the man should be alone; I will make him an help meet for him.>>

Nor is that all. This learned couple represent a team of differing nationalities, a happy omen for mankind joining forces in the development of science.

With sincere regret that these two prize-winners are prevented by commitments from being with us, we are fortunate in having in their stead the distinguished Minister, M.Marchand, representing France who has most kindly consented to receive the prize awarded to his fellow-countrymen.

ANTOINE H. BECQUEREL

On radioactivity, a new property of matter

Nobel Lecture, December 11, 1903

The subject which I propose to speak to you about has become, in only a few years, so vast that in order to deal with it in a single lecture I should have to confine myself to listing the main facts following the chronological order of their discovery. But as M. and Mme. Curie are to describe to you their fine work on radium, I will simply summarize the subject and give some account of my own research.

At the beginning of 1896, on the very day that news reached Paris of the experiments of Röntgen and of the extraordinary properties of the rays emitted by the phosphorescent walls of Crookes' tubes, I thought of carrying out research to see whether all phosphorescent material emitted similar rays. The results of the experiment did not justify this idea, but in this research I encountered an unexpected phenomenon.

Of all the phosphorescent materials, uranium salts seemed particularly suitable for the investigations, because of the exceptional structure indicated by the harmonic series of the bands making up their absorption and phosphorescence spectra. Thus I placed sheets of double sulphate of uranium and potassium on photographic plates enveloped in black paper or protected by a sheet of aluminium and exposed them to light for several hours. On developing the plates, I found that the uranium salt had emitted rays which reproduced the silhouettes of the crystalline sheets through the black paper and various screens of metal or thin glass laid on the plates.

Under these conditions the phenomenon could be ascribed to a transformation of solar energy, like phosphorescence, but I soon recognized that the emission was independent of any familiar source of excitation, such as light, electricity or heat.

We were thus faced with a spontaneous phenomenon of a new order. Figure 1 shows the first print, which revealed the spontaneity of the radiation emitted by the uranium salt. The rays passed through both the black paper which enveloped the plate, and a thin sheet of copper in the shape of a cross. Figure 2 shows the radiograph of an aluminium medal; the non-uniform absorption of the radiation by the different thicknesses of metal reveals the





effigy. As the uranium salts used had been prepared a very long time beforehand, it was to be supposed that the intensity of the phenomenon was independent of time, and hence that the emission was constant. All the later experiments have shown that the activity of uranium does not diminish appreciably with time.

In obtaining these first results I noticed that the radiation of uranium discharged electrically-charged materials located some distance away, and this phenomenon provided a second method of studying the new rays. The pho-



Fig. 2.

tographic method was primarily a qualitative one, the electrical method gave numerical data, and the early measurements revealed the constancy of the radiation with time.

The two methods showed that all uranium salts, whatever their origin, emitted radiation of the same type, that this property was an atomic property connected with the element uranium, and that metallic uranium was about three and a half times as active as the salt used in the first experiments.

A sphere of charged uranium, which discharges spontaneously in the air under the influence of its own radiation, retains its charge in an absolute vacuum. The exchanges of electrical charges that take place between charged bodies under the influence of the new rays, are the result of a special conductivity imparted to the surrounding gases, a conductivity that persists for several moments after the radiation has ceased to act.

These fundamental properties of the radiation emitted by uranium were verified later by numerous investigators ; of these I will only mention Rutherford, who established that the conducting properties of the gases through which the radiation of uranium passes, are completely equal to the ionization caused by other factors.

During the course of these first experiments, the observation of a number of phenomena that were hitherto unexplained led me aside from the path to which my later experiments were to bring me back. Various samples of phosphorescent calcium sulphide resting on small plates of glass and covered with a small bell-jar of glass had been laid on a photographic plate protected by a sheet of aluminium 2 mm thick, as shown in Fig. 3. The print developed after 48 hours (Fig.4) revealed silhouettes of the plates of glass, reproduced with the details which would have been produced by refraction and total



Fig. 3.



Fig. 4.

reflection of the light rays. Although at the same time Troost and Niewenglowski observed the emission of penetrating rays by phosphorescent materials, the above experiment could not be reproduced; the cause of the momentaneous appearance and the disappearance of the activity of these products is unknown. But since, in the experiments with uranium, the silhouettes of all the screens put in between are edged with white lines outlining projected shadows, and similar to those of the print which we have just mentioned, I was led to attribute the properties of light to the radiation from uranium, while all later experiments have shown that this radiation cannot be reflected or refracted like light rays.

In 1898 Schmidt and Mme.Curie observed almost simultaneously that thorium has properties similar to those of uranium; these properties were studied by Owens and by Rutherford. Mme.Curie, after measuring, by means of the ionization of air, the radioactivity of a large number of minerals containing uranium or thorium, noted the remarkable fact that some minerals were more active than metallic uranium. After having verified the fact that the activity accompanied the uranium molecule in its various combinations, M. and Mme. Curie concluded from this that there must be present in the minerals mentioned a substance more active than uranium, and they set about isolating it. They treated one of the most active of these minerals, Joachimsthal pitchblende, and first separated from it active bismuth which they supposed contained a new substance, polonium, and then soon afterwards they obtained extremely active barium, associated with a new element, radium. These products were obtained by fractional crystallizations in conjunction with electrometer readings. The activity of the products in-

1903 A.H.BECQUEREL

creased with their richness in new elements. The activity of pure radium is about one million times greater than that of uranium.

Giesel has succeeded in obtaining very active preparations, and Debierne has studied a product intimately associated with thorium, which he has called actinium.

Of these different preparations, radium alone has the characteristics which we associate with simple substances; it has an emission spectrum formed of lines not belonging to any other known element, and the molecular weights of radium salts increase with their radium content.

The intensive radiation of radium excites the phosphorescence of different materials and restores the ability of crystals to phosphoresce under heat, when they have lost this as a result of a previous rise in temperature; moreover, radium salts become luminous spontaneously under the influence of their own radiation.

The first samples of polonium and radium that M. and Mme. Curie were good enough to lend me, revealed a striking difference in the nature of the radiation emitted by each of these substances. They were put into small paper cylinders closed at the bottom by very thin flakes of mica or aluminium, and the cylinders were placed on a photographic plate. The print in Fig. 5 shows that the radium radiation has easily passed through the various envelopes while the polonium radiation has not penetrated the wall of the paper cylinder; thus the polonium rays are only slightly penetrating.

Towards the end of 1899, first Giesel and then Meyer and von Schweidler observed that the radiation of active preparations is deflected by a magnetic



Fig. 5.

56

field. At the same time, unaware of these experiments, I noted the same in the case of radium radiation, after first having noted that in a non-uniform field the radiation is concentrated on the poles, as are cathode rays in the experiment of Birkeland. Figures 6 and 7 show some pictures which were obtained in the following way:



Several grains of radio-active matter are put on a photographic plate enveloped in black paper and placed horizontally between the poles of a magnet; on developing the plate after a few moments' exposure, it will be seen that beside the mark indicating the position of the active source a strong impression has been produced due to the radiation reflected by the field and collected on the plate, on one side only.

Almost at once I realised that the rays emitted by polonium were not deflected under the above experimental conditions and that there are two kinds of rays, one highly deflected by a magnetic field, and the other apparently not deflected. When studying the emission from radium, M.and Mme. Curie observed the simultaneous presence there of the two types of rays and saw that the rays from polonium, in common with those of the same type emitted by radium, were increasingly absorbable according as they had passed through a greater thickness of absorbent material: the in-



Fig. 8.

verse occurs in the case of the heterogeneous beams of the other rays. The photograph in Fig. 8 shows the two types of rays known nowadays as α -rays for those emitted by polonium, and β -rays for the magnetically deflectable part of the radiation from radium. I further found that thorium emits the two types of rays and that, even in a vacuum, uranium emits only p-rays (Fig. 9) not excluding the existence of much less active, non-deflectable rays.



There is, in fact, a third type of rays, y-rays, not deflected by a magnetic field, attention to which was first drawn by an experiment conducted by Villard and which seem analogous to X-rays.

The action of a magnetic field enables the various components of the radiation from radioactive substances to be separated and analysed.

b -Rays behave like cathode rays; it may be assumed, as has been for the latter, that they are made up of masses m carrying at velocity v negative charges e. In a uniform magnetic field of intensity *H* the trajectories normal to the field must be circular paths, the radius *R* of which is given by the relation RH = (m/e)v.

For an original direction making an angle a with the lines of force, the trajectories are helices which wind on cylinders of radius $R \sin a$. I have verified the various geometrical consequences of this similarity.

The beam of p-rays is made up of an infinity of rays with trajectories having different radii of curvature; the magnetic field disperses them as a prism disperses the light rays of various colours. A photographic plate without black paper wrapping can be placed in, and parallel to, a uniform, horizontal magnetic field, for instance, then on the plate a small lead dish containing a few grains of radiferous barium forming a source of very small diameter. The radiation is directed at the plate and produces an image on just one side. If small strips of different substances - paper, aluminium or various metals - have been placed on this side it will be found that in the diffuse image which represents a kind of spectrum there are rays with varying penetration which, under each screen, give images whose limits are different and which constitute absorption spectra. It will be seen in the following that the image is mainly caused by the secondary radiation which originates at the face where the incident rays emerge. Figure 10 is an example of the photo-



graphs obtained; the screens are: a strip of black paper, a strip of aluminium 0.1 mm thick, and a platinum foil 0.03 mm thick. To secure what might be termed a pure spectrum, i.e.such that each point on the plate is struck by a single beam, all of whose trajectories have the same curvature, the radiation from the point source must be made to pass through a narrow aperture. The result is the same as the foregoing (Fig. 11). The photograph shows, more-over, an image produced by the secondary rays emitted by the inside face of a lead semi-cylinder which covered the source and in which was pierced the small aperture in question. Finally, when the radiation is gathered through a second small aperture, the result is a single ray.

Each single ray may be defined by the value of the product *RH* corresponding to it. In the above tests, the *RH* values of the active rays ranged from 600 to about 2,500.

A more complete analysis of the radiation can be made by applying the following general method:

The active material is placed at the bottom of a deep, narrow groove in a small block of lead to produce a very thin vertical beam issuing from a linear source a few millimetres long. This system is placed in, and parallel to, the uniform field of a magnet. A photographic plate is then arranged above the



Fig.12.







↓ Fig. 15.



source, at right angles to the field and intercepting the deflected beam. The very oblique rays reaching the plate produce thereon an image which differs very little from the actual trajectory of a skimming ray emitted normally to the field. On the photographic plate are placed a number of screens pierced by small slits normal to the plate; these then allow either portions of pure spectra or single rays to pass. To eliminate the light emitted by the source, the latter is covered with a thin aluminium foil. In practice the screens are fixed by means of an adhesive to a glass plate which serves to press them against the photographic plate. Figures 12, 13, 14 and 15 show the arrangement of the screens and some of the photographs obtained by this method. For two of these photographs an aluminium foil 0.1 mm thick, concentric with the pierced screen, was mounted beyond the pure spectra. It can be seen that the least deflectable rays pass through this foil as if it were not there; other more deflectable rays produce, on emerging, secondary rays which are photographically more active than the incident rays, and lastly the most deflectable rays do not pass through the aluminium foil and produce at the entry face secondary rays which give an intense image. The general image within the contours of the screens is also attributable to secondary radiation. The magnetic field had an intensity of 859 c.g.s.units. In these tests the α rays were blocked but the γ -rays give straight line images revealing a discontinuity between these rays and the less deflectable β -rays; for these latter the product *RH* is about 10⁴. In general the not very deflectable β -rays are very penetrating and the rays which are highly deflected are also very readily absorbed. These tests illustrate the advantages of this method for analysing the effects produced for each single ray.

When applied to secondary radiation this method has shown that the rays were deflected by a magnetic field in the same direction as the cathode rays.

While I was conducting these experiments, M. and Mme. Curie demonstrated that the &rays from radium actually carry negative electrical charges; the bodies which receive the radiation become negatively charged while the source itself becomes positively charged. For this double phenomenon to be observed, all the conductors and the source itself must be completely surrounded by insulating materials, e.g. paraffin, or be placed in a vacuum.

On the other hand I have shown that the β -rays from radium were deflected by an electrostatic field. When *F* is the intensity of this field, the trajectory of a single ray, as characterized by the quantities *m*, *e* and *v* defined above, is a parabola with parameter (*m*/*e*) (*v*²/*F*), and the size of this parameter combined with that of the radius of curvature of the same ray's trajectory in

1903 A.H.BECQUEREL

a known magnetic field enables m/e and v to be determined. The experiment performed with the apparatus in Fig. 16 provided the image shown in Fig.17 which reveals the electrical deflection by the shadow projected by a vertical screen normal to the field. By combining for a single beam the crossed electrical and magnetic deflections, Kaufmann has made much more precise measurements than the ones that can be deduced from the earlier experiments. His measurements showed him that the ratio e/m was a function of the velocity v which, for the least deflectable b -rays, tends towards the speed of light. Interpretation of this fact in terms of Max.Abraham's concepts suggests that the mass of the electrons is at least in part, if not entirely, the outcome of electromagnetic reactions - a result which prompts fresh ideas about the nature of the inertia of matter.

Apart from the b-rays, identical with cathode rays, α -rays make up an important part of the radiation from active substances. I mentioned earlier how I had observed them for the first time with polonium, and how their apparent non-deflectability and the peculiarities of their low penetrability



Fig.16.



Fig.17.

had caused them to be classified apart. By means of a very delicate electrical experiment, Rutherford discovered that the α -rays could be deflected very slightly by a very strong magnetic field, and that the deflection was in the opposite direction to that of b -rays. They hence behave as if carrying positive electrical charges and appear identical with Goldstein's <<Kanalstrahlen>>.



Fig.18.

Using the above arrangement I recorded photographically the trajectory described in a magnetic field by α -rays from radium and the rays from polonium which are identical. Figure 18 shows a photograph (enlarged) obtained in a magnetic field of 10,000 c.g.s.units. The two concurrent paths each correspond to a direction of the magnetic field which has been reversed in the middle of the exposure. They do not present any trace of dispersion, which allows us to regard the active beam as homogeneous. It is noted, moreover, that the radius of curvature calculated for the different points of the trajectory continues to increase as the path in the air increases. This phenomenon can be attributed to the fact that the positive charges, with a velocity which is ten times less than that of the β -rays and a real or supposed mass a thousand times larger, attract the neutral molecules of the air, or are discharged progressively in the ionized air.

As the α -rays are very absorbable, they appear in consequence to constitute the most active part of the radiation when this is measured by the ionization of the air in the neighbourhood of the source. These rays are also the most active in exciting the phosphorescence of zinc blende, and of diamond, whereas barium platinocyanide becomes equally luminous under the influence of the α - and β -rays and the phosphorescence of the double sulphate of uranium and potassium is particularly excited by the b-rays. The curious effect of Sir W. Crookes' spinthariscope should be attributed to the

cc-rays, and this effect seems due to the cleavages accompanied by flashes identical with those produced when various crystals are fractured.

The third kind of rays, γ -rays, are characterized by their great penetrability and their non-deflectability in a magnetic field. In the attached illustration (Fig. 19) made by the method described earlier, the α -rays have been stopped near their source, the b-rays are deflected by the magnetic field, whilst the γ -rays and the light emitted by the radium salt form a rectilinear beam which falls upon a quartz prism. The luminous rays are deflected, whereas the γ -rays leave a trace which can be followed without deflection not only past the prism but even through the prism itself.

The great penetrability of the γ -rays and also of the less deflectable b -rays means that neither the ionization of the air nor the photographic plate can give an exact idea of their intensity, since they pass through the gases and the silver salts without being absorbed.

If fairly thick metal plates are placed in their path, these rays are transformed and, either on the entry face or on the exit face, give rise to secondary rays which are more absorbable, so much so that the effect observed immediately behind these screens is more intense than if this screen did not



Fig. 19.

exist. This transformation reminds one of the effect produced by placing a fluorescent screen in the path of a beam of invisible radiations.

A photographic plate receiving the radiation of radium filtered by lead 1 cm thick is affected more under a strip of lead 1 mm thick than in the regions not covered by this screen. Figure 20 shows the effect produced by the radiation leaving through the walls of a lead parallelepiped after passing through 5 to 12 mm of metal.



Fig.20.

These secondary phenomena can account in part for the appearance of cast shadows on the edges of all the more or less transparent screens placed on the photographic plates.

Uranium and polonium emit penetrating rays which appear to be identical with *y*-rays.

Radiation of radioactive substances produces various chemical actions; it acts upon the substances used in photography, and the α - and β -rays are the most active in this respect; it colours glass violet or brown, and the alkaline salts are coloured yellow, violet, blue or green. Under its action paraffin, celluloid and paper turn yellow; white phosphorus is transformed into red phosphorus. This transformation has been noted with β -rays, but it is probable that α -rays are equally active. Ozone is produced in the air around active bodies. Not only gases but also liquid dielectrics (petroleum, liquid air) and insulating solids like paraffin are ionized when they have been penetrated by radium radiation, and they preserve their conductive properties for a few
1903 A.H.BECQUEREL

moments after the radiation has ceased to act. Giesel has observed that an aqueous solution of radium bromide continuously liberates oxygen and hydrogen at the rate of approximately 10 cm³ per gram per day. According to Ramsay and Soddy these gases would also contain helium.

M. Curie has discovered moreover that radium salts continually emit heat ; pure radium would emit approximately 80 calories per gram per hour. Curie and Dewar observed that in plunging a tube containing radium into liquid hydrogen there was a continuous release of hydrogen gas; with 0.7 g of radium bromide 73 cm³ of hydrogen were obtained per minute.

Various physiological effects have been observed with radium rays; they excite phosphorescence in the interior of the eye; when an active product is brought near to the temple, a sensation of light is perceived. They act upon the epidermis and profoundly disorganize the skin, as do X-rays. The effect is produced without any sensation being felt at first and it only develops after several weeks; it then produces more or less deep lesions which can take several months to heal and which leave scars. At present an effort is being made to utilize this action in the treatment of lupus and cancers.

Radium rays have an active effect on the nerve centres and can then cause paralysis and death; they seem to act with particular intensity on living tissues in the process of evolution.

Up to now we have only spoken of the radiation which is transmitted through glass, mica, opaque bodies and metals. In the emission of radioactive bodies there is another phenomenon of a different nature which appears to be intimately connected with radioactivity, if it is not the primordial phenomenon. Thorium and radium emit energy in a particular form; the resultant activity is propagated in the form of an active vapour which has been called *emanation* and which is arrested by any covering, however thin, which is impermeable to gases.

This emanation seems to settle upon all bodies in order to make them radioactive, but the activity disappears when the latter are no longer under the influence of the active source, even when they are in a closed chamber. These facts were discovered simultaneously at the end of 1899 by Rutherford for thorium, and by M. and Mme. Curie for radium. Rutherford when studying the activity of thorium saw that besides the ordinary radiation there was an effect produced by an *emanation* comparable with an active vapour. This latter is deposited on all bodies, principally on those which are negatively charged, and it makes them momentarily active.

66

At the same time M. and Mme. Curie discovered that under the influence of radium the bodies become temporarily active; this induced activity persists for some time after the bodies have been removed from the radium; in the open air it diminishes by about one half in half an hour.

The phenomenon is produced with regularity and with great intensity in a closed space; the induced activity is then the same on all the bodies; it is independent of the nature of the gas and of the pressure within the chamber, but the activation is no longer produced if a vacuum is constantly maintained by removing the gases which are liberated as soon as they are produced. Solutions of radium salts produce activation with greater intensity than the solids.

The water of crystallization extracted from the active salts, or the water separated from an active solution by a semi-permeable celluloid wall, become strongly radioactive. The bodies activated by the radium produce the same effects as radium; the glass walls activated by the emanation emit a penetrating radiation which passes through them and makes them luminous, whilst the activating solution can only emit feeble radiation.

The activating property is diffused gradually through the gases inside a closed chamber, through capillary tubes or imperceptible fissures; the bodies become more active as the volume of gas at their surface is greater.

A gas which has been kept near to radium and has acquired the property of making solid bodies radioactive is itself radioactive, but it only emits rays with very little penetrating power which will not pass through a glass wall. When it is removed from the radium it continues to emit rays and to cause radioactivity. Its activity from this double point of view diminishes by half during each successive period of four days and finally becomes extinct. This period of four days is a time constant characteristic of radium emanation.

Air charged with emanation produces phosphorescence of various substances (glass, zinc blende, etc.) and this phenomenon allows various striking experiments to be conducted with relation to the propagation of emanation.

Radium emanation behaves like a gas from many points of view. M. and Mme. Curie have shown that it divides like a gas between two intercommunicating gas chambers and that it is diffused in the air in accordance with the diffusion law for gases; its diffusion coefficient in air appears to be close to that of carbonic acid.

Rutherford and Soddy have discovered that the emanation condenses at the temperature of liquid air. All experiments lead one to regard the emanation as a material gas. However, the hypothesis of the existence of such a gas is based solely on the radioactive manifestations, and contrary to what happens with ordinary matter, the emanation disappears spontaneously in a sealed tube which encloses it.

Ramsay and Soddy have recently found that by enclosing the emanation from radium in a sealed tube and studying the emanation spectrum, the spectrum of helium could be seen progressively appearing, which was not observable at first. The writers explain these facts by a transformation that would be half complete in four days, and fully complete in 28. Without resorting to the hypothesis of the transformation of matter, while one is still waiting for a more complete demonstration of such an important fact, it would be possible to explain the facts by agreeing that the helium already exists in the gases of the emanation in the sealed tube, but that the special state of the emanation prevents the lines of the helium spectrum from appearing. The latter would gradually appear as the emanation is transformed; and it was observed that the activity of the emanation was reduced by half by the end of four days.

Further, it is relevant to quote a striking method of activation which leads one to make certain reservations about the conclusions to be drawn regarding the presence of new elements in radioactive preparations. Every inactive substance which is put into solutions of uranium, radium or thorium, and then precipitated out, becomes radioactive, but slowly loses its radioactivity. This fact was first noted by Curie and Giesel; the latter activated bismuth in this way.

With uranium, a trace of barium precipitated as the sulphate becomes noticeably more active than uranium; when activated in this way barium, like uranium, gives off only β -rays. After precipitation, the uranium salt, which is collected as a solid, is less active than before. This reduction in activity can be carried further by repeating the process, but the products gradually regain spontaneously their former activity.

The temporary reduction in activity after dissolution is a general phenomenon. Radium salts, when they are taken out of solution again are less active than before they were dissolved; their activity then increases over several months before reaching a maximum. They give off heat following this increase in activity.

According to Debierne, barium activated by actinium can be separated from inactive barium; it fractionates as radiferous barium chloride, the least active portion being least soluble in water and hydrochloric acid. Debierne obtained by this method a product which was one thousand times more active than uranium. Activated barium behaves like a false radium, but differs from true radium in lacking the characteristic spectrum, and in losing its activity with time.

The spontaneous recovery of radioactivity by substances in which it has been reduced may be explained in terms of the substances themselves trapping their emanation, either on the active molecules, or on the inert molecules associated with them.

Following on this research, various workers have found more examples of radioactivity, sometimes as trace elements in metals, sometimes in natural phenomena.

Elster and Geitel discovered that atmospheric air shows to a slight extent the same properties as activated gases. By stretching long negatively-charged wires in the air they were able to recover traces of activated substances on them. Gases trapped in enclosed spaces, and air extracted from the ground or near waterfalls, show these properties, as do gases extracted from certain types of water.

To sum up, the radioactive substances whose nature is now well established are: uranium, thorium, radium, and polonium; actinium can be added, although very little information has been published about this last product. Reservations must be made about various other products obtained by Giesel, and about a preparation of active bismuth or active tellurium obtained electrolytically by Markwald.

Uranium gives off β -and γ -rays; it does not give off an emanation in air, but the activation which it produces in solution can be explained as the effect of an emanation.

Thorium and radium give off α -, β - and γ -rays, and an activating emanation in gases.

Polonium does not give off β -rays. It gives off α - and γ -rays, but loses its activity with time.

Actinium is said to possess a remarkable activation power.

Besides uranium and thorium, only radium has characteristics which enable it to be considered as an element with properties related to, but distinct from, those of barium. However, it is worth noting that this substance is never found, even as a trace element, in ordinary barium minerals, and that it is only met with in uranium minerals, where it is found with barium. This fact may well have a significance which will become clear to us later.

Radioactive substances, especially radium, give off energy in all the known

forms : heat, light, chemical reactions, electrical charges, γ -radiation. They seem to maintain the same state indefinitely, and the source from which they derive the energy they give off escapes us.

Among the hypotheses which suggest themselves to fill the gaps left by current experiments, one of the most likely lies in supposing that the ernission of energy is the result of a slow modification of the atoms of the radioactive substances. Such a modification, which the methods at our disposal are unable to bring about, could certainly release energy in sufficiently large quantities to produce the observed effects, without the changes in matter being large enough to be detectable by our methods of investigation.

In this scheme, there would still be scope to wonder whether the transformation of the atom comprises a slow, spontaneous evolution, or whether it is the result of the absorption of external radiation beyond the range of our senses. If such a radiation were to exist, one could still picture the radioactive substances transforming it without themselves being altered. So far no experiment has confirmed or invalidated these hypotheses.

Biography

Antoine Henri Becquerel was born in Paris on December 15, 1852, a member of a distinguished family of scholars and scientists. His father, Alexander Edmond Becquerel, was a Professor of Applied Physics and had done research on solar radiation and on phosphorescence, while his grand-father, Antoine César, had been a Fellow of the Royal Society and the inventor of an electrolytic method for extracting metals from their ores. He entered the Polytechnic in 1872, then the government department of Ponts-et-Chaussées *in* 1874, becoming *ingénieur* in 1877 and being promoted to *ingénieur-en-chef* in 1894. In 1888 he acquired the degree of *docteur-és-sciences*. From 1878 he had held an appointment as an Assistant at the Museum of Natural History, taking over from his father in the Chair of Applied Physics at the Conservatoire des Arts et Métiers. In 1892 he was appointed Professor of Applied Physics in the Department of Natural History at the Paris Museum. He became a Professor at the Polytechnic in 1895.

Becquerel's earliest work was concerned with the plane polarization of light, with the phenomenon of phosphorescence and with the absorption of light by crystals (his doctorate thesis). He also worked on the subject of terrestrial magnetism. In 1896, his previous work was overshadowed by his discovery of the phenomenon of natural radioactivity. Following a discussion with Henri Poincaré on the radiation which had recently been discovered by Röntgen (X-rays) and which was accompanied by a type of phosphorescence in the vacuum tube, Becquerel decided to investigate whether there was any connection between X-rays and naturally occurring phosphorescence. He had inherited from his father a supply of uranium salts, which phosphoresce on exposure to light. When the salts were placed near to a photographic plate covered with opaque paper, the plate was discovered to be fogged. The phenomenon was found to be common to all the uranium salts studied and was concluded to be a property of the uranium atom. Later, Becquerel showed that the rays emitted by uranium, which for a long time were named after their discoverer, caused gases to ionize and that they differed from X-rays in that they could be deflected by electric or

magnetic fields. For his discovery of spontaneous radioactivity Becquerel was awarded half of the Nobel Prize for Physics in 1903, the other half being given to Pierre and Marie Curie for their study of the Becquerel radiation.

Becquerel published his findings in many papers, principally in the Annules de Physique et de Chimie and the Comptes Rendus del' Academie des Sciences.

He was elected a member of the Académie des Sciences de France in 1889 and succeeded Berthelot as Life Secretary of that body. He was a member also of the Accademia dei Lincei and of the Royal Academy of Berlin, amongst others. He was made an Officer of the Legion of Honour in 1900.

He was married to Mile. Janin, the daughter of a civil engineer. They had a son Jean, b. 1878, who was also a physicist: the fourth generation of scientists in the Becquerel family.

Antoine Henri Becquerel died at Le Croisic on August 25,1908.

PIERRE C URIE

Radioactive substances, especially radium

Nobel Lecture, June 6, 1905

Allow me, first of all, to tell you that I am happy to speak today before the Academy of Sciences which has conferred on Mme.Curie and myself the very great honour of awarding us a Nobel Prize. We must also tender you our apologies for being so tardy in visiting you in Stockholm, for reasons quite outside our control.

I have to speak to you today on the properties of the radioactive *substances*, and in particular of those of *radium*. I shall not be able to mention exclusively our own investigations. At the beginning of our studies on this subject in 1898 we were the only ones, together with Becquerel, interested in this question; but since then much more work has been done and today it is no longer possible to speak of radioactivity without quoting the results of investigations by a large number of physicists such as Rutherford, Debierne, Elster and Geitel, Giesel, Kauffmann, Crookes, Ramsay and Soddy, to mention only a few of those who have made important progress in our knowledge of radioactive properties.

I shall give you only a rapid account of the discovery of radium and a brief summary of its properties, and then I shall speak to you of the consequences of the new knowledge which radioactivity gives us in the various branches of science.

Becquerel discovered in 1896 the special radiating properties of *uranium* and its compounds. Uranium emits very weak rays which leave an impression on photographic plates. These rays pass through black paper and metals; they make air electrically conductive. The radiation does not vary with time, and the cause of its production is unknown.

Mme.Curie in France and Schmidt in Germany have shown that thorium and its compounds possess the same properties. Mme. Curie also showed in 1898 that of all the chemical substances prepared or used in the laboratory, only those containing uranium or thorium were capable of emitting a substantial amount of the Becquerel rays. We have called such substances *radioactive*.

Radioactivity, therefore, presented itself as an atomic property of uranium

and thorium, a substance being all the more radioactive as it was richer in uranium or thorium.

Mme. Curie has studied the minerals containing uranium or thorium, and in accordance with the views just stated, these minerals are all radioactive. But in making the measurements, she found that certain of these were more active than they should have been according to the content of uranium or thorium. Mme. Curie then made the assumption that these substances contained radioactive chemical elements which were as yet unknown. We, Mme. Curie and I, have sought to find these new hypothetical substances in a uranium ore, *pitchblende*. By carrying out the chemical analysis of this mineral and assaying the radioactivity of each batch separated in the treatment, we have, first of all, found a highly radioactive substance with chemical properties close to bismuth which we have called *polonium*, and then (in collaboration with Bémont) a second highly radioactive substance close to barium which we called *radium*. Finally, Debierne has since separated a third radioactive substance belonging to the group of the rare earths, actinium.

These substances exist in pitchblende only in the form of traces, but they have an enormous radioactivity of an order of magnitude 2 million times greater than that of uranium. After treating an enormous amount of material, we succeeded in obtaining a sufficient quantity of radiferous barium salt to be able to extract from it radium in the form of a pure salt by a method of fractionation. Radium is the higher homologue of barium in the series of the alkaline earth metals. Its atomic weight as determined by Mme. Curie is 225. Radium is characterized by a distinct spectrum which was first discovered and studied by Demarçay, and then by Crookes and Runge and Precht, Exner, and Haschek. The spectrum reaction of radium is very sensitive, but it is much less sensitive than radioactivity for revealing the presence of traces of radium.

The general effects of the radiations from radium are intense and very varied.

Various experiments: Discharge of an electroscope. - The rays pass through several centimetres of lead. - A spark induced by the presence of radium. - Excitation of the phosphorescence of barium platinocyanide, willemite and kunzite. - Coloration of glass by the rays. - Thermoluminescence of fluorine and ultramarine after the action of radiation from radium on these substances. - Radiographs obtained with radium.

A radioactive substance such as radium constitutes a continuous source of energy. This energy is manifested by the emission of the radiation. I have

RADIOACTIVE SUBSTANCES

also shown in collaboration with Laborde that radium releases heat continuously to the extent of approx. 100 calories per gram of radium and per hour. Rutherford and Soddy, Runge and Precht, and Knut Ångström have also measured the release of heat by radium, this release seems to be constant after several years, and the total energy released by radium in this way is considerable.

The work of a large number of physicists (Meyer and Schweidler, Giesel, Becquerel, P.Curie, Mme.Curie, Rutherford, Villard, etc.) shows that the radioactive substances can emit rays of the three different varieties designated by Rutherford as α -, β - and γ -rays. They differ from one another by the action of a magnetic field and of an electric field which modify the trajectory of the α - and β -rays.

The β -rays, similar to cathode rays, behave like negatively charged projectiles of a mass 2000 times smaller than that of a hydrogen atom (electron). We have verified, Mme.Curie and I, that the β -rays carry with them negative electricity. The α -rays, similar to the Goldstein's canal rays, behave like projectiles 1,000 times heavier and charged with positive electricity. The γ -rays are similar to Röntgen rays.

Several radioactive substances such as radium, actinium, and thorium also act otherwise than through their direct radiation; the surrounding air becomes radioactive, and Rutherford assumes that each of these substances emits an unstable radioactive gas which he calls *emanation* and which spreads in the air surrounding the radioactive substance.

The activity of the gases which are thus made radioactive disappears spontaneously according to an exponential law with a time constant which is characteristic for each active substance. It can, therefore, be stated that the emanation from radium diminishes by one-half every 4 days, that from thorium by one-half every 55 seconds, and that from actinium by one-half every 3 seconds.

Solid substances which are placed in the presence of the active air surrounding the radioactive substances, themselves become temporarily radioactive. This is the phenomenon of *induced radioactivity* which Mme. Curie and I have discovered. The induced radioactivities, like the emanations, are equally unstable and are destroyed spontaneously according to exponential laws characteristic of each of them.

Experiments: A glass tube filled with emanation from radium which was brought from Paris. - Discharge of an electroscope by the rays from the in-

duced radioactivity. - Phosphorescence of zinc sulphide under the action of the emanation.

Finally, according to Ramsay and Soddy, radium is the seat of a continuous and spontaneous production of helium.

The radioactivity of uranium, thorium, radium and actinium seems to be invariable over a period of several years; on the other hand, that of polonium diminishes according to an exponential law, it diminishes by one-half in 140 days and after several years it has almost completely disappeared.

These are all the most important facts which have been established by the efforts of a large number of physicists. Several phenomena have already been extensively studied by them.

The consequences of these facts are making themselves felt in all branches of science :

The importance of these phenomena for *physics* is evident. Radium constitutes in laboratories a new research tool, a source of new radiations. The study of the b -rays has already been very fruitful. It has been found that this study confirms the theory of J. J. Thomson and Heaviside on the mass of particles in motion, charged with electricity; according to this theory, part of the mass results from the electromagnetic reactions of the ether of the vacuum. The experiments of Kauffmann on the &rays of radium lead to the assumption that certain particles have a velocity very slightly below that of light, that according to the theory the mass of the particle increases with the velocity for velocities close to that of light, and that the whole mass of the particle is of an electromagnetic nature. If the hypothesis is also made that material substances are constituted by an agglomeration of electrified particles, it is seen that the *fundamental principles of mechanics* will have to be profoundly modified.

The consequences for *chemistry* of our knowledge of the properties of the radioactive substances are perhaps even more important. And this leads us to speak of the source of energy which maintains the radioactive phenomena.

At the beginning of our investigations we stated, Mme. Curie and I, that the phenomena could be explained by two distinct and very general hypotheses which were described by Mme. Curie in 1899 and 1900 (*Revue Générale des Sciences*, January 10, 1899, and *Revue Scientifique*, July 21, 1900).

