Physics 1961

ROBERT HOFSTADTER

« *for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons* »

RUDOLF LUDWIG MÖSSBAUER

« *for his researches concerning the resonance absorption of γ-radiation and his discovery in this connection of the effect which bears his name* »

Physics 1961

Presentation Speech by Professor I. Waller, member of the Swedish Academy of Sciences

Your Majesties, Your Royal Highnesses, Ladies and Gentlemen.

Since Rutherford's discovery of the atomic nucleus fifty years ago, one of the most fundamental problems in physics has been to investigate how it is constituted. The ideas on this question could be firmly founded when, shortly after 1930, a neutral particle called the neutron was discovered which has almost the same mass as the hydrogen nucleus i.e. the proton. A theory for the atomic nuclei was proposed according to which they are composed of protons and neutrons which are together called the nucleons. A few years later, Yukawa gave a theory of the forces which keep the nucleons together. It could according to this theory be expected that the nucleons have themselves a complicated inner structure.

Professor Robert Hofstadter has developed a new experimental method for the investigation of the inner structure of the composite atomic nuclei and also of the single nucleons. His method is to bombard the atomic nuclei with electrons of very high energy. The electrons can penetrate the atomic nuclei and are then deviated by the strong electric and magnetic forces inside the nuclei. By separating the scattered electrons of different energies in magnetic spectrometers and by measuring afterwards the number of electrons which have been deviated to each particular direction, Hofstadter has succeeded in obtaining detailed knowledge of the distribution of the electric charge in the nuclei. For the nucleons, important results have also been found concerning the distribution of their magnetic moments.

The experimental method used by Hofstadter is connected with the principles of the ordinary electron microscope. Here the possibilities to observe details are increased by raising the voltage which accelerates the electrons. As the dimensions of the atomic nuclei are of the order of a ten-billionth of a centimeter, Hofstadter had in order to find their structure to bombard them with electrons of a very high energy. The highest energy used was equivalent to an accelerating voltage of nearly one billion volts. When Hofstadter in 1950 began his work at Stanford University a linear accelerator had already been constructed there and was later supplemented to give the

electrons this energy. Hofstadter has built a complicated experimental installation in order to make possible the measurements of the scattering with the accuracy required. He has in a very skilful manner managed to achieve great precision in spite of the very large dimensions of the apparatus.

Hofstadter's results have opened fundamentally new aspects on the properties of the nucleons. His investigations form a pioneering work which in the last years has been beautifully confirmed by similar experiments at Cornell University. It must be expected that investigations of this kind will be made at other institutes also. Electron accelerators which are expected to come into operation in some years will probably increase further our knowledge in this field.

Professor Rudolf Mössbauer's investigations concern the emission and absorption of gamma radiation by the atomic nuclei. This radiation is of the same kind as the light and the radio waves. It is well known that incoming radio waves can be received only if the receiver is tuned to the same frequency as the sender. Resonance is then taking place. It has since long been tried to observe the corresponding phenomenon for nuclei, where it is called « resonance absorption ». The method was to let gamma radiation from some kind of nuclei act upon other nuclei of exactly the same kind. There is however a certain difficulty connected with this experiment. The gamma radiation can be considered as made up of particles. When emitting a gamma particle the atom receives a recoil whereby the energy and therefore also the frequency of the gamma radiation is decreased. The same phenomenon occurs when the gamma particle is absorbed in the receiving nucleus. The resonance will be completely destroyed if the frequency change is not compensated for, as had been done already before Mössbauer's work. Mössbauer discovered experimentally and showed also theoretically that for atoms bound in a solid, an appreciable part of the radiation can be emitted without frequency change whereby the resonance absorption can be studied directly. This discovery was published by Mössbauer in 1958. Because of the very small width of the gamma lines the resonance is very sharp and can, as Mössbauer found, be influenced and finally inhibited by the Doppler effect if the source or the absorber for the gamma radiation is moved. The velocities required depend upon the sharpness of the gamma line and can be as small as some millimeters per hour.