I. In the first hypothesis it can be supposed that the radioactive substances borrow from an external radiation the energy which they release, and their radiation would then be a secondary radiation. It is not absurd to suppose that space is constantly traversed by very penetrating radiations which cer-

76

tain substances would be capable of capturing in flight. According to the recent work of Rutherford, Cooke and McLennan, this hypothesis seems to be useful for explaining part of the extremely weak radiation which emanates from most of the substances.

2. In the second hypothesis it can be supposed that the radioactive substances draw from themselves the energy which they release. The radioactive substances would then be in course of evolution, and they would be transforming themselves progressively and slowly in spite of the apparent invariability of the state of certain of them. The quantity of heat released by radium in several years is enormous if it is compared with the heat released in any chemical reaction with the same weight of matter. This released heat would only represent, however, the energy involved in a transformation of a quanty of radium so small that it cannot be appreciated even after years. This leads to the supposition that the transformation is more far-reaching than the ordinary chemical transformations, that the existence of the atom is even at stake, and that one is in the presence of a transformation of the elements.

The second hypothesis has shown itself the more fertile in explaining the properties of the radioactive substances properly so called. It gives, in particular, an immediate explanation for the spontaneous disappearance of polonium and the production of helium by radium. This theory of the transformation of the elements has been developed and formulated with great boldness by Rutherford and Soddy who state that there is a continuous and irreversible disaggregation of the atoms of the radioactive elements. In the theory of Rutherford the disaggregation products would be, on the one hand, the projectile rays, and on the other hand, the emanations and the induced radioactivities. The latter would be new gaseous or solid radioactive substances frequently with a rapid evolution and having atomic weights lower than that of the original element from which they are derived. Seen in this way the life of radium would be necessarily limited when this substance is separated from the other elements. In Nature radium is always found in association with uranium, and it can be assumed that it is produced by the latter.

This, therefore, is a veritable theory of the transmutation of elements, although not as the alchemists understood it. The inorganic matter would necessarily evolve through the ages and in accordance with immutable laws.

Through an unexpected consequence the radioactive phenomena can be important in geology. It has been found, for example, that radium always

1903 P. CURIE

accompanies uranium in minerals. And it has even been found that the ratio of radium to uranium is constant in all minerals (Boltwood). This confirms the idea of the creation of radium from uranium. This theory can be extended to try to explain also other associations of elements which occur so frequently in minerals. It can be imagined that certain elements have been formed on the spot on the surface of the Earth or that they stem from other elements in a time which may be of the order of magnitude of geological periods. This is a new point of view which the geologists will have to take into account.

Elster and Geitel have shown that the emanation of radium is very widespread in Nature and that radioactivity probably plays an important part in *meteorology*, with the ionization of the air provoking the condensation of water vapour.

Finally, in the biological sciences the rays of radium and its emanation produce interesting effects which are being studied at present. Radium rays have been used in the treatment of certain diseases (lupus, cancer, nervous diseases). In certain cases their action may become dangerous. If one leaves a wooden or cardboard box containing a small glass ampulla with several centigrams of a radium salt in one's pocket for a few hours, one will feel absolutely nothing. But 15 days afterwards a redness will appear on the epidermis, and then a sore which will be very difficult to heal. A more prolonged action could lead to paralysis and death. Radium must be transported in a thick box of lead.

It can even be thought that radium could become very dangerous in criminal hands, and here the question can be raised whether mankind benefits from knowing the secrets of Nature, whether it is ready to profit from it or whether this knowledge will not be harmful for it. The example of the discoveries of Nobel is characteristic, as powerful explosives have enabled man to do wonderful work. They are also a terrible means of destruction in the hands of great criminals who are leading the peoples towards war. I am one of those who believe with Nobel that mankind will derive more good than harm from the new discoveries.

Biography

Pierre Curie was born in Paris, where his father was a general medical practitioner, on May 15, 1859. He received his early education at home before entering the Faculty of Sciences at the Sorbonne. He gained his Licenciateship in Physics in 1878 and continued as a demonstrator in the physics laboratory until 1882 when he was placed in charge of all practical work in the Physics and Industrial Chemistry Schools. In 1895 he obtained his Doctor of Science degree and was appointed Professor of Physics. He was promoted to Professor in the Faculty of Sciences in 1900, and in 1904 he became Titular Professor.

In his early studies on crystallography, together with his brother Jacques, Curie discovered piezoelectric effects. Later, he advanced theories of symmetry with regard to certain physical phenomena and turned his attention to magnetism. He showed that the magnetic properties of a given substance change at a certain temperature - this temperature is now known as the Curie point. To assist in his experiments he constructed several delicate pieces of apparatus - balances, electrometers, piezoelectric crystals, etc.

Curie's studies of radioactive substances were made together with his wife, whom he married in 1895. They were achieved under conditions of much hardship - barely adequate laboratory facilities and under the stress of having to do much teaching in order to earn their livelihood. They announced the discovery of radium and polonium by fractionation of pitchblende in 1898 and later they did much to elucidate the properties of radium and its transformation products. Their work in this era formed the basis for much of the subsequent research in nuclear physics and chemistry. Together they were awarded half of the Nobel Prize for Physics in 1903 on account of their study into the spontaneous radiation discovered by Becquerel, who was awarded the other half of the Prize.

Pierre Curie's work is recorded in numerous publications in the *Comptes Rendus de l'Académie des Sciences,* the *Journal de Physique* and the *Annales de Physique et Chimie.*

Curie was awarded the Davy Medal of the Royal Society of London in

1903 (jointly with his wife) and in 1905 he was elected to the Academy of Sciences.

His wife was formerly Marie Sklodowska, daughter of a secondary-school teacher at Warsaw, Poland. One daughter, Irene, married Frederic Joliot and they were joint recipients of the Nobel Prize for Chemistry in 1935. The younger daughter, Eve, married the American diplomat H. R. Labouisse. They have both taken lively interest in social problems, and as Director of the United Nations' Children's Fund he received on its behalf the Nobel Peace Prize in Oslo in 1965. She is the author of a famous biography of her mother, *Madame Curie* (Gallimard, Paris, 1938), translated into several languages.

Pierre was killed in a street accident in Paris on April 19, 1906.

80

No Lecture was delivered by Mme. Curie.

Biography

Marie Curie, née Sklodowska, was born in Warsaw on November 7, 1867, the daughter of a secondary-school teacher. She received a general education in local schools and some scientific training from her father. She became involved in a students' revolutionary organization and found it prudent to leave Warsaw, then in the part of Poland dominated by Russia, for Cracow, which at that time was under Austrian rule. In 1891, she went to Paris to continue her studies at the Sorbonne where she obtained Licenciateships in Physics and the Mathematical Sciences. She met Pierre Curie, Professor in the School of Physics in 1894 and in the following year they were married. She succeeded her husband as Head of the Physics Laboratory at the Sorbonne, gained her Doctor of Science degree in 1903, and following the tragic death of Pierre Curie in 1906, she took his place as Professor of General Physics in the Faculty of Sciences, the first time a woman had held this position. She was also appointed Director of the Curie Laboratory in the Radium Institute of the University of Paris, founded in 1914.

Her early researches, together with her husband, were often performed under difficult conditions, laboratory arrangements were poor and both had to undertake much teaching to earn a livelihood. The discovery of radioactivity by Henri Becquerel in 1896 inspired the Curies in their brilliant researches and analyses which led to the isolation of polonium, named after the country of Marie's birth, and radium. Mme. Curie developed methods for the separation of radium from radioactive residues in sufficient quantities to allow for its characterization and the careful study of its properties, therapeutic properties in particular.

Mme. Curie throughout her life actively promoted the use of radium to alleviate suffering and during World War I, assisted by her daughter, Irene, she personally devoted herself to this remedial work. She retained her enthusiasm for science throughout her life and did much to establish a radioactivity laboratory in her native city - in 1929 President Hoover of the United States presented her with a gift of \$50,000, donated by American friends of science, to purchase radium for use in the laboratory in Warsaw.

BIOGRAPHY

Mme. Curie, quiet, dignified and unassuming, was held in high esteem and admiration by scientists throughout the world. She was a member of the Conseil du Physique Solvay from 1911 until her death and since 1922 she had been a member of the Committee of Intellectual Co-operation of the League of Nations. Her work is recorded in numerous papers in scientific journals and she is the author of *Recherches sur les Substances Radioactives* (1904), L'Isotopie et les Éléments Isotopes and the classic Traité de Radioactivite' (1910).

The importance of Mme. Curie's work is reflected in the numerous awards bestowed on her. She received many honorary science, medicine and law degrees and honorary memberships of learned societies throughout the world. Together with her husband, she was awarded half of the Nobel Prize for Physics in 1903, for their study into the spontaneous radiation discovered by Becquerel, who was awarded the other half of the Prize. In 1911 she received a second Nobel Prize, this time in Chemistry, in recognition of her work in radioactivity. She also received, jointly with her husband, the Davy Medal of the Royal Society in 1903 and, in 1921, President Harding of the United States, on behalf of the women of America, presented her with one gram of radium in recognition of her service to science.

For further details, *cf.* pp. 79 and 80. Mme. Curie died at Savoy, France, after a short illness, on July 4, 1934.

Physics 1904

Lord RAY LEIGH (JOHN WILLIAM STRUTT)

<<for his investigations of the densities of the most important gases and for his discovery of argon in connection with these studies))

Physics 1904

Presentation Speech by Professor J.E. Cederblom, President of the Royal Swedish Academy of Sciences

Your Majesty, Your Royal Highnesses, Ladies and Gentlemen.

The Royal Academy of Sciences has decided that the Nobel Prize for Physics for the present year is to be awarded to Lord Rayleigh, Professor at the Royal Institution, London, for his investigations on the density of the most important gases, and for his discovery of argon, one of the results of those investigations.

Among the problems in physico-chemical science that have more especially taken up the attention of scientists, the nature and composition of atmospheric air has always held a prominent position. For centuries this problem has been the object of both keen enquiry and extensive experimental investigation, consequently its history affords a very striking picture of the gradual development of those sciences in their entirety, closely connected as it is with the progress made in the various departments of physics and chemistry. The retarding influence, which in former times was continuously exercised not only by incorrect opinions that had become firmly established but also by insufficient experimental groundwork, is plainly observable, and this explains the fact that during the seventeenth century the solution of the problem was not, and could not, be arrived at by such scientists as Boyle, Mayow, and Hales; it was only obtained a hundred years later, after the discoveries of Priestley, Black, Cavendish, and above all Lavoisier, in a manner which not only then, but up to quite a recent date, was considered final.

Under such circumstances it is but natural that the discovery of a new component of the air, one that is present to the considerable amount of about one per cent, excited great and justifiable astonishment. How was it possible, people asked, that in the face of all the improvements in both physical and chemical methods of observation of the present day this gas should for so long have remained unobserved? The answer to this question lies not only in the strange indifference to chemical investigations by which the age is characterized, but also in the investigations on the physical properties of atmospheric gases not having then reached that high degree of

PHYSICS 1904

accuracy which Lord Rayleigh has since succeeded in attaining. This is specially the case in determining densities. It has been shown that nitrogen, when separated from the air, is invariably heavier than when produced from its chemical compounds. As the difference is no less than one half per cent, there is no doubt as to the existence of this divergence, since the accuracy of the weigher was such that the possible fault could only be 1/50 thereof. Since between these two kinds of nitrogen- on the one hand the atmospheric, on the other that obtained from chemical compounds-there is a definite difference in density, the question arose : What could be the cause of this peculiar state of things? All the circumstances of the investigation which might be supposed to have any influence in this respect having been carefully examined, and their influence being found insufficient to explain the difference observed, there remained, in Lord Rayleigh's opinion, but one possibility, viz. that the atmospheric nitrogen was not a simple element, but was a combination of pure nitrogen and some new, hitherto unknown, heavier gas. If so, this gas could be isolated in some way or other. The methods, physical or chemical, available for this isolation were already known in principle, and the problem now was to obtain the new gas not only in the purest form possible, but also in a sufficient quantity to allow of a thorough investigation of its essential properties. These both difficult and tedious tests have been carried out conjointly by Lord Rayleigh and Sir William Ramsay, and have resulted not only in completely proving that the new gas occurs in a ready state in the air, but also in establishing a thorough knowledge of its chief physical and chemical characteristics.

The time at my disposal does not permit of my giving a detailed account of these questions, interesting and important as they undoubtedly are, but I venture to call attention to the fact that besides the great importance always adherent to the proving of the existence of a new element, this one is of special interest owing to the purely physical investigations on which it is based, investigations which - embracing not only nitrogen but several other important gases -are characterized by a delicacy and precision that is very rarely met with in the history of physical research. Considering also that to the discovery of argon we may trace one of the causes of Sir William Ramsay's brilliant discovery of helium and the other so-called <<noble gases>>, which followed shortly after, we may truly aver that Lord Rayleigh's work is of that fundamental character that the award to him of the Nobel Prize in Physics must be greeted with sincere and fully justified satisfaction, more especially since this section of his work is but a single link in a long chain

PRESENTATION

of remarkable investigations with which from various points of view he has enriched Physical Science, and which are of such a nature that they will ensure him a prominent position in its history for all time to come.

Lord RAYLEIGH

The density of gases in the air and the discovery of argon

Nobel Lecture, December 12, 1904

The subject of the densities of gases has engaged a large part of my attention for over 20 years. In 1882 in an address to the British Association I suggested that the time had come for a redetermination of these densities, being interested in the question of Prout's law. At that time the best results were those of Regnault, according to whom the density of oxygen was 15.96 times that of hydrogen. The deviation of this number from the integer 16 seemed not to be outside the limits of experimental error.

In my work, as in the simultaneous work of Cooke, the method of Regnault was followed in that the working globe was counterpoised by a dummy globe (always closed) of the same external volume as itself Under these conditions we became independent of fluctuations of atmosphere density. The importance of this consideration will be manifest when it is pointed out that in the usual process of weighing against brass or platinum weights, it might make more apparent difference whether the barometer were high or low than whether the working globe were vacuous or charged with hydrogen to atmospheric pressure. Cooke's result, as at first announced, was practically identical with that of Regnault, but in the calculations of both these experimenters a correction of considerable importance had been overlooked. It was assumed that the external volume of the working globe was the same whether vacuous or charged to atmospheric pressure, whereas of course the volume must be greater in the latter case. The introduction of the correction reduced Cooke's result to the same as that which I had in the meantime announced, viz. 15.88. In this case therefore the discrepancy from Prout's law was increased, and not diminished, by the new determination.

Turning my attention to *nitrogen*, I made a series of determinations, using a method of preparation devised originally by Harcourt, and recommended to me by Ramsay. Air bubbled through liquid ammonia is passed through a tube containing copper at a red heat where the oxygen of the air is consumed by the hydrogen of the ammonia, the excess of the ammonia being subsequently removed with sulphuric acid. In this case the copper serves merely to increase the surface and to act as an indicator. As long as it remains bright, we have security that the ammonia has done its work.

Having obtained a series of concordant observations on gas thus prepared I was at first disposed to consider the work on nitrogen as finished. Afterwards, however, I reflected that the method which I had used was not that of Regnault and that in any case it was desirable to multiply methods, so that I fell back upon the more orthodox procedure according to which, ammonia being dispensed with, air passes directly over red hot copper. Again a series in good agreement with itself resulted, but to my surprise and disgust the densities obtained by the two methods differed by a thousandth part - a difference small in itself but entirely beyond the experimental errors. The ammonia method gave the smaller density, and the question arose whether the difference could be attributed to recognized impurities. Somewhat prolonged inquiry having answered this question in the negative, I was rather at a loss how to proceed. It is a good rule in experimental work to seek to magnify a discrepancy when it first presents itself, rather than to follow the natural instinct of trying to get quit of it. What was the difference between the two kinds of nitrogen? The one was wholly derived from air; the other partially, to the extent of about one-fifth part, from ammonia. The most promising course for magnifying the discrepancy appeared to be the substitution of oxygen for air in the ammonia method, so that all the nitrogen should in that case be derived from ammonia. Success was at once attained, the nitrogen from the ammonia being now 1/200 part lighter than that from air, a difference upon which it was possible to work with satisfaction. Among the explanations which suggested themselves were the presence of a gas heavier than nitrogen in the air, or (what was at first rather favoured by chemical friends) the existence in the ammonia-prepared gas of nitrogen in a dissociated state. Since such dissociated nitrogen would probably be unstable, the experiment was tried of keeping a sample for eight months, but the density was found to be unaltered.

On the supposition that the air-derived gas was heavier than the <<chemical>> nitrogen on account of the existence in the atmosphere of an unknown ingredient, the next step was the isolation of this ingredient by absorption of nitrogen. This was a task of considerable difficulty; and it was undertaken by Ramsay and myself working at first independently but afterwards in concert. Two methods were available - the first that by which Cavendish had originally established the identity of the principal component of the atmosphere with the nitrogen of nitre and consisting in the oxidation of the

1904 LORD RAYLEIGH

nitrogen under the influence of electric sparks with absorption of the acid compounds by alkali; the other method was to absorb the nitrogen by means of magnesium at a full red heat. In both these ways a gas was isolated of amount equal to about one per cent of the atmosphere by volume and having a density about half as great again as that of nitrogen. From the manner of its preparation it was proved to be non-oxidizable and to refuse absorption by magnesium at a red heat, and further varied attempts to induce chemical combination were without result. On this account the name *argon* was given to it. The most remarkable feature of the gas was the ratio of its specific heats, which proved to be the highest possible, viz. 1.67, indicating that sensibly the whole of the energy of molecular motion is translational.

Argon must not be deemed rare. A large hall may easily contain a greater weight of it than a man can carry.

In subsequent investigations Ramsay and Travers discovered small quantities of new gases contained in the aggregate at first named argon. Helium, originally obtained by Ramsay from clevite, is also present in minute quantity.

Experiments upon the refractivity and viscosity of argon revealed nothing specially remarkable, but the refractivity of helium proved to be unexpectedly low, not attaining one-third of that of hydrogen - the lowest then known.

As regards the preparation of argon, it is advantageous to begin with *liquid air*, for preparing which a plant is now to be found in many laboratories. It should perhaps be remarked that <liquid air>> is something of a misnomer. What is liquified is not the whole of the air supplied or even a fair sample of it. The oxygen, being less volatile, is contained in undue proportion, and this excess increases as evaporation proceeds. Argon, being intermediate in volatility, may be expected to increase relatively to the nitrogen, though it decreases relatively to the oxygen. A number of analyses for oxygen and argon as evaporation proceeded are appended (Table 1); they relate to the *vapour* arising from the liquid and not to the liquid itself. The oxygen, expressed as a fraction of the whole, varied from 30 to 98 per cent. From 43 to 90 per cent of oxygen, the argon, as a percentage of the whole, scarcely varied from 2.0.

The experiment under the head 98 per cent is not quite comparable with the others. The last entry, corresponding to 100 per cent of oxygen, is theoretical and does not represent any actual experiment.

Percentage of oxygen	Percentage of argon	Argon, as a percentage of nitrogen and argon
30	1.3	1.9
43	2.0	3.5
64	2.0	5.6
75	2.1	8.4
90	2.0	20.0
98	0.76	33.0
100	0.00	100.0

Table 1.

The above numbers show that a great advantage may be obtained by starting with liquid air. Something depends upon the procedure to be adopted for eliminating the nitrogen. Upon a moderate scale and where there is a supply of alternating current, the method of oxidation, as in the analyses, is probably the more convenient. In this case it may be an advantage to retain the oxygen. If the oxygen content be about 60 per cent, as in the third experiment, the proportion is about sufficient to oxidize the nitrogen. We may compare this with the mixture of atmospheric air and oxygen which behaves in the same manner. In the latter case the proportion of argon would be reduced from 2.0 per cent to about 0.4 per cent, so that the advantage of using the liquid air amounts to about five times. In an arrangement that I have described for oxidizing nitrogen upon a large scale, the mixed gases were absorbed at the rate of 20 litres per hour.

In the alternative method the nitrogen is absorbed by magnesium or calcium. In this case it is necessary first to remove the oxygen; but oxygen is so much more easily dealt with than nitrogen that its presence, even in large proportion, is scarcely an objection. On this view and on the supposition that liquid air is available in large quantities, it is advantageous to allow the evaporation to proceed to great lengths. A 20 per cent mixture of argon and nitrogen (Experiment 5) is readily obtained.

Although the preparation of a considerable quantity of argon is rather an undertaking, there is no difficulty in demonstrating its existence with the most ordinary appliances. By the use of a specially shaped tube and an ordinary induction-coil actuated by a small Grove battery, I was able to show the characteristic spectrum of argon at atmospheric pressure, starting with 5cc only of air.

1904 LORD RAYLEIGH

Another question relating to the gases of the atmosphere has occupied my attention -namely the amount of free hydrogen. It may be remembered that M. A. Gautier, as the result of very elaborate investigations, announced that the amount of free hydrogen reached 2/10,000, in addition to variable quantities of hydrocarbons dependent upon the locality where the air was collected. My own earlier observations related to the visibility of the C-line in sparks taken through carefully dried air at atmospheric pressure. This line could never be entirely eliminated, but with precaution could be made somewhat faint. When (country) air to which 1/5,000 of hydrogen had been added was substituted for the pure air, the visibility of C was markedly increased; and the difference was such that one might easily believe that the proportion of hydrogen actually operative had been doubled. This conclusion would be in precise accordance with M. Gautier, could we assume that the smaller quantity of hydrogen really accompanied the air. But other observations rendered this assumption extremely doubtful.

In the first place the visibility of C with ordinary air was not perceptibly diminished by passage of the air over red-hot copper oxide. It may be argued that this reagent is not competent in moderate length to remove the last traces of hydrogen from air, even though the air be passed over it in a slow stream. I found, however, on a former occasion that hydrogen purposely introduced into nitrogen could be so far removed in this way that the density remained sensibly unaffected, although 1/10,000 of residual hydrogen might be expected to manifest itself

Moreover, when air purposely contaminated as above with 1/5,000 of hydrogen was passed over the copper oxide, the additional hydrogen appeared to be removed, the visibility of C reducing itself to that corresponding to untreated air.

Subsequently further spectroscopic experiments were made in which the platinum points were replaced by points of aluminium; and the evidence could hardly be reconciled with Gautier's view without coincidences of little a *priori* probability.

I was accordingly induced to make determinations by direct combustion. Ten litres of fresh country air dried as thoroughly as possible were passed over copper oxide at a red heat. The gain in weight of a phosphoric tube through which the air subsequently passed indicated an amount of free hydrogen corresponding to only about one-seventh of that recorded by Gautier, even though no allowance be made for the possible presence of hydrocarbons.

94

A defective gain of weight can hardly be explained as due to faulty manipulation. The important question is as to the efficiency of the copper oxide. Did my furnace tube allow the main part of the free hydrogen to pass unburnt? The question is one that can hardly be answered directly, but I may say that variations of temperature (within moderate limits) did not affect the result.

What it is possible to examine satisfactorily is the effect of small additions of hydrogen to the air as collected. In my later experiments the added hydrogen was only Icc, that is 1/10,000 by volume, or half the quantity originally present according to M.Gautier. The hydrogen was first diluted in a gas pipette with about 100 cc of air and allowed time to diffuse. The 10-litre aspirating-bottle being initially full of water, the diluted hydrogen was introduced at the top and was followed by 10litres of air from the open, after which the mixture stood overnight, precautions which had been found sufficient to ensure a complete mixture in the spectroscopic work. The results showed an *additional* gain of 0.00072 grams, very nearly the full amount (0.00075) corresponding to the Icc of added hydrogen. We may say then that the copper oxide was competent to account for a small *addition* of hydrogen to air.

Another branch of my work upon gases has relation to the law of pressure, especially at low pressures. Under these circumstances the usual methods are deficient in accuracy. Thus Amagat considers that under the best conditions it is not possible to answer for anything less than 0.01 mm of mercury. By the use of a special manometer I was able to carry the accuracy at least 50 times further than Amagat's standard, and thus to investigate with fair accuracy the effect of pressures not exceeding 0.01 mm in total amount. Boyle's law was fully verified, even in the case of oxygen, for which C. Baur had found anomalies, especially in the neighbourhood of 0.7 mm pressure.

More recently I have made determinations of the compressibility of gases between one atmosphere and half an atmosphere of pressure. For this purpose two manometric gauges, each capable of measuring half an atmosphere, were employed. The equality of the gauges could be tested by using them *in* parallel, to borrow an electrical term. One of the gauges alone would thus serve for half an atmosphere, while the two combined *in series* gave the whole atmosphere. In combination with these gauges volumes in the ratio of 2: 1 were needed. Here again the desired result was arrived at by the use of two equal volumes, either alone or in combination. Any question as to the precise equality of the two volumes is eliminated in each set of observations by using the two single volumes alternately. The mean result then necessarily corresponds to the half of the total volume, except in so far as the capacities of the vessels may be altered by change of pressure.

The annexed Table 2 gives a summary of results for the various gases.

Table 2.			
В	Temperature		
1.00038	11.2		
0.99974	10.7		
1.00015	14.9		
1.00026	13.8		
1.00023	11.4		
I.00279	15.0		
1.00327	11.0		
	B 1.00038 0.99974 1.00015 1.00026 1.00023 I.00279 1.00327		

Here

$$B = pv \frac{at \frac{1}{2} atmos.}{pv at 1 atmos.}$$

the temperature beingthe same at both pressures and having the value recorded. That *B* should be less than unity in the case of hydrogen and exceed that value for the other gases, is what was to be expected from the known behaviour at higher pressures.

The principal interest of these results is perhaps to calculate corrections to ratios of densities, as found at atmospheric pressure, so as to infer what the ratios would be in a state of great rarefaction. It is only under this condition that Avogadro's law can be expected to apply accurately, as I pointed out in 1892 in connection with oxygen and hydrogen.

In the case of nitrogen and oxygen, the correction is not important, and the original comparison of densities^{*} is sensibly unaffected. According to this method the atomic weight of nitrogen is 14.01, in opposition to the 14.05 found by Stas.

* Rayleigh and Ramsay, Phil. Trans., (1895).

Biography

John William Strutt, third Baron Rayleigh, was born on November 12,1842 at Langford Grove, Maldon, Essex, as the son of John James Strutt, second Baron, and his wife Clara Elizabeth La Touche, eldest daughter of Captain Richard Vicars, R. E. He was one of the very few members of higher nobility who won fame as an outstanding scientist.

Throughout his infancy and youth he was of frail physique; his education was repeatedly interrupted by ill-health, and his prospects of attaining maturity appeared precarious. After a short spell at Eton at the age of 10, mainly spent in the school sanatorium, three years in a private school at Wimbledon, and another short stay at Harrow, he finally spent four years with the Rev. George Townsend Warner (1857) who took pupils at Torquay.

In 1861 he entered Trinity College, Cambridge, where he commenced reading mathematics, not at first equal in attainments to the best of his contemporaries, but his exceptional abilities soon enabled him to overtake his competitors. He graduated in the Mathematical Tripos in 1865 as Senior Wrangler and Smith's Prizeman. In 1866 he obtained a fellowship at Trinity which he held until 1871, the year of his marriage.

A severe attack of rheumatic fever in 1872 made him spend the winter in Egypt and Greece. Shortly after his return his father died (1873) and he succeeded to the barony, taking up residence in the family seat, Terling Place, at Witham, Essex. He now found himself compelled to devote part of his time to the management of his estates (7000 acres). The combination of general scientific knowledge and acumen with acquired knowledge of agriculture made his practice in estate management in many respects in advance of his time. Nevertheless, in 1876 he left the entire management of the land to his younger brother.

From then on, he could devote his full time to science again. In 1879 he was appointed to follow James Clerk Maxwell as Professor of Experimental Physics and Head of the Cavendish Laboratory at Cambridge. In 1884 he left Cambridge to continue his experimental work at his country seat at Terling, Essex, and from 1887 to 1905 he was Professor of Natural Philosophy in the Royal Institution of Great Britain, being successor of Tyndall.

1904 LORD RAYLEIGH

He served for six years as President of a Government Committee on Explosives and from 1896 to 1919 he was Scientific Advisor to Trinity House. He was Lord Lieutenant of Essex from 1892 to 1901.

Lord Rayleigh's first researches were mainly mathematical, concerning optics and vibrating systems, but his later work ranged over almost the whole field of physics, covering sound, wave theory, colour vision, electrodynamics, electromagnetism, light scattering, flow of liquids, hydrodynamics, density of gases, viscosity, capillarity, elasticity, and photography. His patient and delicate experiments led to the establishment of the standards of resistance, current, and electromotive force; and his later work was concentrated on electric and magnetic problems. Lord Rayleigh was an excellent instructor and, under his active supervision, a system of practical instruction in experimental physics was devised at Cambridge, developing from a class of five or six students to an advanced school of some seventy experimental physicists. His *Theory* of Sound was published in two volumes during 1877-1878, and his other extensive studies are reported in his *Scientific Papers* - six volumes issued during 1889-1920. He has also contributed to the *Encyclopaedia Britannica*.

He had a fine sense of literary style; every paper he wrote, even on the most abstruse subject, is a model of clearness and simplicity of diction. The 446 papers reprinted in his collected works clearly show his capacity for understanding everything just a little more deeply than anyone else. Although a member of the House of Lords, he intervened in debate only on rare occasions, never allowing politics to interfere with science. His recreations were travel, tennis, photography and music.

Lord Rayleigh, a former Chancellor of Cambridge University, was a Justice of the Peace and the recipient of honorary science and law degrees. He was a Fellow of the Royal Society (1873) and served as Secretary from 1885 to 1896, and as President from 1905 to 1908. He was an original recipient of the Order of Merit (1902), and in 1905 he was made a Privy Councillor. He was awarded the Copley, Royal, and Rumford Medals of the Royal Society, and the Nobel Prize for 1904.

In 1871 he married Evelyn, sister of the future prime minister the Earl of Balfour, and daughter of James Maitland Balfour and his wife Blanche, the daughter of the second Marquis of Salisbury. They had three sons, the eldest of whom was to become Professor of Physics at Imperial College of Science and Technology, London.

Lord Rayleigh died on June 30, 1919, at Witham, Essex.

98

Physics 1905

PHILIPP EDUARD ANTON VON LENARD

<< for his work on cathode rays>>

Physics 1905

Presentation Speech by Professor A. Lindstedt, President of the Royal Swedish Academy of Sciences

Your Majesty, Your Royal Highnesses, Ladies and Gentlemen.

The Royal Swedish Academy of Sciences has decided to give this year's Nobel Prize for Physics to Dr.Philipp Lenard, Professor at the University of Kiel, for his important work on cathode rays.

The discovery of the cathode rays forms the first link in the chain of brilliant discoveries with which the names of Röntgen, Becquerel and Curie are connected. The discovery itselfwas made by Hittorf as long ago as 1869 and therefore falls in a period before that which the Nobel Foundation is able to take into account. However, the recognition which Lenard has earned himself by the further development of Hittorf's discovery (which is becoming of increasing importance) shows that he too deserves the same reward as has already come to several of his successors for work of a similar nature.

Cathode rays are a phenomenon which occurs when electricity is discharged in a rarified gas. If an electric current is led through a glass tube containing rarified gas, certain radiation phenomena appear both in the gas and around the metal wires or poles through which the current is carried. These phenomena change in form and nature if the gas contained in the tube is rarified even further. At a given low pressure of gas, rays are emitted from the negative pole, called the <<cathode>>, which are invisible to the naked eye but which can be observed through certain peculiar effects. This is due to the fact that when these rays hit the walls of the glass tube, or other obstacles in their path, they cause them to glow or fluoresce and are able to bring objects against which they are directed to a glowing heat. Like rays of ordinary light they propagate in straight lines, but they differ in that they can be deflected from their straight path by means of a magnet.

The general characteristics of these cathode rays had been known a long time, although not sufficiently to clarify their true nature. Twenty years ago two basically different concepts were prevalent. According to one concept, which was supported especially by German physicists, cathode rays consisted as do normal rays of light, of undulatory motion in the ether. According to the other concept, which was mainly popular among English sci-

PHYSICS 1905

entists, cathode rays were supposed to consist of particles which were ejected from the cathode and were charged with negative electricity. The decision for one or other of these theories rested on the results of experimental research. These experiments, however, were greatly impeded by the fact that one seemed to be restricted to phenomena within the glass tube itself, since the cathode rays ended at the wall of the tube. The question of whether they could at all exist outside the tube remained unanswered.

These were the circumstances prevailing when Lenard began his work on cathode rays in 1893. He started from a fact which had been observed by his great and prematurely deceased teacher Heinrich Hertz : that these rays were able to pass through thin metal plates which had been introduced into the discharge tube. At Hertz's suggestion he utilized this fact in an attempt to lead the rays out of the tube. He used for this a tube which was not wholly made of glass but terminated at one place in a very thin aluminium plate. As the cathode rays reached Lenard's <<al>
aluminium window>>
it was found that they passed through it and continued their course in the air outside the tube. This constituted a discovery which was to have the most far-reaching consequences, above all for the study of the radiation phenomena themselves. It became possible to study cathode rays under much simpler and more convenient experimental conditions than before, and also to separate observations on conditions needed for the production of the rays in the tube from questions concerning their propagation and other characteristics.

Lenard found first of all that the rays coming through the aluminium window possessed the same characteristics as those previously noted in rays inside the tube, i.e. that they cause fluorescence, can be deflected by a magnet and so on. He further proved that cathode rays have certain chemical effects such as causing impressions on photographic plates, ozonizing air, making gases conducting through so-called ionization, etc. It was also discovered that these rays pass unimpeded through empty space but that in gases they are subject to diffusion which increases with the density of the gas; and, moreover, that bodies in general differ in permeability, as their absorptive power bears a direct relationship to their density. Cathode rays proved to be carriers of negative electricity even in empty space and they could be deflected from their path by both magnetic and electricalfields. Finally, Lenard showed that there are various types of cathode rays, differentiated amongst other things by the fact that they are deflected by magnets, to a greater or lesser extent. He also found that the formation of one or other type of ray is determined by the degree of gas rarification in the discharge tube.

102

PRESENTATION

When Lenard began his work on cathode rays he approached the concept of their nature from the German viewpoint noted above, whereby the rays are explained as being vibrations in the ether. Through the results of his work which we have just briefly described and in particular through the discovery that cathode rays are influenced by electrical fields, this view became untenable. He now came closer to the English view, put forward mainly by Crookes, that the rays are composed of particles which are ejected by the cathode and are bearers of negative electricity. Since then, however, this theory has had to be modified in several significant details in order to reconcile it with phenomena which have been brought to light through the work of Lenard and others. It was shown, for example, that these particles which, according to Crookes, are ejected from the cathode- the so-called <<electrons>>-must have a considerably smaller mass than chemical atoms, that the velocity of these electrons can come to about one-third of the speed of light, but that there are also cathode rays which are considerably slower: the various types of cathode rays are in fact explained by the different speeds with which they are ejected from the cathode. In his more recent work Lenard has been able to produce cathode rays with relatively slow speed, rays which are formed through the influence of ultraviolet light on bodies charged with negative electricity. This has also served to explain an important phenomenon noted by other research workers.

The research by Lenard, only a very brief report of which is given here, has been followed by a series of valuable studies by other scientists as well. Development of the theoretical basis for the theory of electrons has gone hand in hand with the experimental work. The study of electrons, their characteristics and their behaviour in relation to matter has been given a sounder basis through these researches on cathode rays and has been gradually developed into one of the foremost theories of modern physics by Lenard himself and by other workers. This theory is in fact not only important for the explanation of cathode rays and other closely related phenomena - the electron theory with its concepts on the constitution of matter has become of the most fundamental importance for the sciences of electricity and of light and for both the physicist and the chemist.

It is clear that Lenard's work on cathode rays has not only enriched our knowledge of these phenomena, but has also served in many respects as a basis for the development of the electron theory. Lenard's discovery that cathode rays can exist outside the discharge tube, in particular, has opened up new fields of research in physics. It gave an impetus to the search for other

PHYSICS 1905

thus far unknown sources of similar rays, and the revolutionary discoveries by past Nobel Prize winners - Röntgen, Becquerel and the two Curies - and by other scientists which have followed can well be considered the fruits of this impetus and links in the history of development of one and the same science.

Because of the overall importance of Lenard's work, and because of its scientific value and pioneering nature, the Royal Swedish Academy of Sciences has decided to award him the Nobel Prize in Physics for the year 1905.

104
On cathode rays

Nobel Lecture, May 28, 1906

I am pleased to fulfil my obligation as a Nobel Prize winner to talk to you here on cathode rays. I assume that you would prefer me to tell you what others could not tell you. I shall describe to you the development of the subject - which also embraces recent theories concerning electricity and matter - as it has appeared to me, on the basis of my own experience.* This will give me a welcome opportunity of showing on the one hand how my work has depended on that of others, and on the other how in one or two points subsequent, or more or less contemporary, work by other investigators is related to mine. Thus - using the simile which you, my esteemed colleagues of the Academy of Sciences, have used at the head of your member's diploma** - I shall now speak not only of the fruits but also of the trees which have borne them, and of those who planted these trees. This approach is the more suitable in my case, as I have by no means always been numbered among those who pluck the fruit; I have been repeatedly only one of those who planted or cared for the trees, or who helped to do this.

In the time at my disposal I can deal at length with only a few aspects of my work in the field under discussion.

The start takes me back 26 years to Crookes. I had read his lecture on << radiating matter>> (5) ** * - his term for cathode rays**** - and was greatly impressed by it. You are all acquainted with the tests he made. Here Fig. 1 is one as a reminder: the glass tubes with highly rarefied air; the negatively charged plate or cathode (*a*) on which the rays are produced; a cross (*b*) in the path of the rays, and here the shadow of the cross (*d*) thrown by the rays

* In this paper I have tried hard to put into their historical perspective all the publications which in my opinion have made basic contributions to knowledge, even if they came to my notice too late for them to influence my work.

** Coat of arms : gardener planting young trees, with the motto <<For our descendants>>. *** The numbers in brackets refer to the bibliography at the end; here <<p.>> gives the page number in the case of voluminous publications.

**** After Faraday, Hittorf (2) and then Goldstein (4) had already produced and progressively studied <<glow rays>> or <<cathode rays>>. But Crookes made more progress than these workers, because he carried out experiments at a higher vacuum.





onto the phosphorescent glass wall. The shadow moves when a magnet is brought near; this is a sign that the cathode rays - unlike light rays - are bent in a magnetic field.

I have always attached great importance in my work to the problem of isolating the phenomenon being studied from interference sources, irrespective of the difficulties that this entails, an approach already adhered to by Crookes in his work. For it was he who produced these cathode rays in a pure form as never reached before, and showed that the phenomena concerned are of a very special type differing from other discharge phenomena through their attractive simplicity. The real nature of <<radiating matter>> or <<th colspan="2">concerned in a gregation)), as he called it, was then beyond my comprehension, just as it must, we may now be sure, have been beyond his. But I readily shared his enthusiasm when he said: <<Here, I believe, are the ultimate realities.>> And we were right: that is why I stand here today!

My interest in these matters found no direct expression during my student days. Electrical gas discharges were not considered a suitable object of study for beginners, and rightly so. But even mature investigators achieved nothing really significant in this field in the years following Crookes' work. They did not obtain any results that in themselves opened new vistas, and so far as purity of experimental conditions was concerned they hardly progressed beyond Crookes' work.

It was only later, when I was assistant to Quincke in Heidelberg, that I had the opportunity and the facilities for building a mercury air pump capable of giving very high rarefaction - then by no means a standard item of equipment in physics institutes - and for carrying out tests myself on cathode rays. I wanted to advance as directly as possible, and thought how fine it would be, in particular, to bring these rays from the tube out into the open air; it would then be possible to carry out direct experiments with them. To do this it was necessary to fit into the wall of the tube an airtight seal that would

107

allow the rays to pass through. Now radiating *matter* would not readily pass through airtight seals, but might not Eilhard Wiedemann be right in assuming that cathode rays were *a* form of ultra-ultraviolet light? Finally, quartz appeared to me to be the most promising material, since it best transmitted all the radiations that were then known. Here (Fig.2) is the tube I built at the time with the cathode plate, and at the top of it you will see the opening sealed by a quartz plate 2.4 mm thick. The test was unsuccessful, however; outside the quartz I found no phosphorescence nor even any electrical* effects that could be ascribed with certainty to the light issuing from the tube.



It was four years later, in 1892, that another opportunity arose. Hertz, whose assistant I then was, had found that thin metal leaf transmits cathode rays (15). He used quite thin, very soft and porous gold, silver and aluminium leaf used in bookbinding, but showed that the cathode rays not only pass through the holes but through the material itself, the metal of the leaf. One day he called me over - an event which to my great regret at the time did not occur often - and showed me what he had just found: uranium glass covered with aluminium leaf inside a discharge tube, glowed under the leaf when irradiated from above. He said to me: <<We ought - and I might simply do this for he was prevented - to separate two chambers with aluminium leaf, and produce the rays as usual in one of the chambers. It should then be possible to observe the rays in the other chamber more purely than has been done so far and even though the difference in air pressure between the two chambers is low because of the softness of the leaf, it might be possible to completely evacuate the observation chamber and see whether this impedes the spread of the cathode rays - in other words find out whether the rays are * Hertz' discovery of such effects of ultraviolet light had at that time just been made (8).

phenomena in matter or phenomena in ether.>> He appeared to consider this last question to be the most important one. I did carry out the test later; but I was primarily interested in my earlier question, that of cathode rays in the open air. I was not put off by the softness of the leaf used by Hertz. I laid more and more of such leaves on top of each other in a suitable tube and found that 10 and 15 layers still transmitted the rays fairly well. I then procured some pieces of aluminium foil of comparable thickness, to see whether they would withstand the air pressure. Such was the case, provided that a sufficiently small area of foil was used. Then, taking the old tube again, I replaced the quartz by a metal plate containing a small hole sealed with aluminium foil, spread a few small grains of alkaline-earth phosphor on this small aluminium window, excited the tube and, lo and behold, the grains glowed brightly! I then fixed them slightly above the aluminium window and they glowed brightly there as well! Thus not only had the cathode rays passed out of the interior of the discharge tube to which they had been hitherto confined, in addition - and nobody could have predicted this they could pass through air of normal density. It thus became clear that a vast new field of investigation had opened up in front of me, a field that not only embraced hitherto unseen phenomena but also gave promise of a breakthrough into the unknown. Cathode rays, which had hitherto stubbornly eluded explanation, had yielded their secret and, more important, now for the first time tests of maximum purity could be carried out. Let us compare the position with that of another type of radiation, light: hitherto it was as if it had been impossible to study light except in the interior of furnaces and flames where it is produced, like the cathode rays in the tube. Where then would the great and detailed science of optics have stopped? ! A window had now been built in the furnace through which pure light only could emerge, freed from the complex and still unexplained processes of its formation. Such processes remain confined to the interior of the discharge tube and, as has since been found, could not be understood until a sufficient study had been made of the cathode rays themselves. As we shall see in our historical survey, this study has also provided a great deal of other information, some of which is now general knowledge, on X-rays and radioactivity, as well as a deeper understanding of electricity and matter.

It was now necessary above all to widen the inroad already made into the new field of knowledge. It was important to increase the intensity of the rays coming out of the window, and to improve the conditions of their production compared with the first tube. This led to the construction of the tube



illustrated in Fig.3, which was used in a large number of experiments (18). Here will be seen the production chamber with the anode (A) and the cathode (C), the seal (m m) with the window, and beyond it the observation chamber into which the *rays* emerge. The number of phenomena possible here is such that although the most obvious ones and also the slightly less obvious ones have probably now all been discovered, so far the consequences of all the phenomena have not yet been studied sufficiently.

It must be noted that the rays are not directly visible; it would be useless to put one's eye to the window, as this organ is not receptive to cathode rays. On the other hand, materials that are capable of becoming luminous without heat, phosphorescent materials as they are called, are suitable for making the rays visible. It is best to use sheets of paper coated with such materials, e.g. a certain ketone, platinum cyanide, or an alkaline-earth phosphor and to hold them as a screen against the rays. If the screen glows, it indicates that it has been hit by the rays. The rays *can* also be photographed directly. These are the same methods that are used to make visible ultraviolet light, at that time the only known example of such demonstrable invisible radiation.

When we use the phosphorescent screen, we find it glowing brightly close to the window; as the distance from the window increases, the intensity of the rays progressively diminishes until at a distance of about 8 cm the screen remains quite dark. Apparently air at full atmospheric pressure is not very permeable to cathode rays, certainly far less permeable than it is to light. But it was far more interesting to find that air is even a turbid medium for these rays, just as milk is for light. If we place an impermeable wall with a hole in it a suitable distance from the window and put the edge of the screen against it, we then get this view (Fig.4). Here the dotted lines indicate the narrow pencil of rays that we should expect in the case of rectilinear propagation; but it is the broad bent bunch of rays that we really see on the screen in the open air, just as if we had passed light through the same hole into a tank containing slightly diluted milk. What clouds the air? In milk it



Fig. 4.

is numerous small suspended fat particles that make it turbid to light. Pure air on the other hand contains nothing except molecules of the gases contained in it, suspended in the ether. These molecules are extremely small, 10,000 times smaller than the fat particles, far too small to act individually on light. But, as we see, the cathode rays are hindered by each of these molecules. Thus these rays must be extremely fine, so fine that the molecular structure of matter, which is minute compared with the very fine light waves, becomes pronounced in comparison with them. It may then be possible to obtain data by means of these rays concerning the nature of molecules and atoms.

It is therefore particularly interesting to study the behaviour of a wide variety of materials relative to cathode rays. The first point to be studied was the permeability. Some idea of this can be obtained by holding a thin layer of the material being studied, between the window and the screen. It is abundantly clear that the permeability or impermeability of a material to light is is not even slightly related to its behaviour in relation to cathode rays. Here is an example (Fig.5), a print of a direct photograph taken at the aluminium window. In the top half will be seen the deep shadow of a completely light-permeable ½ mm thick rectangular quartz plate, and in the left half, as a very mat veil, the picture of an ordinary aluminium leaf, impermeable to light and with somewhat irregular boundaries, laid over the whole of this





half. Great care must be taken in selecting the thickness of the layer throwing the shadow. Thus, for example, the quartz plate used in this experiment is impermeable simply because it is too thick, and the reason why metal leaf was found to be the only example of permeable layers in Hertz' tests lay in the thinness at which metal leaf is available. We shall soon see that most other materials, when of the same thickness, are even more permeable than gold and silver. It is soon evident that the absorption of cathode rays in any substance is a very gradual process, just as in the case of light, where as we know, gold is permeable when it is made sufficiently thin. Here (Fig.6) we see the shadow of leaves of aluminium laid stepwise on top of each other; the numbers on the left give the number of leaves, those on the right their total thickness. Each increase in the number of leaves, and also any unevenness in



Fig.6.

the thickness of the individual leaves, can be noted, and it will be seen how almost total permeability changes into almost total impermeability. Thus, with each material it was not a question of simply deciding between <<pre>permeable>> and <<impermeable>>, but of finding a numerical measure of the degree of absorption of cathode rays therein, of measuring its *absorptive power*, and I did this for a large number of solid and gaseous materials.

The result was astounding. All the great multiplicity of properties that we associate with the different materials around us, disappeared. The sole determining characteristic was the *weight* of the materials(21). Everything of equal weight absorbed equally, anything heavier absorbed more, anything lighter absorbed less, and always in proportion to the weights or the masses. At a first approximation, the chemical composition of the materials, their state of aggregation and other properties, did not count at all-a quite unprecedented finding that was not valid for any radiation known at the time. * At a second approximation, on closer inspection it is seen that the chemical composition has a slight effect: thus, e.g. hydrogen, and anything containing hydrogen, absorbs slightly more than one would expect in proportion to its weight. I must forbear to discuss these deviations and their significance in detail here.** As an illustration of the law of proportionality between mass and cathode ray absorption, that is valid at a first approximation, let us see the direct photographs of the shadows of layers of aluminium, silver and gold of equal thickness (Fig.7). It will be seen that the heavy silver absorbs more than the lighter aluminium, and that gold, which is the heaviest, absorbs the most. If on the other hand we take layers of equal weights of the three metals (Fig. 8), we also get equal shadows and equal absorption, and the result would



* Later X-rays were found to be a second example of radiation that is absorbed more or less in proportion to the mass.

** Compare (21,47,52).

be the same if we had taken any other materials in layers of equal weight. In fact, in relation to cathode rays, not only the absorption, but also the turbidity, which I also studied in relation to a number of different materials (18b p.257; 21, p.265) was found to be related solely to the weight, the mass of the material in question, the quantity of matter-as Newton put it and not the qualify of the material.* If we now recall that cathode rays as they spread in matter are simply affected by the individual molecules of the material, we can conclude that the molecules of the most varied materials, and thus also the atoms of the different chemical elements vary, not qualitatively but only quantitatively, from each other, i.e. they all consist of the same basic material but contain different amounts of it. This old but because of the lack of valid data almost forgotten hypothesis of the alchemists was brought back vividly to our mind, this time however not to disappear again but to be proved; as evidence of this we can quote the recent results of Ramsay (54) and Rutherford (51) concerning the amazing transformation of radium** into other elements. But in order to use the law of proportionality between the mass and cathode ray absorption as a basis for drawing more detailed conclusions on the constitution of matter, it was first necessary to know something about the nature of cathode rays themselves. Let us now turn to this problem, which I have also borne in mind throughout my work.

Straightway we can decide whether cathode rays are phenomena that take place in matter or in the ether. When we completely evacuate a chamber by means of an air pump, it then does not contain any matter, only the ether, as present in the heavens. Now it has long been known for instance that sound cannot pass through such evacuated chambers, while light, and electrical and magnetic forces can. Thus there is no doubt that sound is a phenomenon in matter while light and electrical and magnetic forces are phenomena in the ether. We had been unable to carry out the corresponding test in relation to cathode rays in the ordinary discharge tubes, because once all the air is removed the production of the rays in such a tube ceases. But, without interfering in the least with production, we were able to completely evacuate our observation chamber on the other side of the window and see whether de-

^{*} The diffuse reflection of cathode rays, which can be considered to be pronounced backwards-directed scatter, is also determined by the mass, as can be clearly seen from the measurements of A.Becker (52, p. 448).

^{**} As evidence of the elementary nature of radium its spectrum and atomic weight are given (38,39).

spite this the cathode rays spread in this chamber. We found that the propagation of the rays is particularly good in an extreme vacuum; all absorption and turbidity due to the gas molecules disappear, the rays attain lengths of several meters and are of such rectilinear sharpness as we are accustomed to find only in light rays(18). Thus cathode rays are phenomena in the ether. In particular, on the basis of the hypotheses which we have mentioned, it could be stated that cathode rays were not radiating matter, nor emitted gas molecules, as they had come to be regarded, especially in England. * We were still not clear as to what type of phenomena in the ether they were. Many of my readers believed, very wrongly, that I had concluded beforehand that cathode rays were <<waves in the ether>> I had no desire to say this or in fact anything unless it was shown to be so in my experiments and appeared to provide an explanation. I had the means available to discover new things daily from Nature herself, in further experiments. I hoped so or thought so, at least. I greatly regretted, therefore, that at this stage my experiments were interrupted for considerable time, first by a far-from-simple task that devolved unexpectedly on me through the untimely death of Heinrich Hertz - the publication of his Prinzipien der Mechanik (Principles of Mechanics) and then when I was appointed to a theoretical professorship.

It is barely worth mentioning, but not unimportant for the further development of our subject, that even before this interruption I had designed a new and far more convenient type of discharge tube. I had tested it as far as possible, and had recommended its use and made it generally available *(18b,* p-228). Here (Fig.9) the window seal is fitted to a platinum tube, which in turn is fused into the glass; this means the large amount of puttying which often made the tube very difficult to use, is avoided. This type of tube had however a special advantage that could not be foreseen at the time. In it the



* Even after the experiments with the aluminiumwindow had been reported, this theory continued to be held for some time, and it was suggested that molecular collisions actuated, via the window, the molecules of the outside air or molecules remaining in the vacuum.

intensive cathode rays impinge on the large area of platinum - the metal which, as we now know, is most effective in turning the rays into the - then undiscovered - X-rays. Thus X-rays are produced here in very large quantities, and they are also able to pass through the window, either mixed with or separate from the cathode rays, into the observation chamber. This was not possible in the earlier tube because of the large thick metal cover located in the path of the rays (27). The discovery soon after this of X-rays by Röntgen(22), the first investigator to use the type of tube described above, is generally considered to be a good example of a lucky discovery. But, given the tube, the fact that the attention of the observer was already turned from the interior to the outside of the tube, and the presence of phosphorescent screens outside the tube because of the purpose of the tube, it appeared to me that this discovery had of necessity to be made at this stage of development.

On resuming my experiments I soon occupied myself exclusively with an idea already put forward by Hertz (7b, p. 275) and Schuster (13), which in relation to the nature of the cathode rays had appeared to me to be very important right from the start, and which I had already begun to pursue in the first period of my experiments. It had been known since Hittorf's days that cathode rays are deflected by magnets (2); similarly the deflection of cathode rays noted by Goldstein (4) could be interpreted as being an influence of electrical forces on the rays. Now both the magnetic and the electrical deflection of the rays suggest that the cathode rays consist of emitted negatively charged masses. Moreover, from experiments made to measure the magnitude of the magnetic and electrical effects on a ray it is even possible to calculate the velocity of the supposed masses and also the electric charge per unit of mass (the charge/mass ratio). This is what Hertz and Schuster had done, but their results had contradicted each other. Hertz found that his observations refuted the theory of ejected gas molecules, while Schuster found that his fitted in with it, and thus he took them as support for this theory.

This contradiction did not surprise me. For both investigators had observed the interior of the discharge tube, and they might have been confused by the complications of the production process and the presence of the gas, as in fact they both admitted with reserve. It was now time to carry out these important tests under clearly-defined experimental conditions, i.e. outside the discharge tube and in a very high vacuum, and some excitement as to the result was permissible. For if we know already that the rays are ether, not material phenomena, it should be astonishing that their behaviour still resembled so deceptively that of ejected negatively charged gas molecules.

115

Nothing known so far had made solving this dilemma of the streaming molecules and the ether phenomena possible; these experiments would do this, and in any case therefore they would reveal something quite new.

While I was still doing the preparatory work for the experiments* I heard that others were already convinced of their importance. J.J.Thomson was the first to publish a detailed publication on the subject (25). His experiments, like those of Hertz and Schuster, were carried out in the discharge tube. He sought to avoid the danger of confusion as a result of interaction of the production discharge, by means of shielding devices, and to compensate the lack of reliability due to the presence of the gas by greatly varying the test conditions. It was clear to me that all that followed would have to rest on this pillar which I had learned to distrust from the discrepancy between Hertz and Schuster. It seemed to me that before it was made a part of the structure of science it should be tested as directly and rigorously as was possible with the means at our disposal. I therefore concluded my experiments, the results of which were as follows (28).

The velocity of the supposed masses was about one third the velocity of light, and the ratio of the charge to the mass was about 1,000 times that of a hydrogen atom in electrolysis, which atom is the lightest material carrier of electricity known to us. So, if the rays were streaming hydrogen atoms, their charge would have to be taken as being 1,000 times that in electrolysis. This possibility had however been excluded by my previous tests, which had shown that the rays are not material bodies. It seemed evident that I had discovered hitherto unknown parts of the ether, representing electric charges and moving like inert masses. The smallness of the inertia determined -1/1,000 of the inertia of the hydrogen ion, at an equal charge - and the other behaviour (30) of these parts of the ether, made it easier to identify them with what had long been known as the <<electrical fluidum>>. The solution to the dilemma was therefore as follows: The rays are not emitted electricallycharged molecules but simply streaming *electricity*. Thus, in cathode rays we have found under our very noses what we never believed we should see: electricity without material, electrical charges without charged bodies. We have, in a sense, discovered *electricity itself* a thing whose existence or nonexistence and whose properties have puzzled investigators since Gilbert and Franklin. Earlier workers, even Coulomb, had referred naively to electric-

* These were resumed at Aix under the direction of and with a grant from Wüllner's Institute (1896), and they had again been interrupted when I was appointed to another professorship elsewhere.

ities as something that existed and could almost be grasped. But the number of electrical phenomena known grew steadily without anybody being able to state that they had seen anything of the supposed electricity itself. Thus it was that - about a generation after Coulomb - Faraday (I) and then Maxwell (3) turned their attention completely away from the electricities to concentrate on the electrical forces that could be observed. These forces thought of as states in the ether - appeared in fact in the famous experiments of Hertz (9) to be so likely to exist independently that from then on one felt increasingly inclined to forget their centres, the electricities, that had formerly been regarded as indispensible. Now-again about a generation after Faraday and Maxwell-the picture has changed somewhat : it has become more complete. We have found in cathode rays just as good a way of studying electricity as we found earlier for the electrical forces alone; we can follow the motion of electricity to and fro in these rays over distances stretching several meters, at will and directly with our senses-without any intermediate theoretical conclusions; we can see how electricity behaves under different conditions, and what its properties are; we are now in a position to give to the old term <<electricity>> a new content based on experience.

This new content, of which we now know a great deal, appears quite different now in many ways from what could have been supposed earlier.

Here it should be noted that all our remarks concerning electricity apply *only* to *negative* electricity, not positive electricity, about which even today little can be said that is concrete. We cannot claim to be acquainted with it; we can only recognize positively-charged material, whether it be atoms, molecules or groups of molecules. * We thus use the unitary means of expression, and say that a piece of material is positively charged when it has lost negative electricity.

Let us now therefore consider negative electricity, as it appears in our tests. Here we are amazed by the freedom of its motion, which we hitherto believed was only present inside metallic conductors. Already in the discharge tube, in the centre of the gas, we set this electricity in accelerated motion through the voltage applied to the electrodes, and immediately its velocity becomes one third that of light, 100,000km/set, and it represents a cathode ray. Now it impinges on the aluminium window. <<It will adhere to it and flow to earth>> one would have said on the basis of previous knowledge. Far * Thus, for instance, canal rays and, so far as they have been studied, also the a -rays of radium, have been found to be emitted positively charged molecules. from it: it passes through the metal plate (28,p.28) and, as I was able to check, its velocity does not diminish appreciably (19;46,p.479). Beyond the window it can enter a more or less total vacuum, in which it continues its course linearly, representing an electric current in the empty ether, a phenomenon which we had earlier also thought to be impossible. When it finally hits a piece of metal of sufficient thickness, it penetrates it and sticks there; finally, after following such unusual courses it appears as an ordinary charge on the surface of the metal(28).

The problem of whether electricity fills space continuously or not, of whether it has a structure, is of particular interest. I have seen two cathode rays pass through the same chamber in opposite directions, and found in a quantitative investigation of the phenomena that the two rays did not interfere with each other in the slightest (44,p.165). This indicates that the electricity of these rays consists of discrete and very small parts separated by a large volume of free space. We can represent the parts themselves as being more or less impenetrable to each other, because according to Coulomb's law, as soon as two of the parts come very close to each other they must exert enormous repulsive forces on each other. But the best indication of the structure of electricity comes from quite a different source, and is much older.

Here we come to the connexion between our findings and earlier knowledge. Such knowledge was very scanty, and was related to phenomena taking place in and on individual atoms, i.e.phenomena that could not be studied directly, but the connexion was a very good and fruitful one.

Years earlier, Helmholtz in his lecture in memory of Faraday had noted that electrolysis phenomena would suggest that electricity is split up into pieces of constant size, just as matter is split up in atoms(6). This was the indication already available concerning the structure of electricity, the existence of electrical atoms, *electrical elementary* quanta, as Helmholtz called them.*

In the field of optics moreover, the theory already firmly supported by Hertz' famous experiments(9), that each luminous atom be regarded as an electrical oscillator, had suddenly been given a tangible form by the discovery of Zeeman, who in conjunction with Lorentz concluded from his observations that it is *negative*** - not *positive* - electrical mass that oscillates in the lu-

* I recall hearing him use this expression many times in his demonstration lecture in the summer term of 1885.

** It is interesting that in Zeeman's first publications the word <<positive>> - not <<negative>> - was printed (24, p. 18), so that there was some delay in recognizing the relationship between his discovery and cathode rays.

minous atoms of a sodium or other metal flame, and that there is a definite ratio between the charge and mass of the oscillating material (24). The ratio was of the same magnitude as that found shortly afterwards, in the way described, for cathode rays.

It seemed likely that in all these cases, in the ions in electrolysis, in the luminous metal atoms and in the cathode rays, and perhaps everywhere where electricity plays a part, we might be concerned with the *same* electrical elementary quanta, the existence of which had first been indicated by Faraday's electrolysis law and which might be further elucidated by means of cathode rays. This theory has been proved, so much so that it has engendered a new branch of physics, so fruitful and already so vast that in this paper, which is devoted primarily to my own work, I cannot say any more in general on the subject. I would simply like to mention three points.

First, as an important initial quantitative check on our conclusions, the direct experimental measurement of the velocity of cathode rays carried out by Wiechert, in which the figure obtained was the same as that obtained from the electrical and magnetic deflections (see above) -about one third of the velocity of light(29).

Second, Kaufmann's experimental result, obtained on the basis of the work of J. J. Thomson and Heaviside(10), and concerning electrical elementary quanta, namely that their mass and inertia are of a purely electromagnetic nature (55), a result that we can interpret as follows : We have no evidence that (negative) electricity is a special *material* with inertia; it appears to be simply a state, the state of the ether which we were accustomed, after Faraday(1), Maxwell(3), and Hertz(9), to denote as the electric force field in the environment of electrified bodies, a state which according to Hertz(20) and Bjerknes (33) might consist of latent motion of the ether. Thus, even with the pure elementary quanta of electricity nothing else has been discovered except this ether state in their area. These elementary quanta themselves appear to us in Maxwell's sense to be the probably empty and only purely geometric centres of the electrical forces, except that we can now claim to be able successfully to observe these centres individually, follow their courses and study the geometric proportions of their size and shape. According to this finding, cathode rays, the streaming centres of state, appear to us, more than ever, to be what they seemed to us to be from the beginning, pure ether phenomena.

Thirdly, we must list the names given to these parts of electricity, or centres of state: I have called them *elementary quanta of electricity* or for short *quanta*, after Helmholtz; J.J.Thomson speaks of *corpuscles*, Lord

Kelvin of *electrions;* but the name preferred by Lorentz and Zeeman *electrons* has become the everyday term.

So far we have spoken of cathode rays as such; we shall now discuss their modes of formation, their generation.

The oldest, and for a long time the only known method of generation and the one which we have hitherto used to the exclusion of all others, is the discharge tube. Here, as their name suggests, the rays originate at the cathode. The gas molecules which are under the influence of the prevailing electrical forces have an effect - the proximity effect as I call it (53) - on the electrode metal, whereby quanta are withdrawn from the latter. Immediately they are free they are subjected to the accelerating forces of the field between the electrodes and thus move with increasing velocity away from the cathode; the ray is complete. The ultimate velocity at which we allow it to leave the tube through, say, a window is given by the size of the voltage used; and the very fact that in effect this whole voltage and not just a fraction thereof is determinative for the ultimate velocity proves that the origin of the ray must be sought at the cathode surface and not, say, in the centre of the gas.* By the magnitude of the voltage we can thus produce faster or slower cathode rays and when we previously spoke of 1/3 the speed of light that applied only to one particular voltage about 30,000 V, which I used generally throughout my experiments.

How would faster or slower rays behave? Some predictions could be made on the basis of my first experiments in which the voltage, and hence the velocity, was slightly varied (*18b*,*p*-*266*;*19*;*21*,*p*.*261*). Very fast rays could be expected to have extremely slight absorbability (high penetrating power) ** ; the slow rays on the other hand appeared best suited to yield information on the forces of atoms, the constitution of matter. For a long time, however, it seemed impossible to carry out pure tests over a sufficiently wide

* * When X-rays were discovered this expectation of them appeared to be fulfilled; their first properties to become known agreed with those to be anticipated from my tests for the fastest cathode rays (27). It was just at first Righi's convincing observation that the X-rays do not carry with them a negative charge (23) that had shown the untenability of the theory that they were extremely fast cathode rays. They are nowadays considered to be short, transverse impulses in the ether, a kind of ultra-ultraviolet light. The fact

120

^{*} To start with this was an arbitrary assumption made in many previous studies on cathode rays; the proof of its correctness was supplied with increasing accuracy as time went on, with most accuracy probably by A. Becker (52, p. 404).

range of velocities since the glass of the discharge tube could not withstand the heavy voltages needed for the very fast rays, and the slow rays, although easy to produce in the tube, failed to emerge through the window; they were too absorbable. Other arrangements failed, too.*

Both problems, that of the slowest and that of the fastest rays, were finally solved in quite novel ways.

A discovery by Hertz as early as 1887(8) completed shortly afterwards by Hallwachs(11), had shown that by mere exposure to ultraviolet light metal plates give off negative electricity to the air. This remarkable fact - nowadays usually referred to as the photo-electric effect - immediately captured my interest at that time and has also continued to do so since. Experiments carried out in collaboration with the astronomer Wolf showed me first of all that ultraviolet light roughens substances or pulverizes them (12;46,p. 490). Subsequent experiments, however, caused me to think it unlikely that metal particles carried the negative charge off the plate. At the time I conducted my first experiments on cathode rays, when I had discovered that the air in front of the aluminium window becomes conductive(18) I formed the idea that cathode rays could be driven from the plate into the air by ultraviolet light. Both then and later I made repeated vain attempts to detect possible rays in the vacuum on fluorescent screens. Only my decision - based on Righi's work(14) - to use the electrometer instead of the fluorescent screen revealed the existence of the rays. The apparatus used is illustrated in Fig. 10. U is the plate to be irradiated and is in a complete vacuum; the quartz seal at *B* admits the ultraviolet light. The cathode rays start from *U* and a narrow beam is separated out by the hole in the counterplate *E*. This beam impinges on the small plate a which collects the negative charge brought by the beam and thereby indicates the existence of the radiation on the electrometer. We bring a magnet or the coil indicated by a broken line close to the tube in a suitable manner and then find the charge on the plate β instead of on α , in-

that such impulses can actually occur side by side with heavy absorption of cathode rays, such as e.g. in heavy platinum, follows, as first put forward by Heaviside, from Maxwell's theory(10). The fact that extremely short-wave ultraviolet light will pass unrefracted through prisms was foreseen by Helmholtz in his dispersion theory(17c, p. 517). The low-absorbability cathode rays forecast first became a reality in the rays emitted by radium.

* Amongst other measures I had tried inserting, instead of the window, narrow channels between generating chamber and completely evacuated observation chamber, but they allowed too much gas through.



dicating that the invisible ray is actually deflected by the magnet and in the appropriate direction for cathode rays. When carried out quantitatively, the experiment showed that the deflection is also of the correct degree, and that the same ratio obtains between charge and mass of the quanta as in the case of the rays generated in discharge tubes (32;44,p.150;46).

Immediately it had been established beyond doubt in this way that cathode rays are produced by ultraviolet light and that their behaviour had become suffciently well known, I was soon able to detect them on fluorescent screens(44), then follow them further and use them. I shall refer to those aspects later. The following should be noted as regards the actual generation.

Firstly - an important point for pure experiments - it also occurs in a complete vacuum where the usual method fails. A gas need not be present but it does not interfere with the generation of the rays. What is involved is the direct action of the light on the metal of the plate. The initial velocities with which the quanta leave the plate are so slight that a negative charge of only a few volts on the counterplate is sufficient to compel the rays to reverse before reaching it. They then return to the irradiated plate in the same way as a stone thrown upwards falls black to the ground (32;44).*

* My first detailed communication on the subject(32) appeared in the *Sitzungsberichte der Kaiserl. Akademie der Wiss. zu Wien* for 19th October 1899. In the December issue of *The Philosophical Magazine* of the same year J. J. Thomson published studies <<On the mass of the ions in gases at low pressures>> in which the photo-electric effect is involved although its centre is still sought in the gas adjacent to the irradiated plate, as the remarks on p. 552 indicate. In the same author's book *Conduction of Electricity through Gases,* 2nd. ed., 1903, p. 109, my publication is dated one year later than that just mentioned since a later reprint (*Ann. Physik,* 2(1900) 359, where it is expressly marked as a reprint), and not the original is cited.

Here, therefore, we obtain extremely slow cathode rays; faster ones can be produced merely by charging the counterplate positively. The velocity of the rays can be controlled freely by the level of the voltage of the counterplate.

Secondly, considering the effect of the ultraviolet light on the plate, we must imagine that the light waves cause the interior of the metal atoms in the plate to vibrate. We have previously mentioned that Zeeman's discovery has proved atoms to contain negative electricity capable of vibration. If the co-vibration of a negative quantum in the atom with the light waves becomes too violent, the quantum escapes from the atom^{*} and so from the plate; we have a cathode ray.

The velocity at escape we have already mentioned as very low. I have also found that the velocity is independent of the ultraviolet light intensity(M), and thus concluded that the energy at escape does not come from the light at all, but from the interior of the particular atom. The light only has an initiating action, rather like that of the fuse in firing a loaded gun. I find this conclusion important since from it we learn that not only the atoms of radium - the properties of which were just beginning to be discerned in more detail at that time - contain reserves of energy, but also the atoms of the other elements; these too are capable of emitting radiation and in doing so perhaps completely break down, corresponding to the disintegration and roughening of the substances in ultraviolet light. This view has quite recently been corroborated at the Kiel Institute by special experiments which also showed that the photoelectric effect occurs with unchanged initial velocities even at the temperature of liquid air.

We cannot regard the action of the light as restricted only to the solid state of aggregation. The molecules, or atoms of gases undergo a completely analogous effect under the action of ultraviolet light (35;40); it is reasonable to assume that quanta escape from them (49,p.486); the gas thus becomes electrically conductive in a manner which we shall discuss in detail later. If the gas contains oxygen like the air, ozone is formed as a by-product(35).**

^{*} This is a process which was earlier anticipated in Helmholtz's comprehensive dispersion theory (17 *c*, p.518).