Mössbauer's discovery has been received with considerable interest. Research on the Mössbauer effect has been started at a great number of places. It has thereby been possible to verify in the laboratory, fundamental con-

sequences of Einstein's theory of relativity. Other important applications depend on the separation and displacement of nuclear energy levels which occur in solids because of the influence of the surroundings. Many phenomena of this kind can in spite of their smallness be studied by the Mössbauer effect. It has been possible in this way to get most important information on the properties of solids.

Mössbauer made his discovery when he investigated the resonance absorption on the suggestion of Professor Maier-Leibnitz in München. He found then some unexpected results which he investigated systematically and was thereby led to his discovery.

Professor Hofstadter. You have in your pioneering investigations on the atomic nuclei and the single nucleons, revealed features of their structures which are fundamentally important for the understanding of these almost inconceivably small systems. Your work is characterized by a precision which has scarcely been attained before in high-energy physics. You have achieved this precision by improving unrelentingly your methods and equipment in the course of time. Your results have quite recently stimulated the discovery of new particles which seem to be essential for the understanding of the forces acting in the atomic nuclei.

Professor Mössbauer. While doing research for your doctor's thesis you have discovered an unexpected effect which now bears your name. You have explained this effect experimentally and theoretically, and thereby created a device which is of fundamental importance in numerous realms of physics, and which is nowadays being investigated and put to use in a large number of physical laboratories. By your discovery it has become possible to examine precisely, numerous important phenomena formerly beyond or at the limit of attainable accuracy of measurement.

Professor Hofstadter and Professor Mössbauer. May I congratulate you on behalf of the Academy on your important work and ask you to receive the Nobel Prize from the hands of His Majesty the King.

ROBERT HOFSTADTER

The electron-scattering method and its application to the structure of nuclei and nucleons

Nobel Lecture, *December 11, 1961*

I am very conscious of the high honor that has been conferred on me and I wish to thank the Swedish Academy of Sciences sincerely for this recognition. It is a privilege and a pleasure to review the work which has brought me here and which concerns a very old and interesting problem.

Over a period of time lasting at least two thousand years, Man has puzzled over and sought an understanding of the composition of matter. It is no wonder that his interest has been aroused in this deep question because all objects he experiences, including even his own body, are in a most basic sense special configurations of matter. The history of physics shows that whenever experimental techniques advance to an extent that matter, as then known, can be analyzed by reliable and proved methods into its « elemental » parts, newer and more powerful studies subsequently show that the « elementary particles)) have a structure themselves. Indeed this structure may be quite complex, so that the elegant idea of elementarity must be abandoned. This observation provides the theme of our lecture.

In recent times the structure of matter has been shown to arise from various combinations of the « atoms » of the Periodic System. The picture of the now-familiar atom was first sketched by Rutherford, Bohr, Pauli, etc., and later developed in great detail by many of their colleagues. The efforts of these scientists have led to an understanding of the cloud of electrons which surrounds the dense center of the atoms, the so-called nucleus. In the nucleus practically all the mass of the atom resides in an extremely concentrated form. The nucleus itself was an invention of the aforementioned physicists and in the year 1919 the first vague ideas concerning the sizes of nuclei were worked out. By studying the deviations from Coulomb scattering of alpha particles Rutherford showed that a nuclear radius was of the order of 105 times smaller than an atomic radius. Subsequently other investigators demonstrated by means of studies of or-particle radioactivity, neutron capture cross sections, and comparisons of the energy of decay of mirror nuclei that consistent values of nuclear size parameters could be measured.

All useful methods showed that if a nucleus could be represented by a model of a uniformly charged sphere the radius *(R)* of the sphere would be given by the relation

$$1.0 \times 10^{-13} A^{\frac{1}{3}} \text{ cm} \qquad (1)$$

where *A* is the mass number of the nucleus.

This is the point from which the present studies began. Although much of what we wish to say will concern nucleon structure (nucleon = proton or neutron) the method of investigation we have employed had its origins in the study of larger nuclei. Consequently a historical approach beginning with the larger nuclei seems not only natural but also may be didactically sound. We shall therefore review briefly the method used in studying nuclear sizes and shall at the same time give some of the results, which may not be without interest themselves.

We have used the method of high-energy electron scattering. In essence the method is similar to the Rutherford scattering technique, but in the case of electrons it is presently believed that only a << simple >> and well-understood interaction - the electromagnetic or Coulomb interaction - is involved between the incident electron and the nucleus investigated. Under these conditionsquantum electrodynamics and Dirac theory teach us how to calculate a differential elastic scattering cross section. It can be shown that the differential cross section corresponding to a beam of electrons scattering against a point nucleusof small charge Ze, lacking spin and magnetic moment, is calculable by the Born approximation and takes a form:

$$\left(\frac{Ze^2}{2E}\right)^2 \frac{\cos^2 \theta/2}{\sin^4 \theta/2} \frac{1}{1 + \frac{2E}{Mc^2} \sin^2 \theta/2} \qquad (2)$$

in the laboratory system of coordinates . This is the << Mott >> scattering cross section where E is the incident energy, the θ scattering angle and M the mass of the struck nucleus. Other symbols in Eq. 2 have their usual meanings. if a nucleus has a finite size, and is thus not merely a point, the scattering cross section is decreased below the value of the scattering from a point. The can be described in terms of a factor, represented by F, which is called << form factor >> or << structure factor >>. Thus, in Born approximation,

$$_{NS} F^2 (a)$$

and this is the elastic scattering cross section for a finite nucleus". Here q is the momentum-energy transfer, defined by the relation

$$q = \frac{(2E/\hbar c)\sin\theta/2}{\sqrt{1 + (2E/Mc^2)\sin^2\theta/2}} \tag{4}$$

The parameter q is relativistically invariant and is a very important quantity in electron-scattering studies. The form factor, F, takes account of the interference between scattered wavelets arising from different parts of the same, finite, nucleus and therefore is responsible for diffraction effects observed in the angular distribution. The quantity F is actually given by

$$F = \frac{4\pi}{q}\int_0^\infty \varrho\,(r)\,(\sin\ qr)\,r\,dr \tag{5}$$

in the event that the nucleus exhibits spherical symmetry. The quantity $\varrho\,(r)$ is the electric charge density function, in which r represents the distance from the center of the nucleus to the volume element where ϱ is measured. A mathematical inversion of Eq. 5 allows one to deduce the form of $\varrho\,(r)$ if $F\,(q)$ is known over a large range of values of q.

Of course, since we used the Born approximation and therefore specified small values of the atomic number, the above description of the basic formulae of the electron-scattering process is only an approximate one. More exact methods of finding the scattering cross section have been developed by many authors[3]. These calculations of more precise types employ the « phase-shift » methods and are applicable to heavy nuclei as well as light ones. The qualitative physical ideas involved in the determination of nuclear structure can be adequately described by the Born approximation method (Eq. 3). Nevertheless, quantitative results definitely require the more elaborate phase-shift methods and simple, and in this case, closed formulae cannot be given to describe the scattering cross section.

Early electron-scattering experiments were carried out at the University of Illinois in 1951[4] at an incident electron energy of about 15.7 MeV. Such experiments showed that nuclear radii obeyed an approximate relationship of the type given in Eq. 1. However, few details of nuclear shape or size could be discerned because the energy of the electrons was relatively low and the corresponding De Broglie wavelength of the electrons was larger than a typical size of the nucleus. In 1953 higher energy electrons became