^{**} In the light of subsequent studies by Warburg it can be assumed that the most productive of current methods of producing ozone, i.e.those using what are termed <<silent electrical discharges>> are wholly or largely effective owing to the ultraviolet light of these discharges(48). The rich sources of ultraviolet light obtainable nowadays, e.g.electrical mercury quartz lamps, propagate such a noticeable odour of ozone in their environment that this effect of ultraviolet light has now became a commonplace.

This same action of light, namely the production of cathode rays, the vibration of atoms and the releasing of quanta therefrom, is also involved in phosphorescence (50,p.671) and hence probably also in fluorescence, perhaps, too, in all photochemical effects. Bearing in mind that we have detected transformation of energies from the interior of the atoms associated with the photoelectric effect, we should not be surprised if in future perhaps we encounter phenomena of the same type acting as sources of energy not introduced from outside.

It should also be mentioned that the research carried out by Curie and Sagnac(37) as well as that by Dom(42) indicates that in common with ultraviolet light, X-rays too have the effect of generating cathode rays. This is consistent with their ability to make gases electrically conductive and induce phosphorescent and photochemical effects.

Scarcely had ultraviolet light been shown suited for the generation of the slowest rays when the solution was found to the problem of how the fastest rays originate. The rays emitted by uranium and radium were already known; Becquerel, P. and M. Curie were engaged in pursuing further these discoveries of theirs. By applying to these new rays the methods developed as described for the cathode rays from discharge tubes, it was shown that the new rays are partly cathode rays (34;36;41)*, and amazingly cathode rays of almost or entirely the speed of light(43). What no discharge tube could withstand is thus achieved by the radium atom- and quite spontaneously- although admittedly not without being completely broken down in the process (51;54).

Once the entire range of velocities from rest to the speed of light was thus available it was worthwhile re-examining in more detail the behaviour of matter to irradiation.

From the turbidity of all substances, including e.g. air, to cathode rays, we had concluded that each molecule or atom acts as a separate obstacle to the rays, an obstacle which deflects them from their path to a greater or lesser

Nevertheless, the meteorological significance of the action of ultraviolet sunlight in the upper layers of the atmosphere (35,p. 504) still does not appear to have been sufficiently appreciated. Whether the ionization by cathode rays first found at the aluminium window (IS) is also an effect of the light which occurs there, or else the direct effect of the cathode rays, is still obscure.

* This is the part of the uranium or radium radiation normally designated as β

124

extent. How should we visualize this deflection? Let us first examine whether perhaps the quanta of the rays are reflected from the molecules of the substance in the same way as the molecules of a gas are reflected on one another when they collide. Were that so a cathode ray in the gas would be restricted to that length which can readily and accurately be calculated as the mean free path of very small particles between the gas molecules from the data of the kinetic gas theory. These path lengths are, however, very small; in hydrogen at 40mm pressure, for example, about two hundredths of a millimeter. Beyond this short length, a ray would not be able to develop at all in this gas, that is to say almost instantaneous diffusion would ensue. However, gases are by no means so turbid as my observations published in diagrammatic form had earlier shown (*18b*). Even the air at full atmospheric pressure proved much clearer, as we have already seen (Fig-4), and the lighter hydrogen rarified to the specified pressure of 40mm is much clearer still; Fig. II illustrates the path of the ray in hydrogen as observed on the fluorescent



screen. The broken lines show the extent to which rectilinear light would propagate under the same conditions. It will be seen that over a length of 10 cm the cathode ray still scarcely deviates from this rectilinear propagation, and it becomes distinctly broader only beyond that length. The length of 10 cm is, however, 5,000-fold that of the free path length of 0.02mm. It thus follows that here the radiant quanta must have traversed 5,000 hydrogen molecules before undergoing the first noticeable change of direction. We are amazed to see that we have transcended the old impermeability of matter. Each atom in the substance occupies a space which is impermeable to the

125

other atoms*; but vis-á-vis the fine quanta of electricity all types of atoms are highly permeable structures as if built up of fine constituents with a great many interstices.

What are these fine constituents of atoms? That in all atoms they are the same, only present in varying numbers, we have already concluded from the law of proportionality between mass and absorption. We can now learn further details. We can use the quanta of the cathode rays as small test particles which we allow to traverse the interior of the atoms and thus provide us with information thereon.

The first and most noticeable thing to happen to them during this traverse, i.e. deflection from the rectilinear path, we have just discussed as diffusion of the rays. As far as we know, cathode rays experience such a deflection owing only to electrical and magnetic forces. To assume magnetic forces within the atoms would imply the assumption of mobile electricity in the atoms, thus again electrical forces. We must therefore regard the diffusion of cathode rays in matter as proof for the *existence of* electrical *forces in the interior of the atoms.* The magnitude of these forces can be estimated by considering the extent of the deflection together with the transit time, which latter depends on the velocity of the quanta and, of course, on the size of the atoms. If we take progressively slower rays, the transit times will become longer and correspondingly the diffusions occurring will be stronger (19,p.30;46,p.480). In this way we find for the interior of the atoms electrical field intensities of unusual magnitude such that we can never produce by any means known to us owing to lack of sufficient resistance in even the best insulators: field intensities compared with which those occurring during the most violent storms are insignificantly small(47). The force effects of the radium atom then cease to seem so surprising but we should be more amazed that most of the atoms around us behave so placidly, only revealing something of the force stored within them when subjected to the photoelectric action or through other similar causes.

The further quantitative study of cathode-ray diffusion in the various materials promises to yield valuable information on the precise nature of the electrical fields of atoms. For the present we must turn to a second phenom-

* In any case at the normal velocities of the molecules. For very high velocities such as occur with the m-particles of radium, mutual penetrability of even whole atoms, although probably accompanied by their destruction, would not be impossible in the light of the concepts which we have arrived at regarding the constitution of atoms. Recent studies by Bragg and Kleemann promise to throw light on this subject.

enon, somewhat more easy to determine numerically, which is apt to occur in the course of such atom traverses. It can easily happen that the quantum, after successfully passing thousands of atoms, finally stops in an atom and does not emerge at once. This is the *absorption of cathode rays*. I have determined this effect quantitatively for the entire scale of available ray velocities and found the following(47).

The absorption increases with decreasing ray velocity, in common with the diffusion. This is also to be expected if the absorption, like the diffusion, is an effect of the electrical fields of force within the atoms and if these fields of force concentrate about certain centres in the atoms in the vicinity of which their intensity is greater than at longer range, in the same way as the intensity of a magnetic field of force concentrates about the two poles. A radiation quantum which traverses such fields with mobile centres is only stopped when it enters sufficiently intense parts of these fields along its particular path; otherwise it will pass through and be deflected to a greater or lesser extent. The entire cross-section of the atom, the area which the atom presents to a ray, thus consists of two parts, an absorbing and a transmitting part, and the former - which I refer to briefly as the absorbing cross-section

- is known in square centimetres from my measurements. It affords a measure for the size of those parts of the force fields of the atom, the intensity of which is greater than the relevant level which is just sufficient to arrest the particular velocity of the quantum. The slower the quantum, the larger the parts of the atom's force field which act as absorbing cross-sections. For the slowest rays I have found that the absorbing cross-section not only becomes equal to the entire cross-section of the atom or molecule - which entire crosssection was known from the kinetic theory of gases - but even slightly larger. This is tantamount to direct proof for the existence of electrical fields of forces both within the atoms and molecules and also for a certain distance around them. It is probably correct to identify these external electrical forces of the molecules with the forces of strength, elasticity, cohesion and adhesion, in short with the molecular forces in general which have long been known although not immediately regarded as of an electrical nature. Berzelius' view that the chemical forces of atoms are of an electrical nature will now be held with all the more reason and as the research in progress continues it is to be hoped that concepts of the electrical force fields of the atoms will emerge which give a better and more complete picture of their chemical behaviour than the simple concept of a number of fixed valency positions equipped with electrical charges.

Of equal interest to the transition to the lowest velocities was that to the highest. As the ray velocity increases, the absorbing cross-section contracts; ultimately only those quanta are stopped whose path lies through the highest intensity parts of the internal force fields close to their centres. For that very reason the fastest rays are also capable of supplying the answer to the question whether perhaps these centres have a special, impenetrable proper volume, or in more general terms: whether apart from the force fields there is something else in the atoms which holds back our test particles. What happens when the test is carried out with the fastest rays can best be illustrated by means of an example. Let us imagine a cubic metre block of the most solid and heavy substance known to us, say, platinum. In this block we find altogether not more impenetrable proper volume than at most one cubic millimetre. Apart from this pinhead-sized portion, we find the remainder of our block as empty as the sky. We ought to be astounded at the insignificant degree to which the space in matter is actually filled! What we have found in the space occupied by matter have only been fields of force such as can also form in the free ether. What are then the basic constituents of all atoms to which we have been led by the mass dependence of cathode-ray absorption? Clearly they too are in the main only fields of force in common with the whole atoms. I have therefore termed these basic constituents of all matter <<dynamids>>.

As constituents of electrically neutral atoms the dynamids will also be regarded as electrically neutral, and hence possess the same amounts of negative and positive electricity as the centres of their fields. We may then state : matter - all the tangible, ponderable substances around us - consists ultimately of equal quantities of negative and positive electricity. The previously mentioned findings derived from the Zeeman phenomenon, the photo-electric effect and the secondary cathode radiation, which will presently be discussed, show that the negative electricity is contained in the atoms as precisely the same quanta which we found in the cathode rays, and which the research worker has since variously encountered in their own right, separate from matter. The positive electricity, on the other hand, appears to be something much more specifically proper to the atoms of matter; as has been previously stressed they have not been found with certainty other than in atoms. From our findings on the packing of space it follows that for negative quanta the proper volume, impenetrable for things of the same kind, must then be extraordinarily small. This is consistent with the previously mentioned experiments by Kaufmann. The probable proper volume of the

positive electricity, provided it too were not extremely small, should be regarded as completely penetrable for negative quanta.

With this constitution of matter, the third phenomenon occurring during atom traverses, and one which has still to be referred to, can readily be understood. Owing to the repelling force which it exerts on the other negative quanta proper to the atom the traversing ray quantum will be capable of setting up a tremendous disturbance within the atom and as a result of this disturbance a quantum belonging to the atom can be flung out.*

The process is termed *secondary cathode radiation*. We have allowed one cathode ray-the primary - to penetrate into the atom, against which two emerge, the primary and the secondary**(46,p.481).

The *velocity* of the secondary rays - in common with that of the photoelectrically generated cathode rays - is very low, even when that of the primary rays is high. The *amount* of the secondary radiation, i.e. the probability of quanta emission from atoms during traverse, is largest at a given optimum of the primary velocity; both faster and slower primary rays are less effective and at quite a low primary velocity - below 1/200th of the speed of light - the secondary radiation is absent altogether (44, p.188 et seq.;46, p.474 et seq.;49). This is quite understandable for if the primary quantum approaches too slowly, it has too little energy to cause adequate disturbance of the interior of the atom, and if it approaches too quickly it will generally remain for too short a time in the atom to have that effect.

At its low velocity the secondary radiation must succumb to strong absorption in the surrounding molecules of the material. In gases where the molecules are free, a molecule which has absorbed a secondary quantum will act as a *mobile carrier of negative electricity*, while the molecule from which the secondary quantum has escaped has an excess of positive electricity and is thus a positive electricity carrier. The migrations of such carriers, however for which knowledge we are indebted to the unremitting efforts of Arrhenius and after him to J. J. Thomson in particular - constitute the electrical conductivity in gases*** and in the secondary cathode radiation we have thus

^{*} Two and more quanta can also escape from the atom (46, p.485).

^{**} It seems often to be assumed that the secondary radiation is an exclusive result of the absorption of the primary radiation; but this is not the conception which I have formed from observation (46, p. 474 et seq.).

^{***} Three consecutive steps seem to me to substantiate the belief that molecules or groups thereof carry the electrical conductivity in gases, notably: (i) the thorough study of one of the first cases of gas electrification in which dust-which at first was regarded

found and, as I believe, adequately ascertained by thorough observations, the mechanism whereby cathode rays cause a gas to become electrically conductive (46, p. 474). * This case of conductivity induced and maintained by cathode rays must also be a factor in all gas discharges where sufficiently fast cathode rays occur; hence also in the normal discharge tube which we took at the outset as our first generator of cathode rays.

In other cases as well where gases become electrically conductive the mechanism appears to be the same : escape of quanta from molecules, and reabsorption by other molecules; this occurs under the influence of ultraviolet light on gases, as aforementioned, and also in flames(45) but the cause underlying the escape of quanta is apt to vary from case to case (53, p.242).

In conclusion, I wish to thank you for your attention.

as the sole or at any rate the main carrier of electrical discharges in gases -was found definitely not to be involved. This was the case ofwaterfall electricity (16);(ii) the first measurements of the migration speeds of gas carriers in various cases of conducting gases, performed in rapid sequence by a number of different observers, first of all by Rutherford (26) ; (*iii*) J. J. Thomson's essentially irreproachable first measurements of the absolute electrical charge of the individual gas carriers in different cases (3 I). -In the light of simple considerations of gas kinetics the size of the gas carriers was calculated from (*ii*) and (*iii*) as equal to that of molecules or groups of molecules.

l This mechanism differs from that of ion formation in liquid electrolytes where it consists in the splitting of electrically neutral molecules into two oppositely charged atoms or groups of atoms. In other respects, too, the analogy between the conduction of electricity in gases and in liquids breaks down precisely in the most characteristic points. Magnitude and sign of the charge on a gas carrier are - quite unlike the case with the ions in liquid electrolytes - not determined by the chemical nature of the carrier, and electrolysis proper - that so typically chemical mode of decomposition - hence does not occur at all in gases (53, p.236). I therefore considered it better to emphasize this analogy no longer, notwithstanding its heuristic usefulness at the outset, and for that reason I have always avoided applying the name ions to the gas carriers, and calling the conduction of electricity in gases electrolytic.

130

Chronological list of publications*

- (1860) 1. M. Faraday, Experimental Researches in Electricity (from 1820 onwards).
- (1869) 2. W. Hittorf, << Über die Elektrizitätsleitung der Gase>> (The electrical conductivity of gases), *Pogg. Ann. Pkysik*, Vol.136.
- (1873) 3. J. C. Maxwell, A Treatise on Electricity and Magnetism.
- (1876) 4. E. Goldstein, << Über elektrische Entladungen in verdünnten Gasen>> (Electrical discharges in rarified gases), *Monatsber. Berl. Akad.* Also continued in the volumes of the same journal for 1880 and 1881.
- (1879) 5. W. Crookes, Straklende *Materie oder der vierte Aggregutzustand* (Radiating matter or the fourth state of aggregation). (German translation published in Leipzig.) *Also Phil. Trans. Roy. Soc.*, Vol. 170.
- (1881) 6. H. Helmholtz, <<On the modem development of Faraday's conceptions of electricity,, J. Chem. Soc., Vol. 39; Wiss. Abhandl., Vol. 3, p. 52.
- (1883) 7. H. Hertz, <<Versuche über die Glimmentladung>>. (Experiments on the glow discharge). (a) Wied. Ann. Pkysik, Vol. 19. Also (b) Ges. Werke (Collected works), Vol.1, p. 242.
- (1887) 8. H. Hertz, <<Über einen Einfluss des ultravioletten Lichtes auf die elektrische Entladung>> (An effect of ultraviolet light on electrical discharge), *Sitz.-ber. Berl. Akad.*, 9th June. In more detail *in Wied. Arm. Pkysik*, Vol.31.
- (1887-1888) 9. H. Hertz, Untersuchungen über die Ausbreitung der elektrischen Kraft (Researches on the propagation of electrical force).
- (1888) 10. Heaviside, <<On electromagnetic waves>>, *Phil. Mag.*, Ser. 5, Vols. 25 and 26. Further: <<On the electromagnetic effects due to the motion of electrification through a dielectric>>, *Phil. Mug.*, Ser.5, Vol.27 (1889); <<A charge suddenly jerked into motion>>, <<Sudden stoppage of charge>>, *The Electrician*, May 1, 1891. Also *Electrical Papers*, Vol.2, pp. 375, 504, and *Electromagnetic Theory*, Vol.1, p.54.

- 11. W. Hallwachs, <<Über den Einfluss des Lichtes auf elektrostatisch geladene Körper>> (The effect of light on electrostatically charged substances), *Wied. Ann. Pkysik*, Vol.33.

- (1889) 12. P. Lenard and M. Wolf, <<Zersduben der Körper durch das ultraviolette Licht>> (Pulverization of substances under the action of ultraviolet light), *Wied. Arm. Pkysik*, Vol. 37.
- (1890) 13. A. Schuster, <<The discharge of electricity through gases>>, *Proc. Roy. Soc,* Vol.47. (Received 20th March.)
 - 14. A Righi, <<Sulle traiettorie percorse nella convezione foto-electrica, ...>> (The trajectories described in photoelectric convection), *Atti Accad. Naz. Lincei*, Vol.6 [2]. (Received 3rd August.)
- (1892) 15. H. Hertz, << Über den Durchgang von Kathodenstrahlen durch dünne Me-

* The position of a publication in this sequence has been determined by its date of submission to a learned *society or* by its date of receipt by a *journal* editor. Where no such dates were available, the date of publication, as far as can be determined, has been taken.

tallschichten>> (The passage of cathode rays through thin metal layers), *Wied. Ann. Phys,* Vol. 45. Also *Ges. Werke* (Collected works), Vol.1, p.355.

- 16. P. Lenard, << Über die Elektricität der Wasserfälle>> (Waterfall electricity), Wied. Ann. Physik, Vol.46.
- 17. H. Helmholtz, <<Elektromagnetische Theorie der Farbenzerstreuung>> (Electromagnetic theory of colour dispersion). (a) Sitz.-ber. Berl. Akad., 15th December
 (b) Wied. Arm. Physik, Vol.48. (c) Wiss. Abhandl., Vol.3, p.505.
- (1894) 18. P. Lenard, <<Uber Kathodenstrahlen in Gasen von atmosphärischem Druck und im äussersten Vakuum>> (Cathode rays in gases at atmospheric pressure and in the highest vacuum). (a) Sitz.-ber. Berl. Akad. for 12th January 1893.-(b) In more detail, Wied. Ann. Physik, Vol.51.
- 19. P. Lenard, <<Über die magnetische Ablenkung der Kathodenstrahlen>> (The magnetic deflection of cathode rays), *Wied. Ann. Physik*, Vol.52.
- 20. H. Hertz, *Die Principien der Mechanik in neuem Zusammenhange dargestellt* (The principles of mechanics displayed in a new context.)
- (1895) 21. P. Lenard, <<Über die Absorption der Kathodenstrahlen>> (The absorption of cathode rays), *Wied. Ann. Physik*, Vol.56. (Published in October issue.)
- 22. W. C. Röntgen, <<Über eine neue Art von Strahlen>> (A new type of ray), *Sitz.-ber. Würzburger Phys. Med. Ges.*, for December. Reprinted in *Wied. Ann. Physik*, Vol.64.
- (1896) 23. A. Righi, <<Sulla propagazione dell'elettricità nei gas attraversati dai raggi di Röntgens (The propagation of electricity in gases traversed by X-rays), *Mem. Accad. Sci. Bologna,* Ser.5, Vol.6 (Submitted 31st May.)
- ⁻ 24. P. Zeeman, <<On the influence of magnetism on the nature of the light emitted by a substance>>, *Comm. Phys. Lab. Leiden*, transl. from: *Verslag. Koninkl. Ned. Akad. Wetenschap.*, 31st October.
- (1897) 25. J. J. Thomson, <<Cathode rays>>, *Phil. Mag.*, Ser.5, Vol.44. (Published in October issue.)
- 26. E. Rutherford, <<The velocity and rate of recombination of the ions of gases exposed to Röntgen radiation>., *Phil. Mag.*, Ser.5, Vol.44. (Published in November issue.)
- 27. P. Lenard, <<Über die elektrische Wirkung der Kathodenstrahlen auf atmosphärische Luft>> (The electrical effect of cathode rays on the air of the atmosphere), *Wied. Ann. Physik*, Vol.63. (Published 11th December.)
- (1898) 28. P. Lenard, <<Über die elektrostatischen Eigenschafen der Kathodenstrahlen>> (The electrostatic properties of cathode rays), *Wied. Ann.*, Vol.64. (Received 2nd January.)
- 29. E. Wiechert, <<Experimentelle Untersuchungen über die Geschwindigkeit und die magnetische Ablenlbarkeit der Kathodenstrahlen>> (Experimental studies on the velocity and magnetic deflectability of cathode rays), *Nachr. Kgl. Ges. Wiss. Göttin*gen (Submitted on 19th March.)
- 30. P. Lenard, <<Über das Verhalten von Kathodenstrahlen parallel zu elektrischer Kraft>> (The behaviour of cathode rays parallel to electrical force), *Wied. Ann. Physik,* Vol.65. (Received 1st May.) Also published in *Math. Naturw. Ber. Ungarn,* Vol.16.
- 31. J. J. Thomson, << On the charge of electricity carried by the ions produced by

Röntgen rays>> *Phil. Mag.*, Ser.5, Vol.46. (Published in December issue.) Continued and subsequently corrected in *Phil. Mag.*, December issue 1899, and March issue 1903.

- (1899) 32. P. Lenard, <<Erzeugung von Kathodenstrahlen durch ultraviolettes Licht>> (Production of cathode rays by ultraviolet light), *Sit.z.-ber. Kaiserl. Akad. Wiss. Wien* for 19th October. Reprinted in *Ann. Physik*, Vol.2.
- (1900) 33. V. Bjerknes, *Vorlesungen über hydrodynamische Fernkräfte nach C. A. Bjerknes' Theorie* (Lectures on the hydrodynamic distant forces in accordance with C. A. Bjerknes' theory).
- 34. H. Becquerel, <<Contribution à l'étude du rayonnement du radium>> (Contribution to the study of the radiation from radium), and <<Déviation du rayonnement du radium dans un champ électrique>> (Deflection of radium radiation in an electrical field), *Compt. Rend. (Paris)* for 29th January and 26th March, respectively.
- 35. P. Lenard, <<Über Wirkungen des ultravioletten Lichtes auf gasförmige Körper>> (Effects of ultraviolet light on gaseous substances), *Ann. Physik,* Vol. I. (Received 6th February.)
- 36. P. and M. Curie, <<Sur la charge électrique des rayons déviables du radium>> (The electrical charge of deflectable radium rays), *Compt. Rend. (Paris)* for 5th March.
- 37. P. Curie and G. Sagnac, <<Électrisation negative des rayons secondaires produits au moyen des rayons Röntgen>> (Negative electrification of secondary rays produced by means of X-rays), *Compt. Rend. (Paris)* 130, for 9th April.
- 38. E. Demarcay, <<Sur le spectre du radium>> (The radium spectrum), *Compt. Rend.* (*Paris*) 131, for 25th July.
- 39. M. Curie, <<Sur le poids atomique du baryum radifère>> (The atomic weight of radiferous barium), *Compt. Rend. (Paris)* 131, for 6th August. Also <<Sur le poids atomique du radium>> (The atomic weight of radium), same journal 21st July, 1902.
- 40. P. Lenard, <<Über die Elektrizitätszerstreuung in ultraviolet durchstrahler Luft>> (Scattering of electricity in air irradiated with ultraviolet light), *Ann. Physik*, Vol.3. (Received 17th August.)
- ⁻ 41. E. Dorn, <<Elektrostatische Ablenkung der Radiumstrahlen>> (Electrostatic deflection of radium rays), *Abhandl. Naturforsch. Ges. Halle*, Vol.22.
- 42. E. Dorn, <<Versuche über Sekundästrahlen>> (Experiments on secondary rays), *Arch. Néerl. Sci. (Haarlem)*, Ser.2, Vol.5.
- (1901) 43. W. Kaufmann, <<Die magnetische und elektrische Ablenkbarkeit der Becquerelstrahlen und die scheinbare Masse der Elektronen>> (The magnetic and electrical deflectability of Becquerel rays and the apparent mass of electrons), *Nachr. Kgl. Ges. Wiss. Göttingen*, Vol.8, for 8th November.
- (1902) 44. P. Lenard, <<Über die lichtelektrische Wirkung>> (The photoelectric effect), *Ann. Physik*, Vol.8. (Received 17th March.)
- 45. P. Lenard, << Über die Elektrizitätsleitung in Flammen>> (Electrical conductivity in flames), *Ann. Physik*, Vol.9. (Received 18th August.)
- (1903) 46. P. Lenard, <<<Über die Beobachtung langsamer Kathodenstrahlen mit Hilfe der Phosphoreszenz und über Sekundärentstehung von Kathodenstrablen>> (The observation of slow cathode rays by means of phosphorescence, and the secondary occurrence of cathode rays), *Ann. Physik*, Vol.12. (Received 28th June.)

- 47. P. Lenard, <<Über die Absorption von Kathodenstrahlen verschiedener Geschwindigkeit>> (The absorption of cathode rays of various velocities), *Ann.* Physik, Vol.12. (Received 30th July.)
- 48. E. Warburg, << Über die Ozonisierung des Sauerstoffs durch stille elektrische Entladungen>> (The ozonization of oxygen by silent electrical discharges), *Sitz.-ber. Berl. Akad.* for 11th November.
- (1904) 49. P. Lenard, <<Über sekundäre Kathodenstrahlung in gasförmigen und festen Köpern>> (Secondary cathode radiation in gaseous and solid substances), *Ann. Physik*, Vol. 15. (Received 22nd August.)
- 50. P. Lenard and V. Klatt, <<Über die Erdalkaliphosphore>> (The alkaline-earth phosphors), *Ann. Physik*, Vol.15. (Received 22nd August.) Extracts also published in the *Mat. Naturw. Ber. Ungarn*, Vol. 22.
- 51. E. Rutherford, <<Slow transformation products of radium>>, Phil. *Mag.*, Ser.6, Vol.8. (Published in November issue.)
- (1905) 52. A. Becker, <<Messungen an Kathodensstrahlen>> (Measurements on cathode rays), *Ann. Physik*, Vol.17. (Inaugural dissertation submitted to the Kiel Philosophical Faculty on 1st March.)
- 53. P. Lenard, Über die Lichtemissionen der Alkalimetalldämpfe und Salze und über die Zentren dieser Emissionen>> (The photo-emissions of alkaline metal vapours and salts, and the centres of these emissions), *Ann. Physik*, Vol.17. (Received 13th April.)
- 54. F. Himstedt and G. Meyer, Über die Bildung von Helium aus der Radiumemanation>> (The formation of helium from the emanation of radium), *Ber. Naturforsch. Ges. Freiburg i.B.*, for May. Also *Ann. Physik*, Vol.17.
- (1906) 55. W. Kaufmann, << Über die Konstitution des Elektrons>> (The constitution of the electron), *Ann. Physik*, Vol.19. (Received 3rd January.)

It is not without interest to see from this list how, during the years 1887-1894, the subject under discussion has suddenly, as it were, become the field of more abundant and more successful activity. The years prior to that period, with the exception of the fundamental work by Faraday and Maxwell, are marked by only sporadic and isolated symptoms of that activity, the years thereafter and down to the present by its increasingly fruitful pursuit.

I34

Biography

Philipp von Lenard was born at Pozsony (Pressburg) in Hungary on June 7, 1862. His family had originally come from the Tyrol. He studied physics successively at Budapest, Vienna, Berlin and Heidelberg under Bunsen, Helmholtz, Königsberger and Quincke and in 1886 took his Ph.D. at Heidelberg.

From 1892 he worked as a Privatdozent and assistant to Professor Hertz at the University of Bonn and in 1894 was appointed Professor Extraordinary at the University of Breslau. In 1895 he became Professor of Physics at Aixla-Chapelle and in 1896 Professor of Theoretical Physics at the University of Heidelberg. In 1898 he was appointed Professor Ordinarius at the University of Kiel.

Lenard's first work was done in the field of mechanics, when he published a paper on the oscillation of precipitated water drops and allied problems and in 1894 he published the *Principles of Mechanics* left behind by Hertz.

Soon he became interested in the phenomena of phosphorescence and luminescence. This was a development of the mysterious attraction which weak light appearing in darkness had had for him since his boyhood, when he had, with his schoolfellows, warmed fluorine crystals to make them luminescent; and now he took up, with the astronomer W.Wolf, the study of the luminosity of pyrogallic acid when it is mixed with alkali and bisulphite for developing photographs. He found that its luminosity depended on the oxidation of the pyrogallic acid. At this time he also carried out studies of magnetism with bismuth and, in collaboration with V. Klatt, who had been his first teacher of physics in his native town, he studied, at the Modern College at Pressburg, the so-called self-luminous substances such as calcium sulphide on which Klatt had been working for some years. Together they found that calcium sulphide, after previous illumination, exerts light in the dark, but only if it contains at least some traces of heavy metals, such as copper and bismuth, which form crystals on which the colour and the intensity and durations of the luminosity depend; if it is quite pure, it is not luminous. This work with Klatt was the beginning of work in a field which occupied Lenard for the next 18 years.

In 1888, when he was working at Heidelberg under Quincke, Lenard had done his first work with cathode rays. He investigated the view then held by Hertz that these rays were analogous to ultraviolet light and he did an experiment to find out whether cathode rays would, like ultraviolet light, pass through a quartz window in the wall of a discharge tube. He found that they would not do this; but later, in 1892, when he was working as an assistant to Hertz at the University of Bonn, Hertz called him to see the discovery he had made that a piece of uranium glass covered with aluminium foil and put inside the discharge tube became luminous beneath the aluminium foil when the cathode rays struck it. Hertz then suggested that it would be possible to separate, by means of a thin plate of aluminium, two spaces, one in which the cathode rays were produced in the ordinary way and the other in which one could observe them in a pure state, which had never been done. Hertz was too busy to do this and gave Lenard permission to do it and it was then that he made the great discovery of the Lenard window>>.

After many experiments with aluminium foil of various thicknesses he was able to publish, in 1894, his great discovery that the plate of quartz that had, until then, been used to close the discharge tube, could be replaced by a thin plate of aluminium foil just thick enough to maintain the vacuum inside the tube, but yet thin enough to allow the cathode rays to pass out. It thus became possible to study the cathode rays, and also the fluorescence they caused, outside the discharge tube and Lenard concluded from the experiments that he then did that the cathode rays were propagated through the air for distances of the order of a decimetre and that they travel in a vacuum for several metres without being weakened. Although Lenard at first followed Hertz in believing that the cathode rays were propagated in the ether, he later abandoned this view as a result of the work of Jean Perrin in 1895, Sir J. J. Thomson in 1897 and W. Wien in 1897, which proved the corpuscular nature of the cathode rays.

Later Lenard extended the work of Hertz on the photoelectric effect. Working in a high vacuum, he analysed the nature of this effect, showing that when ultraviolet light falls on a metal it takes from the metal electrons which are then propagated in the vacuum, in which they can be accelerated or retarded by an electric field, or their paths can be curved by a magnetic field. By exact measurements he showed that the number of electrons projected is proportional to the energy carried by the incident light, whilst their speed, that is to say, their kinetic energy, is quite independent of this number and varies only with the wavelength and increases when this diminishes.

136

BIOGRAPHY

These facts conflicted with current theory and were not explained until 1905, when Einstein produced his quantitative law and developed the theory of quanta of light or photons, which was verified much later by Millikan. But Lenard never forgave Einstein for discovering and attaching his own name to this law.

In the course of his work Lenard had, for the purpose of accelerating the speed of the electrons and measuring their energy, invented a photoelectric cell which was the first model of the <<3-electrode lamp>> which is so important today in radioelectric technique. The only difference between these two cells was that in Lenard's cell the electrons were taken from the cathode by light, whereas on the <<3-electrode lamp>> the cathode is a white-hot filament capable of sending into the vacuum currents of much higher intensity.

In 1902 Lenard showed that an electron must have a certain minimum energy before it could produce ionisation when it passed through a gas.

In 1903 he published his conception of the atom as an assemblage of what he called <<dynamides>>, which were very small and were separated by wide spaces; they had mass and were imagined as electric dipoles connected by two equal charges of contrary sign and their number was equal to the atomic mass. The solid matter in the atom was, he thought, about one thousand millionth of the whole atom. This work contributed much to Lorentz' theory of electrons.

In his later years Lenard studied the nature and origin of the lines of the spectrum. Developing the work of Rydberg, Kayser and Runge, who had shown that the lines of the spectrum of a metal can be arranged in two or more different series and that there is a marked mathematical relationship between the wavelengths of these series, Lenard showed that in each series a definite modification of the atom has occurred and that these modifications determine the series and are differentiated by the number of electrons lost.

Lenard was an experimentalist of genius, but more doubtful as a theorist. Some of his discoveries were great ones and others were very important, but he claimed for them more than their true value. Although he was given many honours (for instance, he received Honorary Doctorates of the Universities of Christiania, now Oslo, in 1911, Dresden in 1922 and Pressburg in 1942, the Franklin Medal in 1905, the Eagle Shield of the German Reich in 1933, and was elected Freeman of Heidelberg in the same year), he believed that he was disregarded and this probably explains why he attacked other physicists in many countries. He became a convinced member of Hitler's National Socialist Party and maintained unreserved adherence to it. The party responded by making him the Chief of Aryan or German Physics. Among his publications are several books: *Ueber* Aether *und Materie* (second edition 1911), *Quantitatives über Kathodenstrahlen* (1918), *Ueber das Relativitätsprinzip* (1918) and *Grosse Naturforscher* (second edition 1930).

Von Lenard, who was married to Katharina Schlehner, died on May 20, 1947 at Messehausen.

I38

Physics 1906

JOSEPH JOHN THOMSON

<< in recognition of the great merits of his theoretical and experimental investigations on the conduction of electricity by gases>>

Physics 1906

Presentation Speech by Professor]. P. Klason, President of the Royal Swedish Academy of Sciences

Your Majesty, Your Royal Highnesses, Ladies and Gentlemen.

Every day that passes witnesses electricity obtaining an ever-increasing importance in practical life. The conceptions, which a few decades ago were the subject of investigation in the quiet studies or laboratories of sundry learned men, have by this time become the property of the public at large, who will soon be as familiar with them as with their ordinary weights and measures. Still greater however are the revolutions brought about by electricians' labours in the sphere of science. Immediately after Örsted's epochmaking discovery of the influence of the electric current on a magnetic needle(1820), Ampere, the ingenious French investigator, promulgated a theory explaining magnetic phenomena as results of electrical agencies. The investigations of Maxwell, the brilliantly gifted Scotch physicist (1873), were still more far-reaching in their effect, for by them the phenomenon of light was proved to be dependent upon electromagnetic undulatory movements in the ether. There is reason to believe that the grand discoveries of the last few years respecting the discharge of electricity through gases will prove to be of equally great, or perhaps still greater, importance, throwing as they do a great deal of light upon our conception of matter. In this domain Professor J. J. Thomson of Cambridge, this year's Prize-winner in Physics, has made most valuable contributions through his investigations and researches, which he has assiduously pursued for many years past.

By Faraday's great discovery in the year 1834 it had been shown that every atom carries an electric charge as large as that of the atom of hydrogen gas, or else a simple multiple of it corresponding to the chemical valency of the atom. It was, then, natural to speak, with the immortal Helmholtz, of an elementary charge or, as it is also called, an atom of electricity, as the quantity of electricity inherent in an atom of hydrogen gas in its chemical combinations.

Faraday's law may be expressed thus, that a gram of hydrogen, or a quantity equivalent thereto of some other chemical element, carries an electric charge of $28,950 \times 10^{10}$ electrostatic units. Now if we only knew how
PHYSICS 1906

many hydrogen atoms there are in a gram, we could calculate how large a charge there is in every hydrogen atom. The kinetic gas-theory, a field of investigation as popular as any among the scientists of the century recently ended, is based upon the assumption that the gases consist of freely moving molecules, the impact of which on the walls of the encompassing vessel is recognizable as the pressure of the gas. From this the velocity of the gas molecules could be calculated with great accuracy. From the velocity with which one gas diffuses in another, and from other closely allied phenomena, it was further possible to calculate the volume of space occupied by the molecules, and by that means the investigator was enabled to form an idea of the mass of the molecules and consequently of the number of molecules to be found in one gram of a chemical substance, such as, e.g. hydrogen. The figures thus obtained could not however lay claim to any great amount of accuracy and were regarded by many scientists as purely conjectural. If it had been possible to calculate the number of molecules in a drop of water by the aid of an exceedingly powerful microscope, the case would of course have been quite otherwise. But there was not the remotest hope of the investigator ever being successful in doing that, and thus the existence of the molecules was regarded as very problematical. If from the figures quoted by the champions of the kinetic gas-theory as the most probable ones for the sizes of molecules and atoms we calculate how large a quantity of electricity is carried by one hydrogen atom, we arrive at the conclusion that the atom charge lies between 1.3 x 10⁻¹⁰ and 6.1 x 10⁻¹⁰ electrostatic units.

What no one regarded as probable has however been achieved by J.J. Thomson by devious methods. Richard von Helmholtz found out, as long ago as 1887, that electrically charged small particles possess the remarkable property of condensing steam around them. J. J. Thomson and his pupil C. T.R. Wilson took up the study of this phenomenon. By the aid of Röntgen rays they procured some electrically charged small particles in air. Thomson assumes that each of those particles carries an electrical unit charge. By electrical measurements he was able to determine how great the electric charge was in a given quantity of air. Then, by means of a sudden expansion of the air, which was saturated with steam, he effected a condensation of the steam on the electrically charged small particles, the size of which he could calculate from the velocity with which they sank. Now as he knew the amount of water condensed and the size of each drop, it was not difficult to calculate the number of drops. That number was the same as that of the electrically charged small particles. Having before determined the total quan-

PRESENTATION

tity of electricity in the vessel, he could easily reckon out what quantity there was in each drop or, previously, in every small particle, that is to say the atomic charge. That was thus found to be 3.4×10^{-10} electrostatic units. This value is very close to the mean of the values previously obtained by the kinetic gas-theory, rendering the correctness of these different measurements and the accuracy of the reasoning employed in their determination in a very high degree probable.

Now, even if Thomson has not actually beheld the atoms, he has nevertheless achieved work commensurable therewith, by having directly observed the quantity of electricity carried by each atom. By the aid of this observation the number has been determined of the molecules in a cubic centimetre of gas at a temperature of zero and under the pressure of one atmosphere; that is to say, there has been thereby calculated what is perhaps the most fundamental natural constant in the material world. That number amounts to not less than forty trillions (40 x 10¹⁸). By means of a series of exceedingly ingenious experiments, Professor Thomson, aided by his numerous pupils, has determined the most important properties (such as mass and velocity under the influence of a given force), of these electrically charged small particles, which are produced in gases by various methods, e.g. by Röntgen rays, Becquerel rays, ultraviolet light, needle-point discharge and incandescent metals. The most remarkable of these electrically charged small particles are those constituting the cathode rays in highly rarefied gases. These small particles are called electrons and have been made the object of very thorough-going researches on the part of a large number ofinvestigators, foremost of whom are Lenard, last year's Nobel Prize winner in Physics, and J.J.Thomson. These small particles are to be met with also in the so-called β-rays, emitted by certain radioactive substances. Assuming, on the basis of Thomson's above-mentioned work, that they carry the negative unit charge, we are led to the result that they possess about a thousand times less mass than the least atoms hitherto known, viz. the atoms of hydrogen gas.

On the other hand, the least *positively* charged small particles we know are, according to Thomson's, Wien's and other investigators' calculations, of the same order in mass as ordinary atoms. Now, seeing that all substances yet examined are capable of giving off negatively charged electrons, Thomson was led by these circumstances to assume that the negative charge in the electrons has a real existence, whereas the charge of the positive small particles arises from a neutral atom losing one or more negative electrons with

PHYSICS 1906

their charges. Thomson has herewith given an actual physical import to the view put forward in 1747 by Benjamin Franklin that there is only one kind of electricity, a view eagerly championed too by Edlund. The actually existing electricity is negative electricity, according to Thomson.

As early as 1892 Thomson had shown that a charged body moving forward is thereby in possession of an electromagnetic energy, which produces the effect of the mass of the body being increased. From experiments carried out by Kaufmann regarding the velocity of β -rays from radium, Thomson concluded that the negative electrons do not possess any real, but only an apparent, mass due to their electric charge.

It might now be considered reasonable to assume that all matter is built up of negative electrons, and that consequently mass in matter was apparent and really depended on the effect of electric forces. An experiment of very great interest has moreover been made in this direction by Thomson, but his investigations of most recent date in the present year(1906) seem to intimate that only about a thousandth part of the material is apparent and due to electric forces.

Professor Thomson. As you are aware, the Royal Swedish Academy of Sciences has decided to award you the Nobel Prize in Physics for this year.

I am at a loss to explain how it is, but somehow or another the contemplation of the work you have achieved has revived in my mind a passage in the famous essay on Socrates by Xenophon, a work which you too no doubt perused in your youth. The author tells us that every time conversation turned upon the elements of the Earth, Socrates would say <<of these matters we know nothing>>. Will the sagacity which Socrates displayed in this answer and which has been approved by all ages up to and including our own, continue to be acknowledged as the conclusion of the whole matter? Who shall say? One thing we all know, and that is, that every great period of Natural Philosophy has evolved elements of its own, and furthermore we seem to feel as though we might be at the threshold of a new such period with new elements.

In the name and on behalf of our Academy I congratulate you upon having bestowed upon the world some of the main works which are enabling the natural philosopher of our time to take up new enquiries in new directions. You have thus been worthily treading in the footsteps of your great and renowned compatriots, Faraday and Maxwell, men who set to the world of science the highest and noblest examples.

I44

Carriers of negative electricity

Nobel Lecture, December 11, 1906

Introductory

In this lecture I wish to give an account of some investigations which have led to the conclusion that the carriers of negative electricity are bodies, which I have called corpuscles, having a mass very much smaller than that of the atom of any known element, and are of the same character from whatever source the negative electricity may be derived.

The first place in which corpuscles were detected was a highly exhausted tube through which an electric discharge was passing. When an electric discharge is sent through a highly exhausted tube, the sides of the tube glow with a vivid green phosphorescence. That this is due to something proceeding in straight lines from the cathode - the electrode where the negative electricity enters the tube - can be shown in the following way (the experiment is one made many years ago by Sir William Crookes): A Maltese cross made of thin mica is placed between the cathode and the walls of the tube. When the discharge is past, the green phosphorescence no longer extends all over the end of the tube, as it did when the cross was absent. There is now a well-defined cross in the phosphorescence at the end of the tube; the mica cross has thrown a shadow and the shape of the shadow proves that the phosphorescence is due to something travelling from the cathode in straight lines, which is stopped by a thin plate of mica. The green phosphorescence is caused by cathode rays and at one time there was a keen controversy as to the nature of these rays. Two views were prevalent: one, which was chiefly supported by English physicists, was that the rays are negatively electrified bodies shot off from the cathode with great velocity; the other view, which was held by the great majority of German physicists, was that the rays are some kind of ethereal vibration or waves.

The arguments in favour of the rays being negatively charged particles are primarily that they are deflected by a magnet in just the same way as moving, negatively electrified particles. We know that such particles, when a magnet is placed near them, are acted upon by a force whose direction is

1906 J.J.THOMSON

at right angles to the magnetic force, and also at right angles to the direction in which the particles are moving.

Thus, if the particles are moving horizontally from east to west, and the magnetic force is horizontal from north to south, the force acting on the negatively electrified particles will be vertical and downwards.

When the magnet is placed so that the magnetic force is along the direction in which the particle is moving, the latter will not be affected by the magnet.

The next step in the proof that cathode rays are negatively charged particles was to show that when they are caught in a metal vessel they give up to it a charge of negative electricity. This was first done by Perrin. This experiment was made conclusive by placing the catching vessel out of the path of the rays, and bending them into it by means of a magnet, when the vessel became negatively charged.

Electric deflection of the rays

If the rays are charged with negative electricity they ought to be deflected by an electrified body as well as by a magnet. In the earlier experiments made on this point no such deflection was observed. The reason of this has been shown to be that when cathode rays pass through a gas they make it a conductor of electricity, so that if there is any appreciable quantity of gas in the vessel through which the rays are passing, this gas will become a conductor of electricity and the rays will be surrounded by a conductor which will screen them from the effect of electric force, just as the metal covering of an electroscope screens off all external electric effects.

By exhausting the vacuum tube until there was only an exceedingly small quantity of air left in to be made a conductor, I was able to get rid of this effect and to obtain the electric deflection of the cathode rays. This deflection had a direction which indicated a negative charge on the rays.

Thus, cathode rays are deflected by both magnetic and electric forces, just as negatively electrified particles would be.

Hertz showed, however, that cathode particles possess another property which seemed inconsistent with the idea that they are particles of matter, for he found that they were able to penetrate very thin sheets of metal, e.g. pieces of gold leaf, and produce appreciable luminosity on glass behind them. The idea of particles as large as the molecules of a gas passing through

a solid plate was a somewhat startling one, and this led me to investigate more closely the nature of the particles which form the cathode rays.

The principle of the method used is as follows: When a particle carrying a charge *e* is moving with velocity *v* across the lines of force in a magnetic field, placed so that the lines of magnetic force are at right angles to the motion of the particle, then, if *H* is the magnetic force, the moving particle will be acted on by a force equal to *Hev*. This force acts in the direction which is at right angles to the magnetic force and to the direction of the particle. If also we have an electric field of force *X*, the cathode ray will be acted upon by a force *Xe*. If the electric and magnetic fields are arranged so that they oppose each other, then, when the force *Hev* due to the magnetic field is adjusted to balance the force due to the electric field *Xe*, the green patch of phosphorescence due to the cathode rays striking the end of the tube will be undisturbed, and we have

$$Hev = Xe$$
$$v = \frac{X}{H}$$

or

Thus if we measure, as we can do without difficulty, the values of X and H when the rays are not deflected, we can determine the value of v, the velocity of the particles. In a very highly exhausted tube this may be 1/3 the velocity of light, or about 60,000 miles per second; in tubes not so highly exhausted it may not be more than 5,000 miles per second, but in all cases when the cathode rays are produced in tubes their velocity is much greater than the velocity of any other moving body with which we are acquainted. It is, for example, many thousand times the average velocity with which the molecules of hydrogen are moving at ordinary temperatures, or indeed at any temperature yet realized.

Determination of e/m

Having found the velocity of the rays, let us now subject them to the action of the electric field alone. Then the particles forming the rays are acted upon by a constant force and the problem is like that of a bullet projected horizontally with a velocity *v* and falling under gravity. We know that in time

t, the bullet will fall a depth equal to $1/2gt^2$, where g is the acceleration due to gravity. In our case the acceleration due to the electric field is equal to *Xe/m*, where *m* is the mass of the particle. The time t = l/v, where *l* is the length of path, and *v* the velocity of projection.

Thus the displacement of the patch of phosphorescence where the rays strike the glass is equal to

$$\frac{\frac{1}{2}}{\frac{Xe}{m}} \cdot \frac{l^2}{v^2}$$

We can easily measure this displacement d, and we can thus find e/m from the equation

$$\frac{e}{m} = \frac{2d}{X} \cdot \frac{v^2}{l^2}$$

The results of the determinations of the values of e/m made by this-method are very interesting, for it is found that, however the cathode rays are produced, we always get the same value of e/m for all the particles in the rays. We may, for example, by altering the shape of the discharge tube and the pressure of the gas in the tube, produce great changes in the velocity of the particles, but unless the velocity of the particles becomes so great that they are moving nearly as fast as light, when other considerations have to be taken into account, the value of e/m is constant. The value of e/m is not merely independent of the velocity. What is even more remarkable is that it is independent of the kind of electrodes we use and also of the kind of gas in the tube. The particles which form the cathode rays must come either from the gas in the tube or from the electrodes; we may, however, use any kind of substance we please for the electrodes and fill the tube with gas of any kind and yet the value of e/m will remain unaltered.

This constant value, when we measure e/m in the c.g.s. system of magnetic units, is equal to about 1.7 x 10^7 . If we compare this with the value of the ratio of the mass to the charge of electricity carried by any system previously known, we find that it is of quite a different order of magnitude. Before the cathode rays were investigated, the charged atom of hydrogen met with in the electrolysis of liquids was the system which had the greatest known value of e/m, and in this case the value is only 10^4 , hence for the corpuscle in the cathode rays the value of e/m is 1,700 times the value of the correspond-

NEGATIVE ELECTRICITY CARRIERS

ing quantity for the charged hydrogen atom. This discrepancy must arise in one or other of two ways: either the mass of the corpuscle must be very small compared with that of the atom of hydrogen, which until quite recently was the smallest mass recognized in physics, or else the charge on the corpuscle must be very much greater than that on the hydrogen atom. Now it has been shown by a method which I shall shortly describe, that the electric charge is practically the same in the two cases; hence we are driven to the conclusion that the mass of the corpuscle is only about 1/1,700 of that of the hydrogen atom. Thus the atom is not the ultimate limit to the subdivision of matter; we may go further and get to the corpuscle, and at this stage the corpuscle is the same from whatever source it may be derived.

Corpuscles very widely distributed

It is not only from what may be regarded as a somewhat artificial and sophisticated source, viz. cathode rays, that we can obtain corpuscles. When once they had been discovered, it was found that they are of very general occurrence. They are given out by metals when raised to a red heat; indeed any substance when heated gives out corpuscles to some extent. We can detect the emission of them from some substances, such as rubidium and the alloy of sodium and potassium, even when they are cold; and it is perhaps allowable to suppose that there is some emission by all substances, though our instruments are not at present sufficiently delicate to detect it unless it is unusually large.

Corpuscles are also given out by metals and other bodies, but especially by the alkali metals, when these are exposed to light.

They are being continually given out in large quantities and with very great velocities by radioactive substances such as uranium and radium; they are produced in large quantities when salts are put into flames, and there is good reason to suppose that corpuscles reach us from the sun.

The corpuscle is thus very widely distributed, but wherever it is found, it preserves its individuality, e/m being always equal to a certain constant value.

The corpuscle appear to form *a* part of all kinds of matter under the most diverse conditions; it seems natural therefore to regard it as one of the bricks of which atoms are built up.

1906 J.J.THOMSON

Magnitude of the electric charge carried by the corpuscle

I shall now return to the proof that the very large value of *e/m* for the corpuscle, as compared with that for the atom of hydrogen, is due to the smallness of *m* the mass, and not to the greatness of e the charge. We can do this by actually measuring the value of e, availing ourselves for this purpose of a discovery by C. T. R. Wilson, that a charged particle acts as a nucleus round which water vapour condenses and forms drops of water. If we have air saturated with water vapour and cool it, so that it would be supersaturated if there were no deposition of moisture, we know that if any dust is present, the particles of dust act as nuclei round which the water condenses and we get the familiar phenomena of fog and rain. If the air is quite dust-free, we can, however, cool it very considerably without any deposition of moisture taking place. If there is no dust, C. T. R. Wilson has shown that the cloud does not form until the temperature has been lowered to such a point that the supersaturation in about eightfold. When however this temperature is reached, a thick fog forms even in dust-free air.

When charged particles are present in the gas, Wilson showed that a much smaller amount of cooling is sufficient to produce the fog, a fourfold supersaturation being all that is required when the charged particles are those which occur in a gas when it is in a state in which it conducts electricity. Each of the charged particles becomes the centre round which a drop of water forms; the drops form a cloud, and thus the charged particles, however small to begin with, now become visible and can be observed.

The effect of the charged particles on the formation of a cloud can be shown very distinctly by the following experiment:

A vessel which is in contact with water is saturated with moisture at the temperature of the room. This vessel is in communication with a cylinder in which a large piston slides up and down. The piston to begin with is at the top of its travel; by suddenly exhausting the air from below the piston, the pressure of the air above it will force it down with great rapidity, and the air in the vessel will expand very quickly. When, however, air expands, it gets cool; thus the air in the vessel previously saturated is now super-saturated. If there is no dust present, no deposition of moisture will take place, unless the air is cooled to such a low temperature that the amount of moisture required to saturate it is only about 1/8 of that actually present.

Now the amount of cooling, and therefore of supersaturation, depends upon the travel of the piston; the greater the travel the greater the cooling. Suppose the travel is regulated so that the supersaturation is less than eightfold and greater than fourfold. We now free the air from dust by forming cloud after cloud in the dusty air; as the clouds fall they carry the dust down with them, just as in nature the air is cleared by showers. We find at last that when we make the expansion no cloud is visible.

The gas is now made in a conducting state by bringing a little radium near the vessel; this fills the gas with large quantities of both positively and negatively electrified particles. On making the expansion now an exceedingly dense cloud is formed. That this is due to the electrification in the gas can be shown by the following experiment:

Along the inside walls of the vessel we have two vertical insulated plates which can be electrified. If these plates are charged, they will drag the electrified particles out of the gas as fast as they are formed, so that in this way we can get rid of, or at any rate largely reduce, the number of electrified particles in the gas. If the expansion is now made with the plates charged before bringing up the radium, there is only a very small cloud formed.

We can use the drops to find the charge on the particles, for when we know the travel of the piston, we can deduce the amount of supersaturation, and hence the amount of water deposited when the cloud forms. The water is deposited in the form of a number of small drops all of the same size; thus the number of drops will be the volume of the water deposited divided by the volume of one of the drops. Hence, if we find the volume of one of the drops, we can find the number of drops which are formed round the charged particles. If the particles are not too numerous, each will have a drop round it, and we can thus find the number of electrified particles.

From the rate at which the drops slowly fall we can determine their size. In consequence of the viscosity or friction of the air small bodies do not fall with a constantly accelerated velocity, but soon reach a speed which remains uniform for the rest of the fall; the smaller the body the slower this speed. Sir George Stokes has shown that *v*, the speed at which a drop of rain falls, is given by the formula

$$v = \frac{2}{9} \times \frac{g a^2}{\mu}$$

where *a* is the radius of the drop, *g* the acceleration due to gravity, and *m* the coefficient of viscosity of the air.

If we substitute the values g and μ , we get

$$v = 1.28 \times 10^6 \cdot a^2$$

1906 J.J.THOMSON

Hence if we measure v we can determine *a*, the radius of the drop.

We can in this way find the volume of a drop, and may therefore, as explained above, calculate the number of drops and therefore the number of electrified particles.

It is a simple matter to find by electrical methods the total quantity of electricity on these particles; and hence, as we know the number of particles, we can deduce at once the charge on each particle.

This was the method by which I first determined the charge on the particle; H. A. Wilson has since used a simpler method founded on the following principles : C. T. R. Wilson has shown that the drops of water condense more easily on negatively electrified particles than on positively electrified ones. Thus, by adjusting the expansion, it is possible to get drops of water round the negative particles and not round the positive; with this expansion, therefore, all the drops are negatively electrified. The size of these drops and therefore their weight can, as before, be determined by measuring the speed at which they fall under gravity. Suppose now, that we hold above the drops a positively electrified body: then, since the drops are negatively electrified, they will be attracted towards the positive electricity, and thus the downward force on the drops will be diminished and they will not fall so rapidly as they did when free from electrical attraction. If we adjust the electrical attraction so that the upward force on each drop is equal to the weight of the drop, the drops will not fall at all, but will, like Mahornet's coffin, remain suspended between heaven and earth. If then we adjust the electrical force until the drops are in equilibrium and neither fall nor rise, we know that the upward force on each drop is equal to the weight of the drop, which we have already determined by measuring the rate of fall when the drop was not exposed to any electrical force. If X is the electrical force, e the charge on the drop, and wits weight, we have, when there is equilibrium,

X e = w

Since X can easily be measured and w is known, we can use this relation to determine e, the charge on the drop. The value of e, found by these methods, is 3.0×10^{10} electrostatic units, or 10^{20} electromagnetic units. This value is the same as that of the charge carried by a hydrogen atom in the electrolysis of dilute solutions, an approximate value of which has been long known.

It might be objected that the charge measured in the preceding experi-

ments is the charge on a molecule or collection of molecules of the gas, and not the charge on a corpuscle.

This objection does not, however, apply to another form in which I tried the experiment, where the charges on the corpuscles were got, not by exposing the gas to the effects of radium, but by allowing ultraviolet light to fall on a metal plate in contact with the gas. In this case, as experiments made in a very high vacuum show, the electrification, which is entirely negative, escapes from the metal in the form of corpuscles. When a gas is present, the corpuscles strike against the molecules of the gas and stick to them.

Thus, though it is the molecules which are charged, the charge on a molecule is equal to the charge on a corpuscle, and when we determine the charge on the molecules by the methods I have just described, we determine the charge carried by the corpuscle.

The value of the charge when the electrification is produced by ultraviolet light is the same as when the electrification is produced by radium.

We have just seen that e, the charge on the corpuscle, is in electromagnetic units equal to 10^{20} , and we have previously found that e/m, m being the mass of a corpuscle, is equal to 1.7×10^7 , hence $m = 6 \times 10^{28}$ grammes.

We can realize more easily what this means if we express the mass of the corpuscle in terms of the mass of the atom of hydrogen.

We have seen that for the corpuscle $e/m = 1.7 \times 10^7$. If *E* is the charge carried by an atom of hydrogen in the electrolysis of dilute solutions, and *M* is the mass of the hydrogen atom, $E/M = 10^4$; hence e/m = 1,700 E/M.

We have already stated that the value of e found by the preceding methods agrees well with the value of *E* which has long been approximately known. Townsend has used a method in which the value of *e/E* is directly measured, and has shown in this way also that e equal to *E*. Hence, since e/m = 1,700 E/M, we have M = 1,700 m, i.e. the mass of a corpuscle is only about 1/1,700 part of the mass of the hydrogen atom.

In all known cases in which negative electricity occurs in gases at very low pressures, it occurs in the form of corpuscles, small bodies with an invariable charge and mass. The case is entirely different with positive electricity.

Biography

John Joseph Thomson was born in Cheetham Hill, a suburb of Manchester on December 18, 1856. He enrolled at Owens College, Manchester in 1870 and in 1876 entered Trinity College, Cambridge as a minor scholar. He became a Fellow of Trinity College in 1880, when he was Second Wrangler and Second Smith's Prizeman, and he remained a member of the College for the rest of his life, becoming Lecturer in 1883 and Master in 1918. He was Cavendish Professor of Experimental Physics at Cambridge, where he succeeded Lord Rayleigh, from 1884 to 1918 and Honorary Professor of Physics, Cambridge and Royal Institution, London.

Thomson's early interest in atomic structure was reflected in his *Treatise on the Motion of Vortex Rings* which won him the Adams Prize in 1884. His *Application of Dynamics to Physics and Chemistry* appeared in 1886 and in 1892 he had *his Notes on Recent Researches in Electricity and Magnetism* published. This latter work covered results obtained subsequent to the appearance of James Clerk Maxwell's famous <<Treatise>> and it is often referred to as <<the third volume of Maxwell>>. Thomson co-operated with Professor J. H. Poynting in a four-volume textbook of physics, *Properties of Matter* and in 1895 he produced *Elements of the Mathematical Theory of Electricity and Magnetism*, the 5th edition of which appeared in 1921.

In 1896, Thomson visited America to give a course of four lectures, which summarised his current researches, at Princeton. These lectures were subsequently published as *Discharge of Electricity through Gases* (1897). On his return from America, he achieved the most brilliant work of his life-an original study of cathode rays culminating in the discovery of the electron, which was announced during the course of his evening lecture to the Royal Institution on Friday, April *30*, 1897. His book, *Conduction of Electricity through Gases*, published in 1903 was described by Lord Rayleigh as a review of <<Thomson's great days at the Cavendish Laboratory>>. A later edition, written in collaboration with his son, George, appeared in two volumes (1928 a n d 1 9 3 3).

Thomson returned to America in 1904 to deliver six lectures on electricity

BIOGRAPHY

and matter at Yale University. They contained some important suggestions as to the structure of the atom. He discovered a method for separating different kinds of atoms and molecules by the use of positive rays, an idea developed by Aston, Dempster and others towards the discovery of many isotopes. In addition to those just mentioned, he wrote the books, *The Structure of Light* (1907), *The Corpuscular Theory of Mutter* (1907), *Rays of Positive Electricity* (1913), *The Electron in Chemistry* (1923) and his autobiography *Recollections and Reflections* (1936), among many other publications.

Thomson, a recipient of the Order of Merit, was knighted in 1908. He was elected Fellow of the Royal Society in 1884 and was President during 1916-1920: he received the Royal and Hughes Medals in 1894 and 1902 and the Copley Medal in 1914. He was awarded the Hodgkins Medal (Smithsonian Institute, Washington) in 1902; the Franklin Medal and Scott Medal (Philadelphia) 1923; the Mascart Medal (Paris) 1927; the Dalton Medal (Manchester) 1931; and the Faraday Medal (Institute of Civil Engineers) in 1938. He was President of the British Association in 1909 (and of Section A in 1896 and 1931) and he held honorary doctorate degrees from the Universities of Oxford, Dublin, London, Victoria, Columbia, Cambridge, Durham, Birmingham, Göttingen, Leeds, Oslo, Sorbonne, Edinburgh, Reading, Princeton, Glasgow, Johns Hopkins, Aberdeen, Athens, Cracow and Philadelphia.

In 1890, he married Rose Elisabeth, daughter of Sir George E. Paget, K.C.B. They had one son, now Sir George Paget Thomson, Emeritus Professor of Physics at London University, who was awarded the Nobel Prize for Physics in 1937, and one daughter.

Sir Joseph Thomson died on August 30, 1940.

Physics 1907

ALBERT ABRAHAM MICHELSON

<< for his optical precision instruments and the spectroscopic and metrological investigations carried out with their aid>>

Physics 1907

Presentation Speech* by Professor K. B. Hasselberg, member of the Royal Swedish Academy of Sciences

The Royal Academy of Sciences has decided to award this year's Nobel Prize for Physics to Professor Albert A. Michelson of Chicago, for his optical precision instruments and the research which he has carried out with their help in the fields of precision metrology and spectroscopy.

With untiring eagerness and, it can truly be said, with brilliant results, work is forging ahead today in every field of research in the natural sciences, and new information of ever greater significance is accumulating every day in unprecedented profusion. This is especially true in the case of the exact sciences - astronomy and physics - in which fields we are now obtaining solutions to problems, the mere mention of which up till a short while ago had to be regarded as unreal as Utopia itself. The reason for this gratifying development may be found in improvements in the methods and means of making observations and experiments, and also in the increase in accuracy brought about by these improvements in the quantitative examination of observed phenomena.

Astronomy, the precision science *par excellence*, has not only thus acquired whole new branches, but has also undergone in its older parts a transformation of more far-reaching significance than anything since the time of Galileo; and as for physics, it has developed remarkably as a precision science, in such a way that we can justifiably claim that the majority of all the greatest discoveries in physics are very largely based on the high degree of accuracy which can now be obtained in measurements made during the study of physical phenomena. We can judge how high our standards in this respect have risen from the fact that, for example, as recently as the beginning of the last century an accuracy of two to three hundredths of a millimetre in a measurement of length would have been regarded as quite fantastic. Today, however, scientific research not only demands but achieves an

^{*} Owing to the decease of King Oscar II two days earlier, the presentation ceremony had to be cancelled. The speech, of which the text is rendered here, was therefore not delivered orally.

PHYSICS 1907

accuracy from ten to a hundred times as great. From this it is obvious how fundamental is the importance which must be attached to every step in this direction, for it is the very root, the essential condition, of our penetration deeper into the laws of physics - our only way to new discoveries.

It is an advance of this kind which the Academy wishes to recognize with the Nobel Prize for Physics this year. Everyone is familiar with the significance and scope of the uses to which the telescope and the microscope can be put as measuring instruments in precision physics; but a limit to the efficiency of these instruments has been reached, a limit which cannot be exceeded appreciably, for both theoretical and practical reasons. Professor Michelson's brilliant adaptation of the laws of light interference has, however, perfected a group of measuring instruments, the so-called interferometers, based on those laws, which previously only had occasional uses, to such a degree that an increase in accuracy in measurement of from twenty to a hundred times what can be achieved with the best microscopes has been brought well within our grasp. This is due to the fact that, owing to the peculiar nature of the interference phenomena, the desired value - usually a length is measured -can be obtained in numbers of wavelengths of the type of light in use in the experiment directly from observation in the interferometer of the changes in the image, caused by interference. An accuracy of up to 1/50 of a wavelength-about 1/100,000 of a millimetre-can be achieved by this method. If we now remind ourselves that the quantities the measurement of which has been made possible by this increase in accuracy

⁻ that is, small distances and angles - are precisely those which it is most often necessary to determine in research in precision physics, then without further ado it becomes obvious how powerful an aid has been presented to the physicist in Michelson's interferometer - an invaluable aid, not only because of its efficiency, but also because of the multiplicity of its uses. To illustrate this latter point, it is enough to mention such achievements as, for example, measuring the heat expansion of solid bodies, investigating their elastic behaviour under stress and rotation, determining the margin of error of a micrometric screw, measuring the thickness of thin laminae of transparent solids or liquids, and obtaining the gravitational constant, mass, and average density of the Earth, using both ordinary and torsion balances. Among the more recent uses of the interferometer, by means of which small angle deviations can be recorded with an accuracy of minute fractions of a second, may be mentioned Wadsworth's galvanometric construction, with which can be measured electric currents of vanishingly small intensities with

PRESENTATION

a hitherto unknown degree of accuracy. However, although these uses of the interferometer are important and interesting, nevertheless they are of relatively minor significance in comparison with the fundamental research done by Professor Michelson in the fields of metrology and spectroscopy with the help of these instruments and which, in view of its far-reaching significance for the whole of precision physics, surely deserves in itself to have been recognized with a Nobel Prize. In fact, metrology is concerned with nothing less than finding a method of being able to control the constancy of the intemational prototype metre, the basis of the whole metric system, so accurately that not only will every change, however small, which could possibly occur in it be accurately measured, but also if the prototype were entirely lost, it could nevertheless be reproduced so exactly that no microscope could ever reveal any divergence from the original prototype. The significance of this does not need any particular emphasis, but an outline, however brief, of the course of this research and its results would not be out of place here.

I have already laid emphasis above on the facts that with the help of the interferometer measurements of small length can be made with an extraordinarily high degree of accuracy, and that they may be expressed using the wavelengths of any one type of light as a unit. Moreover, it is possible to measure in this way lengths up to 0.1 metre or more, in suitable conditions, without impairing the accuracy. Thus Michelson's research has first of all prepared the way for the measurement of the value of a standard length of 10 cm in wavelengths of a particular radiation in the cadmium spectrum. Proceeding from the value obtained in this way for the standard 10 cm, with a probable error of at the most \pm 0.00004 mm, Michelson was able, likewise using the interferometer, to ascertain on that basis the length of the normal metre, ten times greater, and he obtained for this length a value of

1,553,164.03

wavelengths of this kind to the metre. The probable error in this measurement can in the least favourable conditions amount to only \pm 0.0004 mm - that is, less than one wavelength - a value which is far too small to be detected directly by the microscope. Subsequently measurements were carried out in the International Bureau of Weights and Measures in Paris by different observers following an entirely different method, which showed that the error was in fact considerably smaller. These measurements actually give as a value for the length of the metre

PHYSICS 1907

1,553,164.13

wavelengths of this kind - a result which differs from Michelson's figure by only 0.1 wavelength, or 0.00006 mm. It is clear from this that Michelson's measurement of the length of the prototype metre must be accurate to within at least 0.0001 mm, and further, that this length can, by the use of his methods, be verified, or in the case of the loss of the prototype be reproduced, with the same degree of accuracy on every occasion. Finally, it also emerges from this that during the interval of 15 years which elapsed between the two series of measurements under discussion, no variation whatsoever from this figure had taken place in the prototype. The great care which had been taken in the execution and preservation of the prototype gave it at least the appearance of a high degree of constancy, but no more; it was only possible to obtain a real proof of its constancy when the metre could be compared with an absolute measure of length, independent of any physical element giving rise to it, the constancy of which under certain given conditions appeared to be guaranteed beyond a shadow of doubt. As far as our present knowledge goes, this is the case with wavelengths of light. It is to Michelson's eternal honour that by his classical research he has been the first to provide such proof.

From the value obtained in this way for the metre in wavelengths of one particular light radiation, it is now also possible to obtain, vice versa, figures for these wavelengths on an absolute scale of measurement, with a corresponding degree of accuracy. This accuracy is exceptionally high, and is in fact about fifty times greater than anything obtained by absolute methods in use up till now to determine wavelength. The conviction which had steadily been gaining ground for a long time past, that Rowland's wavelength system, otherwise quite accurate, which has been in use for the last twenty years as the exclusive basis of all spectroscopic research, is with respect to their absolute values subject to quite considerable errors, has thus received full confirmation; it has thus become apparent that a thoroughgoing reassessment of these values is necessary, using either Michelson's or some other similar interference method. And so we have reached the field of spectroscopy, in which it is clear that Michelson's interferometer is capable of an application no less significant than those which we have already considered. This is, however, not its only use. Considering the almost perfect clarity with which the majority of spectral lines appear in the emission spectra produced with the powerful diffraction-grating spectroscopes of our

PRESENTATION

day, there were good grounds for regarding these radiated lines as simple and indivisible things; this is, however, not the case. Making use of his interferometer Michelson has in fact proved that they are, on the contrary, for the most part more or less complex groups of extremely closely packed lines, for the resolution of which the resolving power of even the strongest spectroscope proved utterly inadequate. The discovery of this internal structure of spectral lines to the more thorough investigation of which Michelson later contributed, in the form of the echelon grating invented by him, an even finer means of research than the interferometer, definitely belongs among the most important advances which the history of spectroscopy has ever been able to record, the more so as the nature and condition of the molecular structure of luminous bodies is extremely closely bound up with this structure of spectral lines. Here we are on the threshold of entirely new fields of research, over the unexplored expanses of which Michelson's experiments enable us to cast our first gaze, and his experiments can at the same time serve as a lead to those who are capable of carrying his work a stage further.