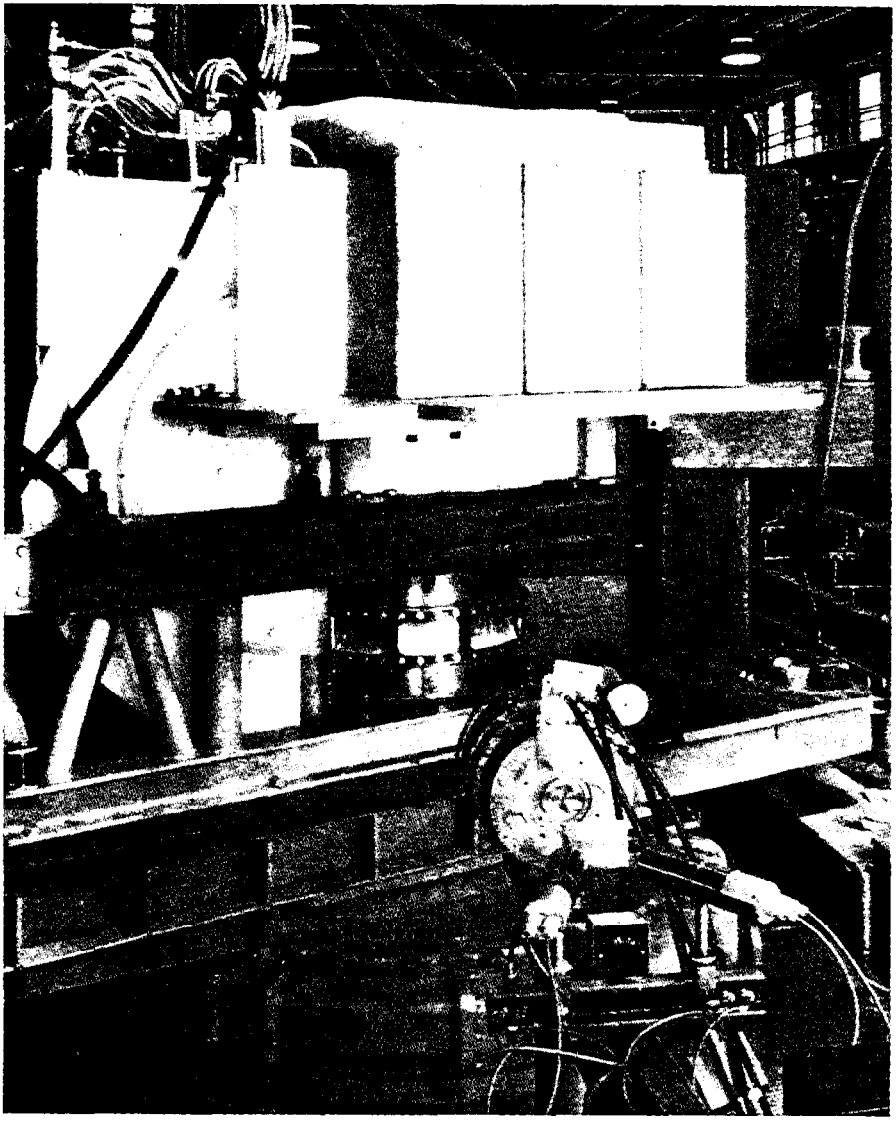

Fig. 1. The first electron-scattering apparatus built at Stanford University. The semicircular 190-MeV spectrometer is shown at the left on its gun-mount support. The upper platform carries lead and paraffin shielding that encloses the Čerenkov counter. The brass scattering chamber is shown below with the thin window encircling it. Early forms of electron monitors appear in the foreground. The spectrometer itself is about four feet high.

available at Stanford University and at the University of Michigan and experiments on various nuclei were carried out[5]. Phase-shift interpretations of the Stanford experiments[6] showed that the rule expressed in Eq. 1 was approximately true, but that in reality the nuclear charge density distribution could not be described in terms of a single size parameter R. If one attempted to do so, only at the expense of an inferior fit between experiment and theory, the resulting R would have to be made 20% smaller than the value of the radius in Eq. 1. Mu-mesonic atom studies[7] showed, a bit earlier, that a similar conclusion was required for a one-parameter description of the size of the nucleus. Two parameters could not be determined from the mu-mesonic atom investigations.