In addition to the more or less complicated structure which owing to the peculiar internal nature of luminous bodies is found in spectral lines, it is also possible to split them under the influence of a magnetic force into several more or less closely packed components. A few years ago this Academy was in a position to reward with the Nobel Prize the first exhaustive research, carried out by Professor Zeeman, into this phenomenon, which is extremely important to the science of physics. By using a powerful spectroscope, it is of course possible to examine this phenomenon in its general aspects; as a rule, however, the details are so subtle and so difficult to make out that the resolving power of that instrument is just not adequate for a full investigation. In this case the interferometer - or still better the echelon grating - may be used to advantage, as Michelson has shown. There can remain no shadow of doubt that through this instrument it will be possible to facilitate substantially research into the Zeeman effect.

I have only been able to give here a brief account of the numerous important problems whose solution has been brought so much nearer by the powerful aid to research, with its unprecedented degree of accuracy, which we have received in Michelson's optical precision instruments. This account would certainly seem incomplete if no mention were made of those applications which these instruments have already found, and will surely go on finding, in the field of astronomy, which are almost as important as

PHYSICS 1907

those in the field of physics. Among these belong the series of measurements of the diameters of the satellites of Jupiter, which have been carried out partly by Michelson himself in the Lick observatory, and partly with the interferometer by Hamy in Paris - a series within which there is substantially closer agreement than it has been possible to achieve with normal micrometric observations through the biggestrefracting telescopes of the present day. Similarly, there can be no doubt whatsoever that it will be possible to obtain considerably more reliable figures in measuring the small planets between Mars and Jupiter than those which have been obtained by the photometric method of observation, which up till now has been the only one available, but which is extremely unreliable. The interferometer method can likewise be of some importance in the investigation of close double and multiple stars, and in this way we may cease to regard as utterly hopeless the problem, which has long been abandoned as completely insoluble, of finding by measurement true values for the diameters of at least the brighter stars. Thus astronomy has once again received from physics in the interferometer - as earlier in the spectroscope - a new aid to research which seems particularly suited to tackling problems whose solution was formerly impossible, as there were no, or at the most inadequate, instruments available.

The aforegoing will suffice, not only to explain to those who are not themselves closely involved in these problems the comprehensive and fundamental nature of Michelson's research in one of the most difficult fields of precision physics, but also to demonstrate how fully justified is the decision of this Academy to reward it with the Nobel Prize in Physics.

The following words were spoken to Professor A. A. Michelson, by Professor the Count K. A. H. Mörner, President of the Royal Swedish Academy of Sciences, during a private ceremony in the premises of the Academy.

Professor Michelson. The Swedish Academy of Sciences has awarded you this year the Nobel Prize in Physics in recognition of the methods which you have discovered for insuring exactness in measurements, and also of the investigations in spectrology which you have carried out in connection therewith.

Your interferometer has rendered it possible to obtain a non-material standard of length, possessed of a degree of accuracy never hitherto attained. By its means we are enabled to ensure that the prototype of the metre has

remained unaltered in length, and to restore it with absolute infallibility, supposing it were to get lost.

Your contributions to spectrology embrace methods for the determination of the length of waves in a more exact manner than those hitherto known.

Furthermore, you have discovered the important fact that the lines in the spectra, which had been regarded as perfectly distinct, are really in most cases groups of lines. You have also afforded us the means of closely investigating this phenomenon, both in its spontaneous occurrence and when it is produced by magnetic influence, as in Zeeman's interesting experiments.

Astronomy has also derived great advantage, and will do so yet more in the future, from your method of measurements.

In bestowing the Nobel Prize in Physics upon you the Academy of Sciences desires to signalize as worthy of especial honour the eminently successful researches you have carried out. The results you have attained are excellent in themselves and are calculated to pave the way for the future advancement of science.

Albert A. Michelson

Recent advances in spectroscopy

Nobel Lecture, December 12,1907

The fame of Newton rests chiefly on his epoch-making discovery of the laws of gravitational astronomy - by means of which the position of the moons, the planets, and the comets, and other members of our solar system can be calculated and verified with the utmost precision - and in many cases such calculation and verification may be extended to systems of suns and planets outside our own.

But in no less degree are we indebted to this monumental genius for that equally important branch of Astrophysics - in which the spectroscope plays so fundamental a role - by means of which we are enabled to discover the physical and chemical constitution of the heavenly bodies, as well as their positions and motions. As the number and intricacy of the wonderful systems of stellar worlds which the telescope can reveal increase with its power, so also do the evidences of the innermost molecular structure of matter increase with the power of the spectroscope. If Newton's fundamental experiment of separating the colors of sunlight had been made under conditions so slightly different from those in his actual experiment that in the present stage of experimental science, they would at once suggest themselves to the veriest tyro - the science of spectroscopy would have been founded.

So simple a matter as the narrowing of the aperture through which the sunlight streamed before it fell upon the prism which separates it into its constituent colors - would have sufficed to show that the spectrum was crossed by dark lines, named after their discoverer, the Fraunhofer lines of the Solar Spectrum. These may be readily enough observed, with no other appliances than a slit in a shutter which is observed through an ordinary prism of glass. Fraunhofer increased the power of the combination enormously by observing with a telescope - and this simple combination, omitting minor details, constitutes that wonder of modern science, the Spectroscope. As the power of a telescope is measured by the closeness of the double stars which it can <<resolve>>, so that of the Spectroscope may be estimated by the closeness of the advance in the power of spectroscopes

ADVANCES IN SPECTROSCOPY

let us for a moment consider the map of the Solar Spectrum (Figure I).

The portion which is visible to the unaided eye extends from the Fraunhofer line A to H; but by photography it may be traced far into the ultraviolet region and by bolometric measurements it is found to extend enormously farther in the region beyond the red. In the yellow we observe a dark line marked D, which coincides in position with the bright light emitted by sodium - as when salt is placed in an alcohol flame. It may be readily shown by a prism of very moderate power that this line is double, and as the power of the instrument increases the distance apart or separation of this doublet furnishes a very convenient measure of its separating or resolving power. Of course this separation may be effected by simple magnification, but this would in itself be of no service, as the <themselves would be broadened by the magnification in the same proportion. It can be shown that the effective resolving power depends on the material of the prism which must be as highly dispersive as possible and on the size, or number, of the prisms employed - and by increasing these it has been found possible to <<resolve>> double lines thirty or forty times as near together as are the sodium lines. It will be convenient to take the measure of the resolving power when just sufficient to separate the sodium lines as 1,000. Then the limit of resolving power of prism spectroscopes may be said not much to exceed 40,000.*

This value of resolving power is found in practice to obtain under average conditions. Theoretically there is no limit save that imposed by the optical conditions to be fulfilled - and especially by the difficulty in obtaining large masses of the refracting material of sufficient homogeneity and high dispersive power. It is very likely that this limit has not yet been reached.

Meanwhile another device for analysing light into its component parts has been found by Fraunhofer (1821) which at present has practically superseded the prism-namely, the diffraction grating. Fraunhofer's original grating consisted of a number of fine equidistant wires, but he afterwards made them by ruling fine lines on a glass plate covered with gold leaf and removing the alternate strips. They are now made by ruling upon a glass or a metal surface fine equidistant lines with a diamond point.

The separation of light into its elements by a grating depends on its action on the constituent light-waves.

Let Fig. 2 represent a highly magnified cross section of a diffraction grating with plane waves of light falling upon it normally, as indicated by the ar-* Lord Rayleigh has obtained results with prism of carbon disulphide which promise a much higher resolving power.





rows. The wave motion will pass through the apertures, and will continue as a series of plane waves; and if brought to a focus by a telescope will produce an image of the slit source just as if no grating were present (save that it is fainter, as some of the light is cut off by the opaque portions). This image may be considered as produced by the concurrence of all the elementary waves from the separate apertures meeting in the same phase of vibration, thus re-inforcing each other. But this may also be true in an oblique direction, as shown in the figure, if the retardation of the successive waves is just one whole wavelength (or any whole number) as is illustrated in Fig. *3*, where the successive waves from apertures 1, 2, 3 ... are shown to reinforce each other just as if they all belong to a single wave-train. In this direction therefore there will also be an image of the slit source; and this direction is determined by the relation:

$$\sin\theta = \frac{m\,l}{s}$$

where *l* is the length of the light-wave of this particular color, s the distance between the apertures (the grating space), and *m* the number of waves in the common retardation (1,2,3, etc.). But even if the light thus diffracted be absolutely homogeneous (that is, consist of an infinite wave-tram of constant wavelength) it does not follow that the light is all diffracted in the given direction; there will be some light in directions differing slightly from this - growing less until the extreme difference of path is (say) n + I waves, (instead of n when it is ml).

In fact, if we divide the pencil having this new direction into two equal parts *AC* and *CB*, the ray *AA*, will be n + 1/2 waves in advance of CC₁ and the two will be in opposite phases of vibration, and will therefore neutralize each other. The same will be true of each pair of rays taken in the same manner over the whole grating space, and the result is total darkness for this direction. Let us suppose we are examining the double sodium line. The difference between the components is about one thousandth of the wavelength. With a grating of *n* lines there will be total darkness in a direction corresponding to a retardation of (n + 1) l. Let this direction correspond to the brightest part of the image for the second sodium line 1_2 so that $(n + 1) l = n 1_2$ or $(1_2 - 1_1)/s = l/n$. Under these conditions the two images are just <<resolved>>. But $(1_2 - 1_1)/l = l/1,000$ for sodium lines, whence n = 1,000. That is, a grating of 1,000 lines will <<resolve>> the sodium lines in the first spectrum, or R = 1,000. In the second (where the common retardation

is two wavelengths) the resolving power is twice as great or *2n*, and in the *mth* spectrum, *m* times as great. The resolving power is therefore the product of the number of lines in the grating by the order of the spectrum, that is, R = mn.

In order, therefore, to obtain high resolving power the grating must have a great number of rulings and if possible a high order of spectrum should be used. The rulings need not be exceedingly close together, but it is found practically sufficient if there are from 500 to 1,000 lines per millimeter. The earlier gratings were relatively small and contained only a few thousand lines. The best of these were ruled by Nobert (1851). A very great advance was made by Rutherford of New York, who (1868) ruled gratings two inches long on speculum metal and containing about 20,000 lines. These gratings exceeded in resolving power the best prism trains in use at the time. The next advance was made by Rowland of the Johns Hopkins University, who succeeded in ruling gratings six inches long (by two to three inches stroke) having about one hundred thousand lines, and capable (theoretically, at least) of resolving in the spectrum, double lines whose distance apart was only one one-hundredth as great as that of the sodium lines. Practically this is about the limit of the power of the best Rowland grating which I have examined.

The difference between the theoretical and the actual performance is due to want of absolute uniformity in the grating space. This is due to the enormous difficulty in constructing a screw which shall be practically perfect throughout its whole length, a difficulty which increases very rapidly as the length of the screw increases; and it has been supposed that the limit of accuracy was reached in these gratings.

The great and rapidly increasing importance of spectrum analysis - especially in determining the distribution of light in so-called spectral lines under normal conditions, the resolution of complicated systems of lines, and in the investigation of the effects of temperature, of pressure, and especially of a magnetic field -justified the untertaking of much larger gratings than these. As an example of progress made in this direction, I have the honor of exhibiting a grating having a ruled surface nine inches long by four and one half inches stroke (220 x 110mm). This has one hundred and ten thousand lines and is nearly perfect in the second order; so that its resolving power is theoretically 220,000 and this is very nearly realized in actual experiments.

It will be observed that the effect produced at the focus of the telescope depends on the concurrence or opposition - in general on the *interference of*

the elementary trains of light-waves. We are again indebted to the genius of Newton for the first observation of such interference; and a comparatively slight modification of the celebrated experiment of <<Newton's rings>> leads to a third method of spectrum analysis which, if more indirect and less convenient than the methods just described, is far more powerful. If two plane surfaces (say the inner surfaces of two glass plates) are adjusted very accurately to parallelism, and sodium light fall on the combination at nearly normal incidence, the light reflected from the two surfaces will interfere, showing a series of concentric rings alternately bright and dark, according to the relative retardation of the two reflected light beams.

If this retardation changes (by slowly increasing the distance between the surfaces) the center of the ring system goes through alternations of light and darkness, the number of these alternations corresponding exactly to the number of light-waves in twice the increase in distance. Hence the measurement of the length of the waves of any monochromatic light may be obtained by counting the number of such alternations in a given distance. Such measurement of wavelengths constitutes one of the most important objects of spectroscopic research.

Another object accomplished by such measurement is the establishment of a natural standard of length in place of the arbitrary standard at present in use - the meter. Originally it was intended this should be the ten-millionth part of an earth-quadrant, but it was found that the results of measurements differed so much that this definition was abandoned. The proposition to make the ultimate standard the length of a pendulum which vibrates seconds at Paris met with a similar fate.

Shortly after the excellent gratings made by Rutherford appeared, it was proposed (by Dr. B. A. Gould) to make the length of a wave of sodiumlight the ultimate standard; but this idea was never carried out. It can be shown that it also is not susceptible of the requisite degree of accuracy, and in fact a number of measurements made with a Rowland grating have been shown to be in error by about one part in thirty thousand. But modern conditions require a much higher degree of accuracy. In fact, it is doubtful if any natural standard could replace the arbitrary standard meter, unless it can be shown that it admits of realization in the shape of a material standard which can not be distinguished from the original.

One of the most serious difficulties encountered in the attempt to carry into practice the method of counting the alternations of light and darkness in the interference method, is the defect in homogeneity of the light employed. This causes indistinctness of the interference rings when the distance is greater than a few centimeters. The light emitted by various kinds of gases and metallic vapors, when made luminous by the electric discharge, differ enormously in this respect. A systematic search showed that among some forty or more radiations nearly all were defective, some being represented by a spectrum of broad hazy <lines>>, others being double, triple, or even more highly complex. But the red light emitted by luminous vapor of metallic cadmium was found to be almost ideally adapted for the purpose. Accordingly this was employed : and the results of three independent measurements, made by different observers and at different times, of the number of light-waves of red cadmium light in the standard meter are as follows:

It will be seen that the differences are less than half a millionth part, and this is about the limit of accuracy of the comparative measurements of the material standards. Within the last year a similar determination has been carried out by Perot and Fabry, with a result not to be distinguished from the above. It follows that we now have a natural standard of length, the length of a light-wave of incandescent cadmium vapor; by means of which a material standard can be realized, whose length can not be distinguished from the actual standard meter-so that if, through accident or in time, the actual standard meter should alter, or if it were lost or destroyed, it could be replaced so accurately that the difference could not be observed.

In the search for a radiation sufficiently homogeneous for the purpose of a standard it became evident that the interference method might be made to yield information concerning the distribution of light in an approximately homogeneous source when such observations would be entirely beyond the power of the best spectroscopes. To illustrate, suppose this source to be again the double radiation from sodium vapor. As the wavelengths of these two radiations differ by about one part in a thousand, then at a difference of path of five hundred waves (about 0.36 mm) the bright fringes of one wave-train would cover the dark fringes of the other, so that if the two radiations were of equal intensity, all traces of interference would vanish. At twice this distance they would reappear and so on indefinitely, if the separate radiations were absolutely homogeneous. As this is not the case, however, there would be a gradual falling off in the clearness or visibility of the bands. Inversely, if such changes are observed in actual experiment, we infer that we are dealing with a double source. Further, from the distance between the maxima of distinctness, we may determine (and with extraordinary accuracy) the ratio of wavelenghts of the components; from the ratio of maxima to minima we may infer the ratio of their intensities; and finally the gradual falling off when the distance becomes large gives accurate information of the <<width>>> of the corresponding spectral lines.





In this way it was found that the red line of hydrogen is a double with components about one fortieth of the distance apart of the sodium lines. Thallium has a brilliant green radiation which is also double, the distance being one sixtieth that of the sodium lines. Mercury shows a brilliant green line, which is highly complex, but whose chief component is a doublet, whose separation is only one seven-hundredth of that of sodium. The interference fringes are still visible when the difference of path is of the order of five hundred millimeters, corresponding to over a million light-waves; and the corresponding width of spectral line would be less than a thousandth part of that which separates the sodium lines.

Fig. 5 illustrates the arrangement of the apparatus as it is actually used. An ordinary prism spectroscope gives a preliminary analysis of the light from the source. This is necessary because the spectra of most substances consist of numerous lines. For example, the spectrum of mercury contains two yellow lines, a very brilliant green line, and a less brilliant violet line, so that if we pass all the light together into the interferometer, we have a combination of all four. It is usually better to separate the various radiations before they enter the interferometer. Accordingly, the light from the vacuum tube at *a* passes through an ordinary spectroscope *b c*, and the light from only one of the lines in the spectrum thus formed is allowed to pass through the slit *d* into the interferometer.

As explained above, the light divides at the plate e, part going to the mirror f, which is movable, and part passing through, to the mirror g. The first ray returns on the path f e h. The second returns to e, is reflected, and passes into the telescope h.

The resolving power of the interferometer is measured by the number of light-waves in the difference of path of the two interfering pencils, and as this is unlimited, the interferometer furnishes the most powerful means for investigating the structure of spectral lines or groups. Its use is, however, somewhat handicapped by the fact that the examination of a single group of lines may require a considerable number of observations which take some time and during which it may be difficult to prevent changes in the light source. Nevertheless it was found possible by its means to investigate the wonderful discovery of Zeeman - of the effect of a magnetic field on the character of the radiation from a source subjected to its influence; and the results thus obtained have been since confirmed by methods which have been subsequently devised.

One of these is the application of the echelon. This is in effect a diffraction grating in which high resolving power is obtained by using a very high order of spectrum into which practically all, the light is concentrated. The number of elements may be quite moderate - since the resolving power is the product of the two. The order of the spectrum is the number of wavelengths in the retardation at each step. This retardation (which must be very accurately constant) is secured by allowing the incident light to fall upon a pile of glass plates optically plane parallel and of the same thickness - each one a little wider than the preceding as in Fig.6.



Thus if the pile has forty plates, each one centimeter thick, the retardation will be about ten thousand light-waves; and the resolving power would be forty times this or four hundred thousand - which is about four times as that of a six-inch diffraction grating of the usual form. The number of elements might be increased till the absorption of the glass brought a limit. A difficulty, which appears long before this limit is reached, is due to the loss of light by repeated reflections between the many surfaces. This has been very ingeniously overcome by Mr. Twyman of the firm of Hilger & Company by pressing the plates together to actual contact - when the reflection vanishes. It is likely that the echelon under these conditions may be used by reflection instead of transmission (the plates being silvered for the purpose) with the advantage of quadrupling the resolving power for the same number of plates and eliminating the absorption.

An illustration of the efficiency of the echelon spectroscope is furnished by the following photographs of the spectrum of green radiations from mercury vapor. The first of the figures shows the spectrum of the second order of a diffraction grating whose ruled surface is nine inches by four and a half - the largest in existence. The second is by an echelon of thirty plates, seven millimeters thick, and in the third the echelon consisted of forty plates, each an inch and a fourth thick (30 mm). The corresponding lines are similarly lettered in the three figures. The scale is in Å.U.(Ångstrom units). It will be noted in the last of the three figures that the midth of the fainter companion is about one one-hundredth of an Å.U. The limit of resolution of the instrument is about half as much, or its resolving power is over a million (Figs. 7,8 and 9).

It will be observed that the echelon spectra are repeated - thus a_i and a_z are two successive spectra of the same line. This is true of any grating spectrum, and the difficulties which arise from the overlapping of the suc-





Fig.10.



Fig.11.



Fig.12.

cessive orders of spectrum may be overcome by separating these by a prism whose refracting edge is perpendicular to the lines of the grating. The same is true of the echelon spectrum - save that the order of the overlapping spectra is so high that a prism is hardly adequate and recourse must be had to a grating - with its plane of diffraction perpendicular to that of the echelon, as shown in Fig. 10.

With this arrangement it is possible to photograph a large part of the spectrum at once.*

Fig. 11 shows such a photograph of the iron spectrum, and it may be noted that this combination of grating and echelon makes it possible to observe absorption spectra as well as bright line spectra.

Fig.12 shows a photograph of the solar spectrum taken in this way. It will be noted that the spectral <s>> are generally too broad to justify the use of so great a resolving power.

Finally it may be pointed out that this combination gives us the means of comparing the wavelengths of spectral lines with a degree of accuracy far superior to that of the grating.

* If the preliminary analysis has been made before the light entered the slit of echelon spectroscope, it would be possible to examine but one-at most a few -lines at a time.

Biography

Albert Abraham Michelson was born in Strelno, Prussia, on December 19, 1852. Two years later his family emigrated to the United States to settle at Virginia City, Nevada, but they eventually moved to San Francisco where Michelson received his early education in public schools, matriculating from the High School in 1809. He was appointed by President Grant to the U.S. Naval Academy and, after graduation as Ensign in 1873 and a two-years' cruise in the West Indies, he became an instructor in physics and chemistry at the Academy under Admiral Sampson. In 1879, he was posted to the Nautical Almanac Office, Washington, to work with Simon Newcomb, but in the following year, he obtained leave of absence to continue his studies in Europe. He visited the Universities of Berlin and Heidelberg, and the College de France and École Polytechnique in Paris. He resigned from the Navy and in 1883 returned to America to take an appointment as Professor of Physics in the Case School of Applied Science, Cleveland, Ohio. In 1890 he accepted a similar position at Clark University, Worcester, Massachusetts, and in 1892 he became Professor of Physics and the first Head of Department at the new University of Chicago. He rejoined the Navy during World War I, and in 1918 returned to Chicago where in 1925 he was appointed to the first of the Distinguished Service Professorships. Michelson resigned in 1929 to work at the Mount Wilson Observatory, Pasadema.

During his career, Michelson touched on many departments of physics but, perhaps due to a special instinct which he appeared to possess, he excelled in optics. He performed early measurements of the velocity of light with amazing delicacy and in 1881 he invented his interferometer for the purpose of discovering the effect of the Earth's motion on the observed velocity. In cooperation with Professor E. W. Morley, and using the interferometer, it was shown that light travels at a constant speed in all internal systems of reference. The instrument also enabled distances to be measured with greater accuracy by means of the length of light-waves. At the request of the International Committee of Weights and Measures, Michelson measured the standard metre in terms of wavelength of cadmium light. He in-
1907 A.A. MICHELSON

vented the echelon spectroscope and during his wartime service in the Navy he performed research work on devices for naval use - he developed a rangefinder which was adapted as part of U.S. Navy equipment. On his return to civilian life, Michelson became more interested in astronomy and in 1920, using light interference and a highly developed version of his earlier instrument, he measured the diameter of the star Betelgeuse: this was the first determination of the size of a star that could be regarded as accurate.

Michelson has contributed numerous papers to many scientific periodicals and among his more substantial works are the classics, Velocity & Light (1902) *Light Waves and their Uses* (1899-1903); and *Studies in Optics* (1927).

Michelson was honoured by memberships of many learned societies throughout America and ten European countries, and he received honorary science and law degrees from ten American and foreign universities. He was President of the American Physical Society (1900), the American Association for the Advancement of Science (1910--1911), and the National Academy of Sciences (1923-1927). He was also a Fellow of the Royal Astronomical Society, the Royal Society of London and the Optical Society, an Associate of l'Académie Française and among the many awards he has received are the Matteucci Medal (Societá Italiana), 1904; Copley Medal (Royal Society), 1907; Elliot Cresson Medal (Franklin Institute), 1912; Draper Medal (National Academy of Sciences), 1916; Franklin Medal (Franklin Institute) and the Medal of the Royal Astronomical Society, 1923; and the Duddell Medal (Physical Society), 1929.

Michelson married Edna Stanton of Lake Forest, Illinois in 1899. They had one son and three daughters. He died in 1941.

Physics 1908

GABRIEL LIPPMANN

<<for his method of reproducing colours photographically based on the phenomenon of intereference>>

Physics 1908

Presentation Speech by Professor K. B. Hasselberg, President of the Royal Swedish Academy of Sciences

Your Majesty, Your Royal Highnesses, Ladies and Gentlemen.

The Royal Academy of Sciences has awarded the Nobel Prize for Physics for 1908 to Professor Gabriel Lippmann of the Sorbonne for his method, based on the phenomenon of interference, which permits the reproduction of colours by photography.

Even before 1849, when the art of photographic reproduction was discovered by the pioneers of Science, Niepce, Daguerre, Talbot and others, the question of means of rendering and of fixing colours on the photographic plate has loomed large. It looked as though the answer was at hand when Edmond Becquerel showed that a silver plate coated with a thin layer of silver chloride coloured up under the action of light with a colour corresponding to that of the light used. This observation led no further. Becquerel had no explanation for the origin of the colours nor did he find a means of fixing them on the plate. They passed off rapidly and so his method, being thus of no practical use, failed to win the attention it undoubtedly deserved.

One explanation for the origin of Becquerel's coloured images was given in 1868 by the German Wilhelm Zenker and then taken further by the Nobel Prize winner Lord Rayleigh. According to this explanation, the colour phenomenon is due to standing light waves that by chemical action form grains of silver metal from the silver chloride. Colour is an interferential phenomenon produced by the reflection of light on this silver layer.

The phenomenon thus became of theoretical interest. If the truth of this theory could be shown, the work of Becquerel would afford further proof of the correctness of our concept of light considered as the result of vibratory movement, since one of the fundamental phenomena of vibratory movement - the standing wave - would thus be verified for light. It was, however, not until 1890 that Otto Wiener by a particularly fine experiment furnished conclusive evidence of the correctness of Zenker's theory.

It was now possible to reproduce pictures in more or less exact colours but still not stable. Explanation had also been found for the origin of these pic-

PHYSICS 1908

tures. It was still not time to talk of photographic reproduction of the colour of objects and their *fixation*. This was the point reached when Professor Lippmann in 1891 communicated to the Paris Academy of Sciences his sensational work *Colour Photography*.

The main features of the Lippmann method are doubtless fairly well known. On plane glass a layer sensitive to light is spread, consisting of gelatine emulsion, silver nitrate, and potassium bromide. To this sensitive layer a layer of mercury is applied, forming a mirror. This is exposed in the dark room in such a way that the glass side of the plate is turned towards the objective. During exposure light has to pass through the glass first, then penetrate the imprint layer and encounter the reflecting surface of the mercury, which throws it back. These incident and reflected light waves form what are called standing waves, characterized by a series of maxima and minima of illumination, distant from each other by half a wavelength of the incident light. Once the plate is developed, fixed, and dried by normal processes, there will be found in the layer of gelatine planes of reduced silver whose reciprocal distances depend on the wavelength - that is to say, on the colour of the light which produced the image. Let us suppose that white light falls in the normal way on a photographic plate disposed as we have described. The ray will be reflected by the different planes of silver and, following known laws of interference of light in thin laminae, the foil will appear coloured - and coloured with the same colour as the light that gave rise to the corresponding photographic print. The reproduction of colours is thus being carried out here by the same way as in soap bubbles and thin laminae in general, with additional strengthening by the existence of successive planes. The effect of colour in Lippmann's experiments does not therefore arise from pigment colours. We have to do with what are called virtual colours, unalterable in composition and bright for as long as the photographic plate is intact. Thus Lippmann's photographs show up favourably in comparison with later attempts at solving this problem of colour reproduction - Lumière's photographs-so-called three-colour photographs, obtained by using pigment colours, a delightful discovery, which owing to the simplicity of the operational method has rightly won a large measure of popularity.

One glance at the illustrated works of our day, both in the domain of science and of art and industry, is enough to show the key position of photographic reproduction in present-day life. Lippmann's colour photography marks a further step forward, which is of great importance, in the art of photography, since his method has been the first to give us the means of

PRESENTATION

presenting to posterity in unalterable picture form not only the shape of an object with its play of light and shade but its colours as well.

Through sustained effort directed towards his end and through his complete grasp of all the resources that physics can offer, Professor Lippmann has created this elegant method of obtaining images which combine stability with colorific splendour. This achievement the Royal Academy of Sciences has considered worthy of the award of the Nobel Prize for Physics for 1908.

Colour photography

Nobel Lecture, December 14, 1908

The problem of direct colour photography has been facing us since the turn of the last century. Edmond Becquerel, as is known, gave a first solution though only an imperfect one. Becquerel showed that the colours of the image of the dark room print on a layer of violet silver chloride. Zenker explained Becquerel's finding by a phenomenon of interference. Experiment shows that this explanation is not true and that Zenker's theory does not hold good for silver chloride. Becquerel's prints remained, however, what they were: not fixed, and fading in light. Then Otto Wiener fixed by photography a shot of interference fringes that are found in the neighbourhood of a silver mirror. That physicist did not, however, envisage obtaining colours by an interference method. I will not lay any further stress on the background of experiments and ideas which preceded the method on which I am to have the honour of addressing you, and which furnishes the coloured image of objects.

The method is very simple. A plate is covered with a sensitive transparent layer that is even and grainless. This is placed in a holder containing mercury. During the take, the mercury touches the sensitive layer and forms a mirror. After exposure, the plate is developed by ordinary processes. After drying the colours appear, visible by reflection and now fixed.

This result is due to a phenomenon of interference which occurs within the sensitive layer. During exposure, interference takes place between the incident rays and those reflected by the mirror, with the formation of interference fringes half a wavelength distant from each other. The fringes imprint photographically through the whole thickness of the film and form a casting for the light rays. When the shot is afterwards subjected to white light, colour appears because of selective reflection. The plate at each point only sends back to the eye the simple colour imprinted. The other colours are destroyed by interference. The eye thus perceives at each point the constituent colour of the image. This is no more than a phenomenon of selective reflection as in the case of the soap bubble or mother-of-pearl. The print in itself is formed of colourless matter like that of mother-of-pearl or soap film.

COLOUR PHOTOGRAPHY

This explanation can be checked by an experiment we are going to carry out in front of you. Here first is a print of the spectrum projected on to the screen. As you see, the colours are bright. We wet the plate and project it on to the screen again. There is no colour there. The gelatine has swollen and the intervals between the images of the interference fringes (Zenker's laminae) have become two or three times too large. Wait one minute while the water dries off. We see the colours re-appear in accordance with and at the speed of the drying process. They re-appear according to an order which can be predicted. Red, which corresponds to the greatest wavelengths, reappears first, followed by orange, green, blue, and violet.

The reproduction of the simple colours of the spectrum was the easiest to carry out. The photography of composite colours that exterior objects present posed a harder problem. At first sight it might have been held impossible. In effect, in the case of simple light, the interference maxima are equidistant planes separated by intervals equal to half a wavelength. In the case of composite colour, an infinity of systems must be obtained for maxima infinitely slight and with an infinity of interval values separating them that is to say, the whole thickness of the sensitive layer is occupied in continuous manner by these maxima. The spaces that exist in the instance of simple light and which allow to assimilate the photographic plate with a series of fine laminae have disappeared. It was thus necessary to reshape the theory of the phenomenon in wider terms. First it must be noted that the amplitude resulting from the interference varies according to a function that is continuous even in the case of simple light. The general case is derived by an analysis based on one of Fourier's chapters. It can thus be demonstrated that photography of composite colours is possible.

Once all theoretic reserve was gone, the technical difficulties appertaining to the isochromatism of the films remained to be overcome. I got quite good results from protein plates. Later, Valenta in Vienna and the Lumières at Lyons found means of coating the plates in grainless gelatine, sufficiently isochromatic and very much better than the protein plate. Dr. Neuhauss in Berlin carried isochromatism to perfection. Thanks to the work of Messrs. Miethe, Krone, H. Lehmann, and others whom I will not detain you by mentioning, the technique of colour photography has been perfected. Allow me to show you projections of results obtained.

(Series of slides-still-life paintings, vases with-flowers, views of Fontainebleau, Lake Annecy, Biarritz, Zermatt, Venice, and child portrait from life.)

The photographs that you are seeing needed approximately one minute

1908 G.LIPPMANN

of exposure to sunlight. The series of photographic operations, developing, washing, final drying, takes about quarter of an hour. Most of these pictures, taken while travelling, were developed on the mantelpiece of a hotel room, which proves that the method is easy enough to carry out.

It nevertheless still remains to be perfected in some points. The length of exposure (one minute in sunlight) is still too long for the portrait. It was fifteen minutes when I first began my work. Progress may continue. Life is short and progress is slow.

Biography

Gabriel Lippmann was born of French parents at Hollerich, Luxembourg on August 16, 1845. The family moved to Paris and he received his early education at home. In 1858 he entered the Lycèe Napoléon and ten years later he was admitted to the École Normale. His school career was not markedly successful, for he concentrated only on the work which interested him and neglected that which did not appeal to his taste, and he failed the examination which would have qualified him as a teacher. In 1873, he was appointed to a Government scientific mission visiting Germany to study methods for teaching science: he worked with Kühe and Kirchhoff in Heidelberg and with Helmholtz in Berlin.

Lippmann joined the Faculty of Science in Paris in 1878 and in 1883 he was appointed Professor of Mathematical Physics. Three years later he became Professor of Experimental Physics, succeeding Jamin, and he was appointed Director of the Research Laboratory which was subsequently transferred to the Sorbonne. He retained this position until his death.

Lippmann, of original and independent mind, made many valuable fundamental contributions to many different branches of physics, especially electricity, thermodynamics, optics and photochemistry. In Heidelberg he studied the relationship between electrical and capillary phenomena: this led to the development, amongst other instruments, of his extraordinarily sensitive capillary electrometer.

Professor Lippmann had evolved the general theory of his process for the photographic reproduction of colour in 1886 but the practical execution presented great difficulties. However, after years of patient and skilful experiment, he was able to communicate the process to the Academy of Sciences in 1891, although the photographs were somewhat defective due to the varying sensitivity of the photographic film. In 1893, he was able to present to the Academy photographs taken by A. and L. Lumière in which the colours were produced with perfect ortho-chromatism. He published the complete theory in 1894.

In 1895, Lippmann evolved a method of eliminating the personal equation

1908 G.LIPPMANN

in measurements of time, using photographic registration, and he studied the eradication of irregularities of pendulum clocks, devising a method of comparing the times of oscillation of two pendulums of nearly equal period. He contributed to astronomy with his invention of the coelostat, a device which immobilizes the image of a star and its surrounding stars so that a photograph may be taken. He was also responsible for many more ingenious devices and improvements to standard instruments to the benefit of many branches of physics.

His work is mainly recorded in communications to the Paris Academy of Sciences where his papers are noted for their conciseness and originality. His method of reproducing colours in photography, based on the interference phenomenon, gained him the Nobel Prize for Physics for 1908.

Professor Lippmann became a member of the Academy of Sciences in 1883 and served as its President in 1912. He was a member of the Board of the Bureau des Longitudes and a Foreign Member of the Royal Society of London.

In 1888 Lippmann married the daughter of the writer V. Cherbuliez, member of the French Academy.

He died at sea on July 13,1921, during his return from a journey to North America as a member of a mission headed by Marshal Fayolle.

I90

Physics 1909

GUGLIELMO MARCONI CARL FERDINAND BRAUN

<< in recognition of their contributions to the development of wireless telegraphy>>

Physics 1909

Presentation Speech by the former Rector General of National Antiquities H. Hildebrand, President of the Royal Swedish Academy of Sciences

Your Majesty, Your Royal Highnesses, Ladies and Gentlemen.