Fig. 1 shows a photograph of the first high-energy electron-scattering equipment. This apparatus gave the above results and was employed up to an energy of about 190 MeV. An obsolete naval-gun mount was used as the rotating platform for the heavy equipment, weighing about 5 tons. The type of geometry employed in a modern electron-scattering experimental area is shown in Fig. 2. A photograph of the corresponding magnetic spectrometers and associated equipment is shown in Fig. 3. A larger form of gun mount is used again to carry the spectrometers, whose total weight is approximately

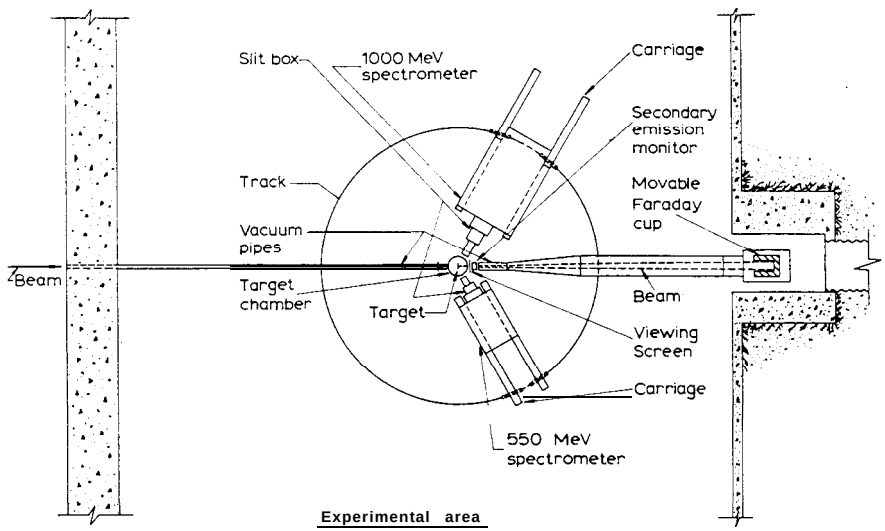

Fig. 2. This figure shows a schematic diagram of a modem electron-scattering experimental area. The track on which the spectrometers roll has an approximate radius of 13.5 feet.

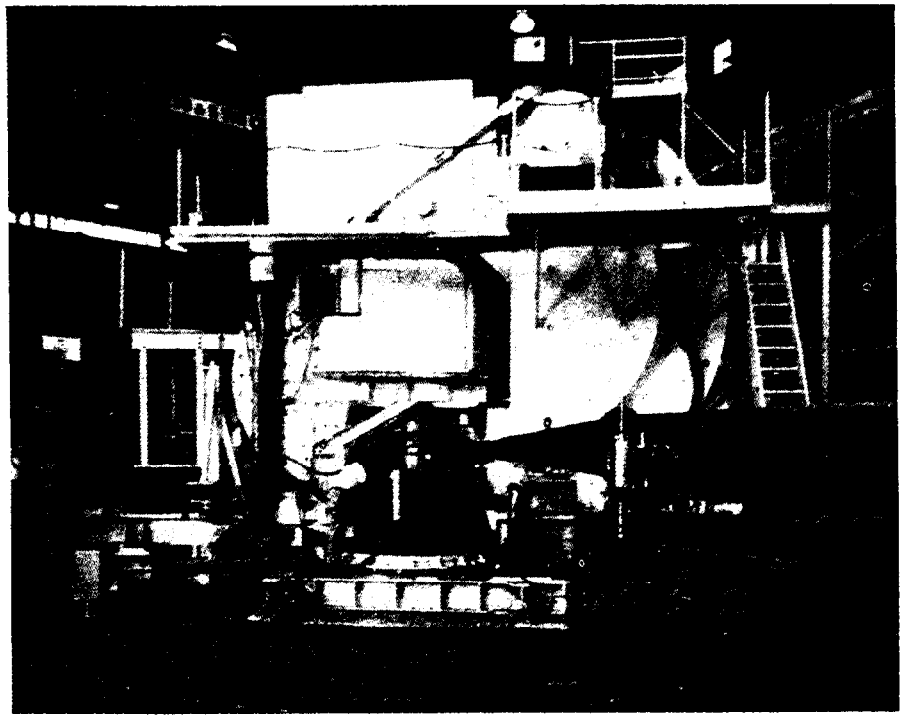

Fig. 3. A recent photograph of the double-spectrometer system is shown in this figure. The shield of the smaller spectrometer can be removed easily with the aid of an auxiliary stand, not shown in the photograph. The long tube in the foreground is the vacuum pipe leading to the Faraday cup, which is not visible in the photograph.