Research in physics has provided us with many surprises. Discoveries which at first seemed to have but theoretical interest have often led to inventions of the greatest importance to the advancement of mankind. And if this holds good for physics in general, it is even more true in the case of research in the field of electricity.

The discoveries and inventions for which the Royal Academy of Sciences has decided to award this year's Nobel Prize for Physics, also have their origin in purely theoretical work and study. Important and epoch-making, however, as these were in their particular fields, no one could have guessed at the start that they would lead to the practical applications witnessed later.

While we are, this evening, conferring Nobel's Prize upon two of the men who have contributed most to the development of wireless telegraphy, we must first register our admiration for those great research workers, now dead, who through their brilliant and gifted work in the fields of mathematical and experimental physics, opened up the path to great practical applications. It was Faraday with his unique penetrating power of mind, who first suspected a close connection between the phenomena of light and electricity, and it was Maxwell who transformed his bold concepts and thoughts into mathematical language, and finally, it was Hertz who through his classical experiments showed that the new ideas as to the nature of electricity and light had a real basis in fact. To be sure, it was already well known before Hertz's time, that a capacitor charged with electricity can under certain circumstances discharge itself oscillatorily, that is to say, by electric currents passing to and fro. Hertz, however, was the first to demonstrate that the effects of these currents propagate themselves in space with the velocity of light, thereby producing a wave motion having all the distinguishing characteristics of light. This discovery - perhaps the greatest in the field of physics throughout the last half-century - was made in 1888. It forms the foundation, not only for modern science of electricity, but also for wireless telegraphy.

PHYSICS 1909

But it was still a great step from laboratory trials in miniature where the electrical waves could be traced over but a small number of metres, to the transmission of signals over great distances. A man was needed who was able to grasp the potentialities of the enterprise and who could overcome all the various difficulties which stood in the way of the practical realization of the idea. The carrying out of this great task was reserved for Guglielmo Marconi. Even when taking into account previous attempts at this work and the fact that the conditions and prerequisites for the feasibility of this enterprise were already given, the honour of the first trials is nevertheless due, by and large, to Marconi, and we must freely acknowledge that the first success was gained as a result of his ability to shape the whole thing into a practical, usable system, added to his inflexible energy with which he pursued his self-appointed aim.

Marconi's first experiment to transmit a signal by means of Hertzian waves was carried out in 1895. During the 14 years which have elapsed since then, wireless telegraphy has progressed without pause until it has attained the great importance it possesses today. In 1897 it was still only possible to effect a wireless communication over a distance of 14-20 km. Today, electrical waves are despatched between the old and the New World, all the larger ocean-going steamers have their own wireless telegraphy equipment on board, and every Navy of significance uses a system of wireless telegraphy. The development of a great invention seldom occurs through one individual man, and many forces have contributed to the remarkable results now achieved. Marconi's original system had its weak points. The electrical oscillations sent out from the transmitting station were relatively weak and consisted of wave-series following each other, of which the amplitude rapidly fell-so-called <<damped oscillations>>. A result of this was that the waves had a very weak effect at the receiving station, with the further result that waves from various other transmitting stations readily interfered, thus acting disturbing at the receiving station. It is due above all to the inspired work of Professor Ferdinand Braun that this unsatisfactory state of affairs was overcome. Braun made a modification in the layout of the circuit for the despatch of electrical waves so that it was possible to produce intense waves with very little damping. It was only through this that the so-called <distance telegraphy>> became possible, where the oscillations from the transmitting station, as a result of resonance, could exert the maximum possible effect upon the receiving station. The further advantage was obtained that in the main only waves of the frequency used by the transmitting station

I94

PRESENTATION

were effective at the receiving station. It is only through the introduction of these improvements that the magnificent results in the use of wireless telegraphy have been attained in recent times.

Research workers and engineers toil unceasingly on the development of wireless telegraphy. Where this development can lead, we know not. However, with the results already achieved, telegraphy over wires has been extended by this invention in the most fortunate way. Independent of fixed conductor routes and independent of space, we can produce connections between far-distant places, over far-reaching, waters and deserts. This is the magnificent practical invention which has flowered upon one of the most brilliant scientific discovery of our time!

$Guglielmo \ M \ \text{arconi}$

Wireless telegraphic communication

Nobel Lecture, December 11, 1909

The discoveries connected with the propagation of electric waves over long distances and the practical applications of telegraphy through space, which have gained for me the high honour of sharing the Nobel Prize for Physics, have been to a great extent the results of one another.

The application of electric waves to the purposes of wireless telegraphic communication between distant parts of the earth, and the experiments which I have been fortunate enough to be able to carry out on a larger scale than is attainable in ordinary laboratories, have made it possible to investigate phenomena and note results often novel and unexpected.

In my opinion many facts connected with the transmission of electric waves over great distances still await a satisfactory explanation, and I hope to be able in this lecture to refer to some observations, which appear to require the attention of physicists.

In sketching the history of my association with radiotelegraphy, I might mention that I never studied physics or electrotechnics in the regular manner, although as a boy I was deeply interested in those subjects.

I did, however, attend one course of lectures on physics under the late Professor Rosa at Livorno, and I was, I think I might say, fairly well acquainted with the publications of that time dealing with scientific subjects including the works of Hertz, Branly, and Righi.

At my home near Bologna, in Italy, I commenced early in 1895 to carry out tests and experiments with the object of determining whether it would be possible by means of Hertzian waves to transmit to a distance telegraphic signs and symbols without the aid of connecting wires.

After a few preliminary experiments with Hertzian waves I became very soon convinced, that if these waves or similar waves could be reliably transmitted and received over considerable distances a new system of communication would become available possessing enormous advantages over flashlights and optical methods, which are so much dependent for their success on the clearness of the atmosphere.

My first tests were carried out with an ordinary Hertz oscillator and a

Branly coherer as detector, but I soon found out that the Branly coherer was far too erratic and unreliable for practical work.

After some experiments I found that a coherer constructed as shown in Fig. I, and consisting of nickel and silver filings placed in a small gap between two silver plugs in a tube, was remarkably sensitive and reliable. This improvement together with the inclusion of the coherer in a circuit tuned to the wavelength of the transmitted radiation, allowed me to gradually extend up to about a mile the distance at which I could affect the receiver.



Fig. 1.

Another, now well-known, arrangement which I adopted was to place the coherer in a circuit containing a voltaic cell and a sensitive telegraph relay actuating another circuit, which worked a tapper or trembler and a recording instrument. By means of a Morse telegraphic key placed in one of the circuits of the oscillator or transmitter it was possible to emit long or short successions of electric waves, which would affect the receiver at a distance and accurately reproduce the telegraphic signs transmitted through space by the oscillator.

With such apparatus I was able to telegraph up to a distance of about half a mile.

Some further improvements were obtained by using reflectors with both the transmitters and receivers, the transmitter being in this case a Righi oscillator.

This arrangement made it possible to send signals in one definite direction, but was inoperative if hills or any large obstacle happened to intervene between the transmitter and receiver.

In August 1895 I discovered a new arrangement which not only greatly increased the distance over which I could communicate, but also seemed to make the transmission independent from the effects of intervening obstacles.

This arrangement (Figs.2 and 3) consisted in connecting one terminal of the Hertzian oscillator, or spark producer, to earth and the other terminal to a wire or capacity area placed at a height above the ground, and in also connecting at the receiving end one terminal of the coherer to earth and the other to an elevated conductor.



I then began to examine the relation between the distance at which the transmitter could affect the receiver and the elevation of the capacity areas above the earth, and I very soon definitely ascertained that the higher the wires or capacity areas, the greater the distance over which it was possible to telegraph.

Thus I found that when using cubes of tin of about 30 cm side as elevated conductors or capacities, placed at the top of poles 2 meters high, I could receive signals at 30 meters distance, and when placed on poles 4 meters high, at 100 meters, and at 8 meters high at 400 meters. With larger cubes 100 cm side, fixed at a height of 8 meters, signals could be transmitted 2,400 meters all round.1

These experiments were continued in England, where in September 1896 a distance of 1 3/4miles was obtained in tests carried out for the British Government at Salisbury. The distance of communication was extended to 4 miles in March 1897, and in May of the same year to 9 miles. Tape messages obtained during these tests, signed by the British Government Officers who were present, are exhibited.²

In all these experiments a very small amount of electrical power was used,

the high tension current being produced by an ordinary Rhumkorff coil.

The results obtained attracted a good deal of public attention at the time, such distances of communication being considered remarkable.

As I have explained, the main feature in my system consisted in the use of elevated capacity areas or antennae attached to one pole of the high frequency oscillators and receivers, the other pole of which was earthed.

The practical value of this innovation was not understood by many physicists³ for quite a considerable period, and the results which I obtained were by many erroneously considered simply due to efficiency in details of construction of the receiver, and to the employment of a large amount of energy.

Others did not overlook the fact that a radical change had been introduced by making these elevated capacities and the earth form part of the high frequency oscillators and receivers.

Prof. Ascoli of Rome gave a very interesting theory of the mode of operation of my transmitters and receivers in the *Elettricista* (Rome) issue of August 1897, in which he correctly attributed the results obtained to the use of elevated wires or antennae.

Prof. A. Slaby of Charlottenburg, after witnessing my tests in England in 1897, came to somewhat similar conclusions.4

Many technical writers have stated that an elevated capacity at the top of the vertical wire is unnecessary.

This is true if the length or height of the wire is made sufficiently great, but as this height may be much smaller for a given distance if a capacity area is used, it is more economical to use such capacities, which now usually consist of a number of wires spreading out from the top of the vertical conductor.

The necessity or utility of the earth connection has been sometimes questioned, but in my opinion no practical system of wireless telegraphy exists where the instruments are not connected to earth.

By <<connected to earth>> I do not necessarily mean an ordinary metallic connection as used for ordinary wire telegraphs.

The earth wire may have a condenser in series with it, or it may be connected to what is really equivalent, a capacity area placed close to the surface of the ground (Fig. 4).

It is now perfectly well known that a condenser, if large enough, does not prevent the passage of high frequency oscillations, and therefore in these cases the earth is for all practical purposes connected to the antennae.



After numerous tests and demonstrations in Italy and England over distances varying up to 40 miles, communication was established for the first time across the English Channel between England and France⁵ in March 1899 (Fig.5).



Fig.5.

From the beginning of 1898 I had practically abandoned the system of connection shown in Fig.2, and instead of joining the coherer or detector directly to the aerial and earth, I connected it between the ends of the secondary of a suitable oscillation transformer containing a condenser and tuned to the period of the electrical waves received. The primary of this oscillation transformer was connected to the elevated wire and to earth (See Fig. 6.)



Fig.6.

This arrangement allowed of a certain degree of syntony, as by varying the period of oscillation of the transmitting antennae, it was possible to send messages to a tuned receiver without interfering with others differently syntonized.⁶

As is now well known, a transmitter consisting of a vertical wire discharging through a spark gap is not a very persistent oscillator, the radiation it produces being considerably damped. Its electrical capacity is comparatively so small and its capability of radiating energy so large, that the oscillations decrease or die off with rapidity. In this case receivers or resonators of a considerably different period or pitch are likely to be affected by it.

Early in 1899 I was able to improve the resonance effects obtainable by increasing the capacity of the elevated wires by placing adjacently to them earthed conductors, and inserting in series with the aerials suitable inductance coils.7

By these means the energy-storing capacity of the aerial was increased,

whilst its capability to radiate was decreased, with the result that the energy set in motion by the discharge formed a train or succession of feebly damped oscillations.

A modification of this arrangement, by which excellent results were obtamed, is shown in Fig.7.



Fig.7.

In 1900 I constructed and patented a complete system of transmitters and receivers* which consisted of the usual kind of elevated capacity area and earth connection, but these were inductively coupled to an oscillation circuit containing a condenser, an inductance, and a spark gap or detector, the conditions which I found essential for efficiency being that the periods of electrical oscillation of the elevated wire or conductor should be in tune or resonance with that of the condenser circuit, and that the two circuits of the receiver should be in electrical resonance with those of the transmitter (Fig.8).

The circuits consisting of the oscillating circuit and the radiating circuit were more or less closely <<coupled>> by varying the distance between them.



- -0. - .

By the adjustment of the inductance inserted in the elevated conductor and by the variation of capacity of the condenser circuit, the two circuits were brought into resonance, a condition which, as I have said, I found essential in order to obtain efficient radiation.

Part of my work regarding the utilization of condenser circuits in association with the radiating antennae was carried out simultaneously to that of Prof. Braun, without, however, either of us knowing at the time anything of the contemporary work of the other.

A syntonic receiver has already been shown in Fig.6, and consists of a vertical conductor or aerial connected to earth through the primary of an oscillation transformer, the secondary circuit of which included a condenser and a detector, it being necessary that the circuit containing the aerial and the circuit containing the detector should be in electrical resonance with each other, and also in tune with the periodicity of the electric waves transmitted from the sending station.

In this manner it was possible to utilize electric waves of low decrement and cause the receiver to integrate the effect of comparatively feeble but properly timed electrical oscillations in the same way as in acoustics two tuning forks can be made to affect each other at short distances if tuned to the same period of vibration. It is also possible to couple to one sending conductor several differently tuned transmitters and to a receiving wire a number of corresponding receivers, as is shown in Figs.9 and 10, each individual receiver responding







only to the radiations of the transmitter with which it is in resonance.⁹

At the time (twelve years ago) when communication was first established by means of radiotelegraphy between England and France, much discussion and speculation took place as to whether or not wireless telegraphy would be practicable for much longer distances than those then covered, and a somewhat general opinion prevailed that the curvature of the Earth would be an insurmountable obstacle to long distance transmission, in the same way as it was, and is, an obstacle to signalling over considerable distances by means of light flashes.

Difficulties were also anticipated as to the possibility of being able to control the large amount of energy which it appeared would be necessary to cover long distances.

What often happens in pioneer work repeated itself in the case of radiotelegraphy, the anticipated obstacles or difficulties were either purely imaginary or else easily surmountable, but in their place unexpected barriers manifested themselves, and recent work has been mainly directed to the solution of problems presented by difficulties which were certainly neither expected nor anticipated when long distances were first attempted.

With regard to the presumed obstacle of the curvature of the Earth, I am of opinion that those who anticipated difficulties in consequence of the shape of our planet had not taken sufficient account of the particular effect of the earth connection to both transmitter and receiver, which earth connection introduced effects of conduction which were generally at that time overlooked.

Physicists seemed to consider for a long time that wireless telegraphy was solely dependent on the effects of free Hertzian radiation through space, and it was years before the probable effect of the conductivity of the Earth between the stations was satisfactorily considered or discussed.

Lord Rayleigh, in referring to transatlantic telegraphy, stated in May 1903 : << The remarkable success of Marconi in signalling across the Atlantic



Fig.11.

1909 G.MARCONI

suggests a more decided bending or diffraction of the waves round the perturberant Earth than had been expected, and it imparts a great interest to the theoretical problem¹⁰.

Prof. J. A. Fleming,in his book on *The Principles of Electric Wave Telegraphy*¹¹, gives diagrams showing what is now believed to be the diagrammatic representation of the detachment of semi-loops of electric strain from a simple vertical wire (Fig.11). As will be seen, these waves do not propagate in the same manner as free radiation from a classical Hertzian oscillator, but glide along the surface of the Earth.

Prof. Fleming further states in the above quoted work :

<<The view we here take is that the ends of the semi-loops of electric force, which terminate perpendicularly on the Earth, cannot move along unless there are movements of electrons in the Earth corresponding to the wave-motions above it. From the point of view of the electronic theory of electricity, every line of electric force in the ether must be either a closed line or its ends must terminate on electrons of opposite sign. If the end of a line of strain abuts on the Earth and moves, there must be atom-to-atom exchange of electrons, or movements of electrons in it. We have many reasons for concluding that the substances we call conductors are those in which free movements of electrons can take place. Hence the movements of the semi-loops of electric force outwards from an earthed oscillator or Marconi aerial is hindered by bad conductivity on the surface of the Earth and facilitated over the surface of a fairly good electrolyte, such as sea-water.>>

Prof. Zenneck¹² has carefully examined the effect of earthed transmitting and receiving aerials, and has endeavoured to show mathematically that when the lines of electrical force, constituting a wave front, pass along a surface of low specific inductive capacity, such as the Earth, they become inclined forward, their lower ends being retarded by the resistance of the conductor to which they are attached.

It therefore seems well established that wireless telegraphy, as practised at the present day, is dependent for its operation over long distances on the conductivity of the Earth, and that the difference in conductivity between the surface of the sea and land is sufficient to explain the increased distance obtamable with the same amount of energy in communicating over sea as compared to over land.

I carried out some tests between a shore station and a ship at Poole, in England, in 1902, for the purpose of obtaining some data on this point, and I noticed that at equal distances a perceptible diminution in the energy of the

received waves always occurred when the ship was in such a position as to allow a low spit of sand about I kilometer broad to intervene between it and the land station.

I therefore believe that there was some foundation for the statement so often criticized which I made in my first English Patent of June 2, 1896 to the effect that when transmitting through the earth or water I connected one end of the transmitter and one end of the receiver to earth.

In January 1901 some successful experiments's were carried out between two points on the South Coast of England 186 miles apart, i.e. St. Catherines' Point (Isle of Wight) and The Lizard in Cornwall (Fig. 12).



Fig.12.

The total height of these stations above sea level did not exceed 100 meters, whereas to clear the curvature of the Earth a height of more than 1,600 meters at each end would have been necessary.

The results obtained from these tests, which at the time constituted a record distance, seemed to indicate that electric waves produced in the manner I had adopted would most probably be able to make their way round the curvature of the Earth, and that therefore even at great distances, such as those dividing America from Europe, the factor of the Earth's curvature would not constitute an insurmountable barrier to the extension of telegraphy through space.

The belief that the curvature of the Earth would not stop the propagation of the waves, and the success obtained by syntonic methods in preventing mutual interference, led me in 1900 to decide to attempt the experiment of testing whether or not it would be possible to detect electric waves over a

1909 G.MARCONI

distance of 4,000 kilometers, which, if successful, would immediately prove the possibility of telegraphing without wires between Europe and America.

The experiment was in my opinion of great importance from a scientific point of view, and I was convinced that the discovery of the possibility to transmit electric waves across the Atlantic Ocean, and the exact knowledge of the real conditions under which telegraphy over such distances could be carried out, would do much to improve our understanding of the phenomena connected with wireless transmission.

The transmitter erected at Poldhu, on the coast of Cornwall, was similar in principle to the one I have already referred to, but on a very much larger scale than anything previously attempted.¹⁴

The power of the generating plant was about 25 kilowatts.

Numerous difficulties were encountered in producing and controlling for the first time electrical oscillations of such power. In much of the work I obtained valuable assistance from Prof. J. A. Fleming, Mr. R. N. Vyvyan, and Mr. W. S. Entwistle.

My previous tests had convinced me that when endeavouring to extend the distance of communication, it was not merely sufficient to augment the power of the electrical energy of the sender, but that it was also necessary to increase the area or height of the transmitting and receiving elevated conductors.

As it would have been too expensive to employ vertical wires of great height, I decided to increase their number and capacity, which seemed likely to make possible the efficient utilization of large amounts of energy.



Fig.13.

The arrangement of transmitting antennae which was used at Poldhu is shown in Fig. 13, and consisted of a fan-like arrangement of wires supported by an insulated stay between masts only 48 meters high and 60 meters apart. These wires converged together at the lower end and were connected to the transmitting apparatus contained in a building.

For the purpose of the test a powerful station had been erected at Cape Cod, near New York, but the completion of the arrangements at that station were delayed in consequence of a storm which destroyed the masts and antennae.

I therefore decided to try the experiments by means of a temporary receiving station erected in Newfoundland, to which country I proceeded with two assistants about the end of November 1901.

The tests were commenced early in December 1901 and on the 12th of that month the signals transmitted from England were clearly and distinctly received at the temporary station at St. John's in Newfoundland.

Confirmatory tests were carried out in February 1902 between Poldhu and a receiving station on the S.S. <<Philadelphia>> of the American Line. On board this ship readable messages were received by means of a recording instrument up to a distance of 1,551 miles and test letters as far as 2,099 miles from Poldhu (Fig. 14).

The tape records obtained on the <<Philadelphia>> at the various distances were exceedingly clear and distinct, as can be seen by the specimens exhibited.

These results, although achieved with imperfect apparatus, were sufficient to convince me and my co-workers that by means of permanent stations and the employment of sufficient power it would be possible to transmit messages across the Atlantic Ocean in the same way as they were sent over much shorter distances.

The tests could not be continued in Newfoundland owing to the hostility of a cable company, which claimed all rights for telegraphy, whether wireless or otherwise, in that colony.

A result of scientific interest which I first noticed during the tests on S.S. <<Philadelphia>> and which is a most important factor in long distance radiotelegraphy, was the very marked and detrimental effect of daylight on the propagation of electric waves at great distances, the range by night being usually more than double that attainable during daytime.15

I do not think that this effect has yet been satisfactorily investigated or explained. At the time I carried out the tests I was of opinion that it might be



due to the loss of energy at the transmitter, caused by the dis-electrification of the highly' charged transmitting elevated conductor under the influence of sunlight.

I am now inclined to believe that the absorption of electric waves during the daytime is due to the electrons propagated into space by the sun, and that if these are continually falling like a shower upon the earth, in accordance with the hypothesis of Prof. Arrhenius, then that portion of the Earth's atmosphere which is facing the sun will have in it more electrons than the part which is not facing the sun, and therefore it may be less transparent to electric waves.

Sir J. J. Thomson has shown in an interesting paper in the *Philosophical Magazine* that if electrons are distributed in a space traversed by electric waves, these will tend to move the electrons in the direction of the wave, and will therefore absorb some of the energy of the wave. Hence, as Prof. Fleming has pointed out in his Cantor Lectures delivered at the Society of Arts, a medium through which electrons or ions are distributed acts as a slightly turbid medium to long electric waves.16

Apparently the length of wave and amplitude of the electrical oscillations have much to do with this interesting phenomenon, long waves and small amplitudes being subject to the effect of daylight to a much lesser degree than short waves and large amplitudes.

According to Prof. Fleming¹⁷ the daylight effect should be more marked on long waves, but this has not been my experience. Indeed, in some very recent experiments in which waves of about 8,000 meters long were used, the energy received by day was usually greater than at night.

The fact remains, however, that for comparatively short waves, such as are used for ship communication, clear sunlight and blue skies, though transparent to light, act as a kind of fog to these waves. Hence the weather conditions prevailing in England, and perhaps in this country, are usually suitable for wireless telegraphy.

During the year 1902 I carried out some further tests between the station at Poldhu and a receiving installation erected on the Italian Cruiser <<Carlo Alberto>>, kindly placed at my disposal by H.M. The King of Italy. (See Fig. 15.¹⁸)

During these experiments the interesting fact was observed that, even when using waves as short as 1,000 feet, intervening ranges of mountains, such as the Alps or Pyrenees, did not, during the night time, bring about any considerable reduction in the distance over which it was possible to communicate. During daytime, unless much longer waves and more power were used, intervening mountains greatly reduced the apparent range of the transmitter.

Messages and press despatches of considerable length were received from



Fig.15.

Poldhu at the positions marked on the map, which map is a copy, on a reduced scale, of the one accompanying the official report of the experiments (Fig.16).

With the active encouragement and financial assistance of the Canadian Government, a high power station was constructed at Glace Bay, Nova Scotia, in order that I should be able to continue my long-distance tests with a view to establishing radiotelegraphic communication on a commercial basis between England and America.¹⁹

On December 16, 1902 the first official messages were exchanged at night across the Atlantic, between the stations at Poldhu and Glace Bay (Figs. 17 and 18).

Further tests were shortly afterwards carried out with another long-distance station at Cape Cod in the United States of America, and under favourable circumstances it was found possible to transmit messages to Poldhu 3,000 miles away with an expenditure of electrical energy of only about 10 kilowatts.

In the spring of 1903 the transmission of press messages by radiotelegraphy from America to Europe was attempted, and for a time the London *Times* published, during the latter part of March and the early part of April of that year, news messages from its New York correspondent sent across the Atlantic without the aid of cables. A breakdown in the insulation of the apparatus at Glace Bay made it necessary, however, to suspend the service and unfortunately further accidents made the transmission of messages uncertain and unreliable.

As a result of the data and experience gained by these and other tests which I carried out for the British Government, between England and Gibraltar, I was able to erect a new station at Clifden in Ireland, and enlarge the one at Glace Bay in Canada, so as to enable me to initiate, in October 1907, communication for commercial purposes across the Atlantic between England and Canada.

Although the stations at Clifden and Glace Bay had to be put into operation before they were altogether complete, nevertheless communication across the Atlantic by radiotelegraphy never suffered any serious interruption during nearly two years, until, in consequence of a fire at Glace Bay this autumn, it has had to be suspended for three or four months.

This suspension has not, however, been altogether an unmitigated evil, as



Fig.16.



Fig.17.

it has given me the opportunity of installing more efficient and up-to-date machinery.

The arrangements of elevated conductors or aerials which I have tried²⁰ during my long-distance tests, are shown in Figs. 19, 20 and 21.

The aerial shown in Fig.21 consisted of a nearly vertical portion in the middle, 220 feet high, supported by four towers, and attached at the top to nearly horizontal wires, 200 in number and each 1,000 feet long, extending radially all round and supported at a height of 180 feet from the ground by an inner circle of 8, and an outer circle of 16 masts.

The natural period of oscillation of this aerial system gave a wavelength of 12,000 feet. Experiments were made with this arrangement in 1905 and with

a wavelength of 12,000 feet, signals, although very weak, could be received across the Atlantic by day as well as by night.

The system of aerial I finally adopted for the long-distance stations in England and Canada is shown in Fig. 22. This arrangement not only makes it possible to efficiently radiate and receive waves of any desired length, but it also tends to confine the main portion of the radiation to a given direction. The limitation of transmission to one direction is not very sharply defined, but the results obtained with this type of aerial are nevertheless exceedingly useful.

Many suggestions respecting methods for limiting the direction of radiating have been made by various workers, notable by Prof. F. Braun, Prof. Artom, and Messrs. Belhni and Tosi.

In a paper read before the Royal Society of London²¹ in March 1906 I showed how it was possible by means of horizontal aerials to confine the emitted radiations mainly to the direction of their vertical plane, pointing away from their earthed end.

In a similar manner it is possible to locate the bearing or direction of a sending station.

The transmitting circuits at the long-distance stations are arranged in ac-



Fig.18.



Fig.22.

cordance with a comparatively recent system for producing continuous or slightly damped oscillations, which I referred to in a lecture before the Royal Institution of Great Britain on March 13, 1908.

An insulated metal disc A (see Fig.23) is caused to rotate at a high rate of speed by means of an electric motor or steam turbine. Adjacent to this disc, which I will call the middle disc, are placed two other discs C' and C" which may be called polar discs, and which are also revolved. These polar discs have their peripheries very close to the surface or edges of the middle disc. The two polar discs are connected by rubbing contacts to the outer ends of two condensers K, joined in series, and these condensers are also connected through suitable brushes to the terminals of a generator which should be a high-tension continuous-current generator.

On the middle disc a suitable brush or rubbing contact is provided and between this contact and the middle point of the two condensers an oscillating circuit is inserted, consisting of a condenser E in series with an inductance, which last is inductively connected with the radiating antennae. The apparatus works probably in the following manner:

The generator charges the double condenser, making the potential of the discs, say C' positive and C" negative. The potential, if high enough will cause a discharge to pass across one of the gaps, say between C' and A. This charges the condenser E through the inductance F, and starts oscillations in the circuit. The charge of F in swinging back will jump from A to C", the potential of which is of opposite sign to A, the dielectric strength between C' and A having meanwhile been restored by the rapid motion of the disc, driving away the ionized air.



Fig.23.

The condenser E therefore discharges and recharges alternatively in reverse directions, the same process going on so long as energy is supplied to the condensers K by the generator H.

It is clear that the discharges between C' and C" and A are never simultaneous as otherwise the centre electrode would not be alternatively positive and negative.

The best results have, however, been obtained by an arrangement as shown in Fig. 24, in which the active surface of the middle disc is not smooth, but consists of a number of regularly spaced copper knobs or pegs, at the ends of which the discharges take place at regular intervals. Thave found that with this arrangement each tram of oscillations may have a decrement as low as 0.02.


Fig.24.

In this way it is also possible to cause the groups of oscillations radiated to reproduce a high and clear musical note in a receiver, thereby making it easy to differentiate between the signals emanating from the sending station and noises caused by atmospheric electrical discharges. By this method very efficient resonance can be also obtained in appropriately designed receivers.

With regard to the receivers employed, important changes have taken place. By far the larger portion of electric wave telegraphy was, until a few years ago, conducted by means of some form or other of coherer, or variable contact either requiring tapping or else self-restoring.

At the present day, however, I may say that at all the stations controlled by my Company my *magnetic receiver* (Fig.25) is almost exclusively employed.22

This receiver is based on the decrease of magnetic hysteresis which occurs



in iron when under certain conditions this metal is subjected to the effects of electrical waves of high frequency.

It has recently been found possible to increase the sensitiveness of these receivers, and to employ them in connection with a high-speed relay, so as to record messages at great speed.

A remarkable fact, not generally known, in regard to transmitters is, that none of the arrangements employing condensers exceed in efficiency the plain elevated aerial or vertical wire discharging to Earth through a spark gap, as used in my first experiments (see Figs.2 and 3).

I have also recently been able to confirm the statement made by Prof. Fleming *in* his book *The Principles* of Electric *Wave Telegraphy*, 1906, page 555, that with a power of 8 watts in the aerial it is possible to communicate to distances of over 100 miles.

I have also found that by this method, when using large aerials, it is possible to send signals 2,000 miles across the Atlantic, with a smaller expenditure of energy than by any other method known to myself.

The only drawback to this arrangement is, that unless very large aerials are used, the amount of energy which can be efficiently employed is limited by the potential beyond which brush discharges and the resistance of the spark gap begin to dissipate a large proportion of the energy.

By means of spark gaps in compressed air and the addition of inductance coils placed between the aerial and earth, the system can be made to radiate very pure and slightly damped waves, eminently suitable for sharp tuning.

In regard to the general working of wireless telegraphy, the widespread application of the system and the multiplicity of the stations have greatly facilitated the observation of facts not easily explainable.

Thus it has been observed that an ordinary ship station, utilizing about 1/2 kilowatt of electrical energy, the normal range of which is not greater than 200 miles, will occasionally transmit messages across a distance of over 1,200 miles. It often occurs that a ship fails to communicate with a nearby station, but can correspond with perfect ease with a distant one.

On many occasions last winter, the S.S. <<Caronia>> of the Cunard Line, carrying a station utilizing about 1/2 kilowatt, when in the Mediterranean, off the coast of Sicily, failed to obtain communication with the Italian stations, but had no difficulty whatsoever in transmitting and receiving messages to and from the coasts of England and Holland, although these latter stations were considerably more than 1,000 miles away, and a large part of the continent of Europe and the Alps lay between them and the ship.

1909 G.MARCONI

Although high power stations are now used for communicating across the Atlantic, and messages can be sent by day as well as by night, there still exist short periods of daily occurrence, during which transmission from England to America, or vice versa, is difficult. Thus in the morning and evening, when in consequence of the difference in longitude, daylight or darkness extends only part of the way across the ocean, the received signals are weak and sometimes cease altogether. It would almost appear as if electric waves in passing from dark space to illuminated space, and vice versa, were reflected in such a manner as to be deviated from their normal path.

It is probable that these difficulties would not be experienced in telegraphing over equal distances north and south, on about the same meridian, as in this case the passage from daylight to darkness would occur almost simultaneously over the whole distance between the two points.

Another curious result, on which hundreds of observations continued for years leave no further doubt, is that regularly, for short periods, at sunrise and sunset, and occasionally at other times, a shorter wave can be detected across the Atlantic in preference to the longer wave normally employed.

Thus at Clifden and Glace Bay when sending on an ordinary coupled circuit arranged so as to simultaneously radiate two waves, one 12,500 feet and the other 14,700 feet, although the longer wave is the one usually received at the other side of the ocean, regularly, about three hours after sunset at Clifden, and three hours before sunrise at Glace Bay, the shorter wave alone was received with remarkable strength, for a period of about one hour.

This effect occurred so regularly that the operators tuned their receivers to the shorter wave at the times mentioned, as a matter of ordinary routine.

With regard to the utility of wireless telegraphy there is no doubt that its use has become a necessity for the safety of shipping, all the principal liners and warships being already equipped, its extension to less important ships being only a matter of time, in view of the assistance it has provided in cases of danger.

Its application is also increasing as a means of communicating between outlying islands, and also for the ordinary purposes of telegraphic communication between villages and towns, especially in the colonies and in newly developed countries.

However great may be the importance of wireless telegraphy to ships and shipping, I believe it is destined to an equal position of importance in furnishing efficient and economical communication between distant parts of the world and in connecting European countries with their colonies and with

220

America. As a matter of fact, I am at the present time erecting a very large power station for the Italian Government at Coltano, for the purpose of communicating with the Italian colonies in East Africa, and with South America.

Whatever may be its present shortcomings and defects, there can be no doubt that wireless telegraphy - even over great distances - has come to stay, and will not only stay, but continue to advance.

If it should become possible to transmit waves right round the world, it may be found that the electrical energy travelling round all parts of the globe may be made to concentrate at the antipodes of the sending station. In this way it may some day be possible for messages to be sent to such distant lands by means of a very small amount of electrical energy, and therefore at a correspondingly small expense.

But I am leaving the regions of fact, and entering the regions of speculation, which, however, with the knowledge we have gradually gained on the subject, promise results both useful and instructive.

Not having the fortune of being conversant with the Swedish language, I have thought it best, although an Italian, to use the medium of the English language in delivering this address, as I know that English is more generally understood here than Italian.

- 1. G. Marconi, Brit. Patent No. 12,039, June 2, 1896.
- 2. J. Inst. Elec. Engrs. (London), 28 (1899) 278.
- 3. See letter of Dr. Lodge in The Times (London), June 22, 1897.
- 4. A. Slaby, *Die Funkentelegraphie*, Verlag von Leonhardt Simion, Berlin, 1897; see also A. Slaby, <<The New Telegraphy>>, *The* Century *Magazine*, 55 (1898) 867.
- 5. J. Inst. Elec. Engrs. (London), 28 (1899) 291.
- 6. Brit. Patent No. 12,326, June 1, 1898; Brit. Patent No. 6,982, April 1, 1899.
- 7. A. Blonde1 and G. Ferrie, <<État actuel et Progrés de la Télégraphie sans Fil>>, read at *the Congrés International d'Électricité,Paris, 1900;* see also *J. Soc. Arts,* 49 (1901) 509.
- 8. Brit. Patent No. 7,777, April 26, 1900; see also J. Soc. Arts, 49 (1901) 510-11.
- 9. See Letter of Prof. J. A. Fleming in The Timer (London), October 4, 1900.
- 10. Proc. Roy. Soc. (London), 72 (May 28, 1903).
- 11. J.A. Fleming, *The Principles of Electric Wave Telegraphy*, Longmans, Green & Co., London, 1906, p. 348.
- 12. J. Zenneck, Ann. Physik, [4], 23 (Sept. 1908) 846; Physik. Z., 9 (1908) 50, 553.
- 13. J. Soc.Arts, 49 (1901) 512.
- 14. G. Marconi, lecture before the Royal Institution of Great Britain, June 13, 1902.

1909 G.MARCONI

- 15. G. Marconi, <<A Note on the Effect of Daylight upon the Propagation of Electromagnetic Impulses>>, *Proc. Roy. Soc. (London)*, 70 (June 12, 1902).
- 16. See also J. J. Thomson, <<On Some Consequences, etc.>>, Phil. Mag., [6] 4 (1902) 253.
- 17. See Ref. 11, p. 618.
- 18. Riv. Marittima (Rome), October 1902.
- 19. G. Marconi, Paper read before the Royal Institution of Great Britain, March 3, 1905.
- 20. See also G. Marconi, Lecture before the Royal Institution of Great Britain, March 13, 1908.
- 21. G. Marconi, <<On Methods whereby the Radiation of Electric Waves may be mainly confined, etc.>>, *Proc. Roy. Soc. (London)*, A 77 (1906).
- 22. G. Marconi, <<Note on a Magnetic Detector of Electric Waves>>, Proc. Roy. Soc. (London), 70 (1902) 341.

222

Biography

Guglielmo Marconi was born at Bologna, Italy, on April 25, 1874, the second son of Giuseppe Marconi, an Italian country gentleman, and Annie Jameson, daughter of Andrew Jameson of Daphne Castle in the County Wexford, Ireland. He was educated privately at Bologna, Florence and Leghorn. Even as a boy he took a keen interest in physical and electrical science and studied the works of Maxwell, Hertz, Righi, Lodge and others. In 1895 he began laboratory experiments at his father's country estate at Pontecchio where he succeeded in sending wireless signals over a distance of one and a half miles, thus becoming the inventor of the first practical system of wireless telegraphy.

In 1896 Marconi took his apparatus to England where he was introduced to Mr. (later Sir) William Preece, Engineer-in-Chief of the Post Office, and later that year was granted the world's first patent for a system of wireless telegraphy. He demonstrated his system successfully in London, on Salisbury Plain and across the Bristol Channel, and in July 1897 formed The Wireless Telegraph & Signal Company Limited (in 1900 re-named Marconi's Wireless Telegraph Company Limited). In the same year he gave a demonstration to the Italian Government at Spezia where wireless signals were sent over a distance of twelve miles. In 1899 he established wireless communication between France and England across the English Channel. He erected permanent wireless stations at The Needles, Isle of Wight, at Boumemouth and later at the Haven Hotel, Poole, Dorset.

In 1900 he took out his famous patent No. 7777 for <<tuned or syntonic telegraphy>> and, on an historic day in December 1901, determined to prove that wireless waves were not affected by the curvature of the Earth, he used his system for transmitting the first wireless signals across the Atlantic between Poldhu, Cornwall, and St. John's, Newfoundland, a distance of 2100 miles.

Between 1902 and 1912 he patented several new inventions. In 1902, during a voyage in the American liner <<Philadelphia>>, he first demonstrated <<daylight effect>> relative to wireless communication and in the same year patented his magnetic detector which then became the standard wireless re-

1909 G.MARCONI

ceiver for many years. In December 1902 he transmitted the first complete messages to Poldhu from stations at Glace Bay, Nova Scotia, and later Cape Cod, Massachusetts, these early tests culminating in 1907 in the opening of the first transatlantic commercial service between Glace Bay and Clifden, Ireland, after the first shorter-distance public service of wireless telegraphy had been established between Bari in Italy and Avidari in Montenegro. In 1905 he patented his horizontal directional aerial and in 1912 a <<ti>timed spark>> system for generating continuous waves.

In 1914 he was commissioned in the Italian Army as a Lieutenant being later promoted to Captain, and in 1916 transferred to the Navy in the rank of Commander. He was a member of the Italian Government mission to the United States in 1917 and in 1919 was appointed Italian plenipotentiary delegate to the Paris Peace Conference. He was awarded the Italian Military Medal in 1919 in recognition of his war service.

During his war service in Italy he returned to his investigation of short waves, which he had used in his first experiments. After further tests by his collaborators in England, an intensive series of trials was conducted in 1923 between experimental installations at the Poldhu Station and in Marconi's yacht <<Elettra>> cruising in the Atlantic and Mediterranean, and this led to the establishment of the beam system for long distance communication. Proposals to use this system as a means of Imperial communications were accepted by the British Government and the first beam station, linking England and Canada, was opened in 1926, other stations being added the following year.

In 1931 Marconi began research into the propagation characteristics of still shorter waves, resulting in the opening in 1932 of the world's first microwave radiotelephone link between the Vatican City and the Pope's summer residence at Castel Gandolfo. Two years later at Sestri Levante he demonstrated his microwave radio beacon for ship navigation and in 1935, again in Italy, gave a practical demonstration of the principles of radar, the coming of which he had first foretold in a lecture to the American Institute of Radio Engineers in New York in 1922.

He has been the recipient of honorary doctorates of several universities and many other international honours and awards, among them the Nobel Prize for Physics, which in 1909 he shared with Professor Carl Braun, the Albert Medal of the Royal Society of Arts, the John Fritz Medal and the Kelvin Medal. He was decorated by the Tsar of Russia with the Order of St. Anne, the King of Italy created him Commander of the Order of St. Maurice and St. Lazarus, and awarded him the Grand Cross of the Order of the Crown of

BIOGRAPHY

Italy in 1902. Marconi also received the freedom of the City of Rome (1903), and was created Chevalier of the Civil Order of Savoy in 1905. Many other distinctions of this kind followed. In 1914 he was both created a Senatore in the Italian Senate and appointed Honorary Knight Grand Cross of the Royal Victorian Order in England. He received the hereditary title of Marchese in 1929.

In 1905 he married the Hon. Beatrice O'Brien, daughter of the 14th Baron Inchiquin, the marriage being annulled in 1927, in which year he married the Countess Bezzi-Scali of Rome. He had one son and two daughters by his first and one daughter by his second wife. His recreations were hunting, cycling and motoring.

Marconi died in Rome on July 20, 1937.

CARL FERDINAND BRAUN

Electrical oscillations and wireless telegraphy

Nobel Lecture, December 11, 1909

In accepting, today, the great honour and privilege of addressing the members of an Academy which though of venerable age is constantly renewed and invigorated by the contribution of fresh strength and energy, I hope for your indulgence and understanding when I conceive my task not to be that of talking about wireless telegraphy in general. I have felt it more fitting to limit myself to the narrower field of the activities in which I have been successful in taking some part in the development of the whole.

I shall ignore my experiments on the propagation of electrical waves through water which I carried out in the summer of 1898, and shall turn at once to the experiments which were described and conceived at that time as being transmission through the air.

The following should first be mentioned: Marconi, as far as I know, had begun his experiments on his father's estate in 1895, and continued them in England in 1896. His experiments in Spezia harbour were, with other ones, carried out in 1897, and a distance of 15 km was attained. In the autumn of the same year, Slaby, using much the same arrangement, reached 21 km over land but only by means of balloons to which were attached wires of 300 m in length. Why, must one ask, was it so difficult to increase the range? If the whole arrangement functioned satisfactorily over a distance of 15 km, why could not double and more the distance be attained by increasing the initial voltage, the means of doing which was available? It seemed, however, as if ever larger antennae were necessary. It was with this impression - whether the papers had correctly reported the experiments or not, I shall let pass - that I turned my attention to the subject in the autumn of 1898. I set myself the task of obtaining stronger effects from the transmitter.

If I am to give you the general thoughts and concepts which guided me I must ask you to carry yourselves back with me to the standpoint of our knowledge at that time. What facts were at our disposal and what conclusions could be drawn from them? It was known how sensitive the Hertzian oscillations were to the quality of the spark, and also that lengthening the spark led to definitely deleterious effects whereby the spark became <<iin-

ELECTRICAL OSCILLATIONS AND WIRELESS TELEGRAPHY 227

active,. Hertz had already, in his first work, called attention to the strong damping of the oscillators and compared their electrical oscillations with the ill-defined acoustic oscillations of wooden rods. Bjerknes, in 1891, had successfully measured the damping and found the logarithmic decrement (as well known the measure for damping) for a linear oscillator to be 0.26, when he used only a minute spark gap. When, however, the spark gap was increased to 5mm, the decrement rose to 0.40. This, and a series of other facts, indicated the existence of strong spark damping. All known facts became understandable if one assumed that at low capacities the spark consumed a great part of the energy, and the longer the spark was, the larger was the part of energy it consumed. On the other hand, it had long been known that the discharge of bigger capacities in the customary arcs was always oscillatory, and (in radiation-free paths) was obviously much less attenuated. In fact Feddersen had already directly photographed up to 20 half-cycles of oscillations in 1862. I took hold of this fact.

Considering the greater amounts of energy which can be collected and stored in suitable experimental form in capacitors, one could expect to deliver radiated energy for some time from them. Taken all-in-all, I concluded that if a *sparkless* antenna could be excited, from a closed Leyden-jar circuit of large capacity, into potential oscillations whose average value was that



Fig. 1.

of the initial charge in a Marconi transmitter, then one would possess a more effective transmitter. There was some doubt as to whether this could be attained. And further, it was necessary to decide, by experiments on effects at a distance, whether any disturbing factor had been overlooked in these considerations. By suitable dimensioning of the exciter circuit it was found possible to fulfil the first requirement, and comparative experiments on longdistance effects were in favour of the new arrangement.



Fig. 2.

Three circuits arose from this, which I described as inductive and direct transmitter excitation, together with a mixed circuit derived from both. In Fig. 1 is shown the direct circuit. The transmitter is earthed. In Fig.2 is shown the inductive circuit, in which Marconi's direct earthing is replaced by a <<symmetry wire>>. This name would be entirely suitable if the complete transmitter were floating in free space (e.g., in a balloon). The transmitter would then form a half-wavelength and the excitation point, which should lie at the antinode of the current, would be in the middle. Fig.2 shows how this circuit is adapted to a mobile station. The set-up is now unsymmetrical due to the proximity of earth. The symmetry wire can be shortened by loading its end with capacity. This arrangement is then known as a counterpoise. It disappears entirely if the connected capacity is infinitely large, that is to say, when the excitation point is on well-conducting earth.

ELECTRICAL OSCILLATIONS AND WIRELESS TELEGRAPHY $2\,2\,9$

By a suitable design of the Leyden-jar circuit, significantly higher voltages are attained in the transmitter than the charging voltage of the Leyden-jar circuit. There was some suspicion in my mind that large capacities with bigger spark lengths would behave in the same way as small capacities. At that time, little was known about this. The results of later experiments have, in part, contradicted each other, since other losses appearing with high voltages were overlooked. But as far as the spark resistance was concerned my fears, as M. Wien has recently shown, were without foundation. Since I wanted, however, to be prepared for every eventuality, I asked myself whether it might not still be possible to increase the power, for instance by connecting several circuits of the same frequency of oscillation into the excitation circuit of the transmitter. The difficulty was to so couple circuits of this kind together that they would all start to discharge at the same moment, for example within exactly 1/10 of a millionth of a second. This task occupied me on repeated occasions. One solution, attained in a somewhat different way and to which I was led in the course of my experiments, is given here (Fig.3). It has been described as an <<energy coupling>>. I will touch later upon the advantages possessed by this arrangement, which remain despite the results obtained by Wien.

The experiments were to be carried further under practical conditions after Easter of 1899. The choice of location for the tests fell upon Cuxhaven. In addition to the main task there was an almost overwhelming pressure of



¦W3

Fig.3,

other allied tests and problems, e.g., how does the coherer work, particularly under the practical conditions occurring? Is it a resistance or does it behave like a capacitance or both? Can it be replaced by something better-defined, and if possible, more quantitatively informative? How do nearby buildings or metal masses such as masts and stays, which play such an important part in practice, affect the antenna? And there was a further multitude of problems with respect to the particular receiving apparatus. And all these problems affected the overall solution so that they all needed to be solved nearly simultaneously. Owing to my professional duties I could devote but little time to the tests, and they were carried on by two of my assistants until the autumn of 1900. The way in which the most favourable conditions were discovered in practice by systematic methods has been described by me elsewhere.

On November 16, 1900, I gave my first public lecture on this subject to the Natural Sciences Society in Strasbourg. There I described, among other matters, the advantages offered by my circuits for tuned telegraphy, advantages which Marconi had by then also recognized. On the following February I, I demonstrated before the same Society the methods on which I had based the tuning of a receiver. I carried out more or less the same experiments before the Assembly of Research Workers in Natural Sciences in Hamburg during the autumn of the same year, as well as demonstrating the practical results on the station at Heligoland.

In the receiver, too, the most important feature was the capacitor circuit



Fig.4.

ELECTRIAL OSCILLATIONS AND WIRELESS TELEGRAPHY $2\,3\,1$

which was directly coupled to the antenna, and which, as I expressed it, collects the energy radiated towards the receiver into the best possible lossfree paths, localizes it and thus passes it onwards in the most suitable form for the detector.

By my arrangements, so-called coupled systems were introduced throughout in the wireless telegraphy system, and at this point we might briefly examine their properties. For preference I have used Oberbeck's pendulum model for illustration although it does not correspond completely to the electrical conditions. I produce it here (Fig. 4). Two pendulums of identical frequency are <<coupled>> through a loaded thread. I draw the first pendulum away from the position of rest and release it. It transmits its energy to the second pendulum and the latter increases its energy at the cost of the first, exciting pendulum. After some time the whole of the energy appears in the second pendulum. At this point, however, the process repeats itself in the opposite sequence. If I make the first pendulum heavy and the second one light, I can make the oscillation amplitude of the second greater than that of the first. The first pendulum represents the Leyden-jar circuit, the second the transmitter to which-in this case - the whole of the energy of the Leyden-jar circuit is passed. According to the ratio of the capacities the voltage can be amplified (or, if desired, reduced).

Now Oberbeck in 1895 demonstrated the following by calculation. If a capacitor circuit is allowed to operate inductively upon a second circuit of the *same* natural frequency there appear - most strikingly - *two* oscillations in both circuits, one higher and one lower than the natural frequency of oscillation. The closer the coupling, i.e., the quicker the energy transference from the first to the second circuit becomes the further apart lie the frequencies. Only for the case of infinitely loose coupling do the two oscillations approximate to the natural frequency, that is to say, become equal to each other.

This result holds also for mechanical systems, which includes our pendulums. If our two equally-tuned pendulums are coupled, then each should exhibit *two* different frequencies of oscillation. The result loses its surprise, when the phenomenon, I would like to say, is not treated mathematically but actually takes place before our eyes. The characteristic is this : the oscillations of the second pendulum increase steadily from zero upwards, then again decrease, and vice versa. We note from each pendulum what is known in acoustics as <
beating>>. I shall recall now a method of representing graphically the acoustic beating (Fig.5). An oscillating tuning fork carries a glass



Fig. 6.

, MMMMMMM · MMMMMMM

Fig.7.

plate covered in soot (carbon black). A second tuning fork writes upon this oscillating glass plate by means of a small pin whilst it itself is drawn across the plate. One tuning fork would describe a curve of constant amplitude (Fig.6). The oscillations of both forks are added algebraically. And when both forks have different frequencies, as is here the case, a curve as in Fig. 7 results.

I shall call them briefly <
beating (or pulsating) oscillations>>. Just such curves would arise if we allowed our *pendulum* to write upon a moving plate. If the exciting pendulum gave the upper curve, a, then the excited pendulum would give the lower curve, *b*.

Each *such* beating oscillation can be considered - from the elementary laws of trigonometry - as arising from the superposition of two harmonic oscillations of different frequency, say n_1 and n_2 .

Although this is mathematically possible, however, experience teaches us that if this pulsating oscillation is applied to a structure capable of oscillation whose natural frequency fits in with one or other of the frequencies n_1 or n_2 , then it will be excited in its own natural frequency of oscillation. It selects one of the fictitious harmonic components and endows it thereby with an independent existence. A body so excited is called a resonator, and the phenomenon itself is known as resonance.

The thing is clear to the mind in the case of the tuning fork example. In space we would observe the beats, but resonators would separate the two tuning-fork tones. The application to our pendulum model is also obvious. Each part of the system performs pulsating oscillations, resonators react to two different harmonic oscillations.* If we wish (and here I return to the electrical example), to record, by means of resonators, oscillations from the radiation sent into space by the antenna, then we have to adjust the resonator to one of the two oscillations.

These electrical oscillations can be separated by means of a variable capacitor circuit, the so-called resonance Leyden-jar circuit (to which I will return later), *so long us cure is taken* that as far as possible the circuit has no feed-back into the system being investigated. Oberbeck's result was concerned with the case where both system components had closed current circuits (with quasi-stationary flow) and were inductively coupled. It can now be easily

* If time allowed, I would be able to demonstrate both these oscillations <<analytically>> by means of the pendulum model. This second model, introduced by Dr. Mandelstam, and representing direct coupling through its correct mechanical analogue, allows every detail to be recognized.

shown that both oscillations also exist in the open current path of an antenna, whether it is excited directly or inductively (I am ignoring higher harmonics).

In the summer of 1902 I was able to erect two experimental stations on two forts at Strasbourg for the purpose of closer study. The task which I had set for us was to determine the most favourable conditions in the receiver. We adopted the resonant circuit, in which known capacitances were combined with calculated self-inductances, so as to bring both parts of the transmitter system into the same natural frequency of oscillation. We fixed likewise the two oscillations arising from the coupling and searched for these with the receiver. The result of the test was, for that time, surprising, as an example will show. If, by means of a coil in the receiver circuit, the oscillations were transferred inductively into a second coil located in a tuned circuit containing the indicator (parallel to a small capacitor), not only was the sharpness of the resonance but also - and here was the surprise - the intensity of the excitation was raised as soon as the two coils were moved away from one another. The intensity increased with increasing distance between the coils, though naturally beyond a certain limit there was again a decrease. Described in the customary expression, the effectiveness increased with looser coupling. This result in the receiver was not subject to a similar loose coupling in the transmitter.

There were two important results from these experiments : (a) greater freedom from disturbance in the receiver; and (b) a valuable measuring instrument for wireless engineering. When Dr. Franke of Siemens & Halske (who were working with us) saw the tests he proposed to base technicallyuseable equipment on them. Until then the resonance circuit had been assembled from existing parts to suit the particular requirements, and from whatever came to hand. Through the combination of a Köpsel's calibrated variable rotating capacitor and a number of calculated self-inductances, an apparatus was constructed which covered a large range of wavelengths both conveniently and continuously. The <<current effect>> was measured by means of a Riess's air thermometer which I had long used for intensity measurements of oscillations. The technical preparation fell to Mr.Dönitz. So arose the wave-meter, described by him and generally named after him, an apparatus which, using the theory already developed by Bjerknes in 1891, permitted simultaneously the dumping or attenuation of electrical waves to be measured, a quantity whose numerical value was ever more needed. There are other wave-meters with open current paths; these are simpler, but despite this the closed-circuit apparatus has because of its other advantages held the field.

ELECTRICAL OSCILLATIONS AND WIRELESS TELEGRAPHY $2\,3\,5$

By means of this instrument the foundation of measuring techniques for wireless telegraphy were laid. It soon displaced our cumbersome laboratory equipment and gave us great help in our scientific investigations, whilst it became indispensible for rational technical work in the field of electrical oscillations.

In the summer of 1902 came the publication of a theoretical study of the coupled transmitter by Max Wien. This particularly concerned the effect of damping. Wien showed by calculation the versatility of the coupled transmitter. He summed up the qualitative results of his work as follows: <<According to the kind of coupling, a powerful but quickly attenuated excitation can be attained which reaches far into the distance, or alternatively a slowly decreasing wave-train which is capable of exciting a similarly-tuned resonator while passing all others by - a cannon shot to be heard afar, or a soft, slowly declining tuning-fork tone>>.

This theoretical investigation was most effective in clarifying the problem basically, and it will remain the foundation. It remains to be seen, however, how closely the data chosen for the numerical examples correspond to actual practice. Some calculated figures and a few laboratory figures were all that were available on the subject of damping. The field of measurements in relation to practice was beginning to be opened up. From then on, the work spread further and further outwards, branching into that of the scientific laboratories on the one hand, and the conversion of their results into practice with its complicated conditions and extensive requirements on the other. Success in the latter connection is due to Count Arco and Mr.Rendahl.

The circumstances which led me, more than ten years ago, to introduce the capacitor circuit, have altered greatly in the meantime. The Leyden-jar circuit is still to-day indispensible in wireless telegraphy. Two properties should be mentioned which I have not yet touched upon:

(I) For equal powers it is easier to design an inductor for use with high charging capacities and low voltages than vice versa. This was a determining factor at the time for the energy circuit mentioned earlier and remained so for this set-up.

(2) Insulation difficulties are practically non-existent in the Leyden-jar circuit, but the contrary is the case in the antenna circuit. If, for example, the insulators in a coupled transmitter are damp, the transmitter still works, whilst it can become impossible to charge it statically or with low frequency.

I illustrated the latter point in my lecture in November of 1900 by means of the following experiment. I allowed the transmitter to operate inductively upon a neighbouring receiver and so produced current in the latter which

brightly lit up an incandescent bulb. I touched the transmitter wire with a moist binding thread which was connected to earth. This had no effect on the operation in the case of the coupled transmitter, but the transmitter with direct inductor charging could not be operated once the damp thread was placed in contact with it.

Before I leave the subject of the coupled system I might perhaps recall an accessory which was of great use to me and other experimenters. I mean the cathode-ray tube which I described in 1897. It provided a visual picture of current- and voltage-waveforms up to 100kc/s, and was the means by which investigations of period, waveform, intensity and thereby damping, as well as relative phases, could be made.

One of the first applications of this tube was Knut Ångström's neat method of showing directly the hysteresis curve. In a similar way, the permeability of iron up to 130kc/s was investigated at the Strasbourg Institute, and a number of other problems concerned with electrical oscillations were also studied.

Three oscillograms made with the tube will serve to show its application. They illustrate the primary current pattern in the inductor, which interests us, and the significance of the capacitor therein.



Fig.8.

In Fig.8 the primary current in the non-capacitative circuit falls away relatively slowly when the circuit is broken. On the other hand, if a capacitor (Fig.9) is switched in, *oscillations* occur on breaking the circuit. The current falls much more steeply and by nearly twice the value. The secondary coil was open. If this coil circuit is closed (Fig. 10), the oscillations are faster and are attenuated more strongly.

Many applications of the tube are given in Zenneck's well-known book.

236

ELECTRICAL OSCILLATIONS AND WIRELESS TELEGRAPHY 237

I will show you now only the current oscillations in two coupled (but strongly damped) capacitor circuits. You will see that the tubes do in fact show actual beating or pulsating oscillations (Fig.11).

In still another place, wireless telegraphy brought me into contact with earlier investigations which I had made, this time in connection with work in my youth. I found in 1874 that materials such as galena, pyrite, pyrolusite,



Fig. g.



Fig. 10.



Fig. II.

tetrahedrite, etc., departed from Ohm's Law, particularly when an electrode made contact over a small surface area. These materials greatly interested me since they conduct without electrolysis although they are binary compounds. The resistance appeared to be dependent upon the direction and intensity of the current and I could, for instance, separate the opening and closing currents of a small inductor by means of such materials, in a similar way to that of a Geisler's tube. I did not succeed in finding an <<explanation>> for the phenomena, for instance to what material unsymmetry the electrical unsymmetries (which without doubt existed) corresponded. I had to content myself with showing that the observed phenomena were not brought about through secondary effects such as heating. I was able to demonstrate that it appeared - at least qualitatively - even in 1/500 second, and I was convinced that - perhaps at the furthest limits - an inertialess process was concerned, a view which was supported by E. Cohn whilst carrying out some other experiments, when he found that the unsymmetrical d.c. resistance could follow current oscillations of 25kc/s. But always there remained with me a feeling of dissatisfaction, and with it, a faint memory which had obviously never died, but remained half-somnolent at the back of my mind. Instinctively I was driven back to this valve effect (with which I had repeatedly, though in vain, attempted to obtain direct current from oscillations of light) when I began to occupy myself with wireless telegraphy in 1898. The elements showed the expected detector effect, but at that time offered no advantages over the coherer. As the swing to aural reception of messages took place, I came back to these materials, and recognized their usefulness for this purpose in 1901. In 1905 the Gesellschaft für drahtloseTelegraphie (Wireless Telegraphy Co.) decided, on my recommendation, to start up a technical project in this sphere of activity. Today, these detectors - including other combinations of a similar nature - are extensively used. Pierce, by means of the cathode-ray tube, has demonstrated for slow oscillations an almost complete separation of positive and negative current components in the case of molybdenite. It seems to me that it is still an open question whether this will hold also for rapid oscillations.

I will turn now to another series of experiments.

It had always seemed most desirable to me to transmit the waves, in the main, in one direction only. I will not concern myself with the successful experiments of this kind made at the Strasbourg Forts in 1901, since it came out later that similar proposals had already been made by others.

ELECTRICAL OSCILLATIONS AND WIRELESS TELEGRAPHY 239

I found in 1902 that an antenna, inclined at somewhat less than 10° to the horizon, formed a kind of directional receiver. The receptivity showed a clearly defined maximum for waves passing through the vertical plane in which the antenna was situated. The results were published in March of 1903.

A directional transmitter is made up in the following way (Fig.12). It is assumed that the antennae A and B, located at comers of an equilateral triangle, are equal in phase, but are *delayed* by a quarter of a cycle of oscillation relative to antenna C, which is in the third comer. The height CD of the triangle is to be a quarter wavelength. The radiation will then prefer the direction CD. The wave emanating from C will reach AB at the moment that A and B start to oscillate.



The task arose to attain this kind of phase difference for rapid oscillations, and prior to this, to measure such differences. A measuring method came easily to hand, one which has also proved itself in practical experiments. The solution of the other task did not go well using the scheme which I had thought out. On the other hand, two of my assistants found an ingenious solution when they took up the work, at my suggestion, in the Strasbourg Institute. Experiments were carried out on a big parade-ground in the vicinity of Strasbourg (spring of 1905).

In Fig.13 is shown, schematically, the layout used. The field was measured at a fair distance away, that is to say, in the so-called wave-zone. There was satisfactory agreement between theory and observation, and the results were checked in various ways. It was further shown that the experimental layout functioned in the desired sense. By suitable distribution of the amplitudes in the three transmitters, a field as in Fig.14 was calculated (the



singly dotted curve is the measured field). The radial vectors represent the range. If the roles of the three transmitters are exchanged - by simply tripping a change-over switch - the preferred direction can be rotated through 120° or 60° .

ELECTRICAL OSCILLATIONS AND WIRELESS TELEGRAPHY 241

It would appear to be of general interest to remark that one is led to the conclusion that the radiation of a transmitter is reduced here by the oscillations in its neighbour, which are shifted in position and phase, a conclusion which could be proved experimentally.

If nowadays optical phenomena are ascribed to electrical molecular resonators, then electrical processes, as demonstrated here by a single example, can also be linked up with optical phenomena, though this can hardly be experimentally verified in this field.

Here, the study of electrical oscillations supplements that of optical oscillations, and since we are in the position to tackle a problem in either field by analogy with a phenomenon which is comprehended in the other field, the first attack on the problem can be made from the electrical or the optical standpoint according to whichever presents the easier concept to realize. I can perhaps illustrate this by means of two worked-out examples.

Elementary considerations led me to the conclusion that a medium, composed of layers of different dielectric constants, must behave as a uniaxial crystal if it is assumed that the layer thicknesses are only a fraction of a wavelength. I was able to confirm this conclusion in the following way (Fig.15). A beam of practically parallel electrical rays emerges from the Hertzian reflector. It strikes a structure made of bricks in layers having the same breadth of air layers. These layers lie open to short waves, but if the wavelength is 12 times, or so, longer than the layer thickness, then the brick grating behaves towards it as a body which homogeneously occupies the space but exhibits double refraction. The electrical oscillations are linearly polarized and incident at an azimuth of 45° upon the brick layers. A brick structure which is



Fig.15.

about 2 1/2 times the thickness of a single brick has the effect of a quarter-wave foil of mica, and the linearly-incident ray emerges circularly polarized as we deduce from the investigations with a Righi's resonator. Assume it is righthanded circular. If the layer thickness is now doubled, the emergent wave is again linearly polarized, though in the other quadrant. And so we can transform the ray, by continuous addition of further thicknesses, into a lefthanded circular one, and finally back into a ray which is linearly polarized parallel to the incident ray. The double refraction of the brick grating surpasses that of calcite. Optically, this brick structure would correspond to a tiny crystal of a few thousandths of a millimetre length of edge, but electrically it is 2 1/2 metres thick, weighs 4000 kg, and its raw material is worth about 200 marks. The analogue of a corresponding optical phenomenon was also demonstrated by me at a later date.

This phenomenon of double refraction does not depend upon the use of rigid materials. Whether the double refraction occurring in cross-striated muscle results from a similar layer structure is thus a closely related question.

We have so far studied an electrically unknown, but optically conjectured phenomenon and both have been discovered to exist. The following example is concerned with demonstrating the unknown optical phenomenon corresponding to a known electrical phenomenon. It seemed to me to be of interest to reproduce the Hertzian grid experiment in the field of visible rays. For this to be realized, a very fine grating of metal wires was necessary and from 10,000 to 100,000 tiny wires, separated by air gaps, had to be located within a width of 1 mm. Mechanical methods of manufacture are impossible, but a Hertzian grid could be made in the following way. If a powerful discharge is passed through a thin metal wire on a glass plate, or between two such plates, the well-known sputtering or vaporization effect occurs, as you can see from Fig.16. The metal wire vaporizes (temperatures of up to 30,000°



Fig.16.

ELECTRICAL OSCILLATIONS AND WIRELESS TELEGRAPHY $2\,4\,3$

are calculated). The metal vapour is driven outwards by the pressure arising from the explosive effect (Fig. 17) and is then again precipitated obviously in a kind of grid structure on the glass. If we allow linearly polarized light to fall upon the prepared surface, it will, if the oscillations are parallel to the lines of the grid, be strongly reflected and strongly absorbed-the preparation appears dark (Fig. 18). If the plane of the oscillations is turned so that it is perpendicular to the lines of the grid, the metal layer becomes transparent



Fig.17.



Fig.18.

(Fig.19). We have the complete optical analogue to a Hertzian grid made out of moderately good conductors.

This experiment permits a further development. If we imagine that in an organized fabric such as muscle tissue, plant fibres, etc. there exists a similar fine grating structure somewhat in the form of the finest possible channels, then if we could succeed in filling these with metal, the preparation would have the optical effect of a Hertzian grid. H. Ambronn, in 1896, treating the



Fig.19.

above mentioned substances with gold or silver salts, discovered phenomena which I explained in this way. In an exhaustive investigation into this matter I have everywhere found confirmation of my concept, and nowhere a contradiction. Yet a direct and incontrovertible proof would be extremely desirable because of the importance of its consequences. For if my idea is, as I believe, correct, then we would in this way not only discover sub-microscopic gratings, but, as a result of electrical imitation, we would even be able to some extent to make a picture of the material structure which is as yet invisible to the human eye. This method would augment those so far available in a most valuable manner, for it takes its place just where the microscope and -because of the density of the particles - even the ultramicroscope, reach the limit of their capacity.

I must now finish this address. The sputtering experiments led me back to the Leyden-jar circuit. I pursued for a long time the aim of automatically switching out the Leyden-jar circuit from the oscillating system as soon as it had given up its energy to the secondary conductor. I attempted this in the following way. A thin wire was connected into the Leyden-jar circuit, and I hoped that, at the right moment, the primary circuit would be switched out as a result of vaporization of the wire. The experiment was not successful, at any rate at the frequencies which I used, apparently because the highly heated metal vapour remained ionized for too long a time. The problem was solved, however, by Max Wien using the so-called quenched spark, and by Rendahl using the mercury spark-gap. Practical experience has augmented

ELECTRICAL OSCILLATIONS AND WIRELESS TELEGRAPHY 245

Wien's discovery. Arising from this and through the agency of Rendahl and Arco, came the so-called tone-spark. The small hissing or quenched sparks of Wien of itself meet the conditions which I had hoped to produce artificially. The Leyden-jar circuit cuts itself out at the most suitable moment, and the greater part of the primary energy then oscillates in the highly conductive paths in the transmitter at its own natural frequency.

On the occasion of my first lecture in November 1900 I closed with the following words :

<<Sometimes, wireless telegraphy has been described as spark telegraphy, and so far a spark in one place or another has been unavoidable. Here, however, it has been made as harmless as possible. This is *important*. For the spark which produces the waves also destroys them again as Saturn destroyed his own children. What was pursued here could be truthfully described as *sparkless telegraphy.>>*

Finishing as I did with these words at that time, I feel happy to think that with the means I have described we have come appreciably nearer to this target, and have thereby made the coupled transmitter still more effective.

Biography

Carl Ferdinand Braun was born on June 6, 1850 at Fulda, where he was educated at the local <<Gymnasium>> (grammar school). He studied at the Universities of Marburg and Berlin and graduated in 1872 with a paper on the oscillations of elastic strings. He worked as assistant to Professor Quincke at Würzburg University and in 1874 accepted a teaching appointment to the St. Thomas Gymnasium in Leipzig. Two years later he was appointed Extraordinary Professor of Theoretical Physics at the University of Marburg, and in 1880 he was invited to fill a similar post at Strasbourg University. Braun was made Professor of Physics at the Technische Hochschule in Karlsruhe in 1883 and was finally invited by the University of Tübingen in 1855 ; one of his tasks there was to build a new Physics Institute. Ten years later, in 1895, he returned to Strasbourg as Principal of the Physics Institute, where he remained, in spite of an invitation from Leipzig University to succeed G. Wiedemann.

Braun's first investigations were concerned with oscillations of strings and elastic rods, especially with regard to the influence of the amplitude and environment of rods on their oscillations. Other studies were based on thermodynamic principles, such as those on the influence of pressure on the solubility of solids.

His most important works, however, were in the field of electricity. He published papers on deviations from Ohm's law and on the calculations of the electromotive force of reversible galvanic elements from thermal sources. His practical experiments led him to invent what is now called Braun's electrometer, and also a cathode-ray oscillograph, constructed in 1897.

In 1898 he started to occupy himself with wireless telegraphy, by attempting to transmit Morse signals through water by means of high-frequency currents. Subsequently he introduced the closed circuit of oscillation into wireless telegraphy, and was one of the first to send electric waves in definite directions. In 1902 he succeeded in receiving definitely directed messages by means of inclined beam antennae.

Braun's papers on wireless telegraphy were published in 1901 in the form

BIOGRAPHY

of a brochure under the title *Drahtlose Telegraphic durch Wasser und Luft* (Wireless telegraphy through water and air).

After the outbreak of the First World War, Braun was summoned to New York to attend as a witness in a lawsuit regarding a patent claim. Owing to his absence from his laboratory and due to illness he was unable to carry out further scientific work. Braun thus spent the last years of his life peacefully in the United States, where he died on April 20, 1918.