250 tons. Each of the two magnetic spectrometers in this apparatus is similar to the well-known Siegbahn double-focussing instrument. The two spectrometers may be used in coincidence experiments as well as « in parallel ». The massive equipment of Fig. 3 can bend and focus 1.0-BeV electrons and is required in order to resolve the elastic-scattering process from the many types of inelastic-scattering processes occurring in electron-nucleus collisions. An example of the resolution obtained in early experiments is shown in Fig. 4 in the case of a carbon target[8]. When an angular distribution in carbon is measured one may observe, e.g. in Fig. 5, the position of a diffraction minimum. The value of the angle at this minimum gives immediately an indication of the nuclear size if one employs results similar to Eqs. 2-5, when modified appropriately in terms of the phase-shift method. The solid line in the figure shows the result of a theoretical calculation of the scattering cross

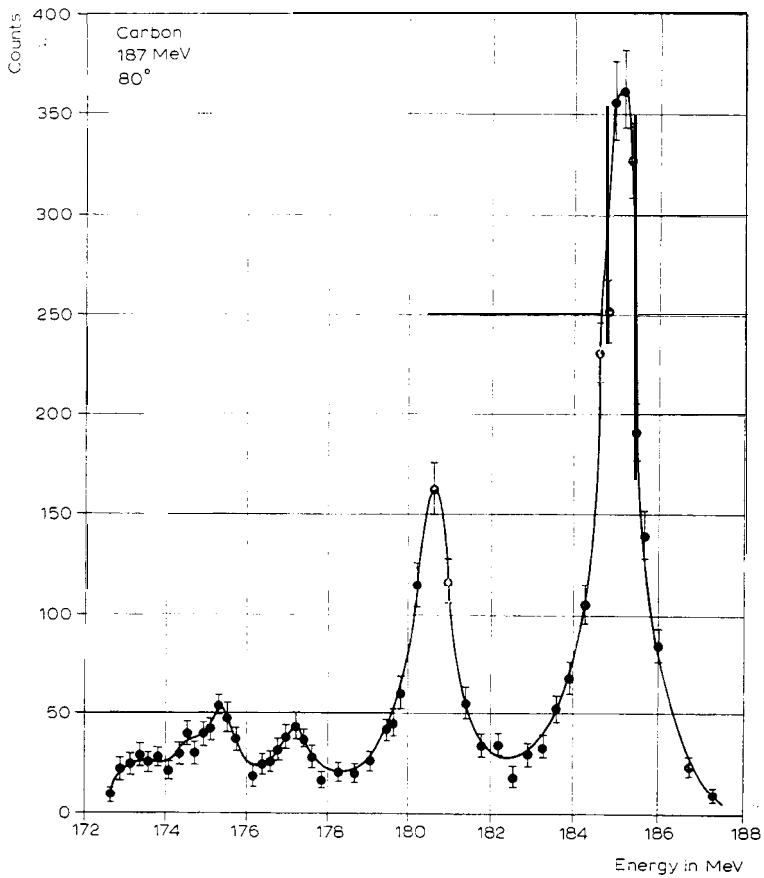

Fig. 4. This figure[8] shows the elastic-scattering peak from carbon at an abscissa near 185 MeV, and the inelastic-scattering peaks from the excited states of ^{12}C. The peak near 180.7 MeV is associated with the 4.43-MeV level.

section. From the theoretical calculation one may deduce the charge density distribution, which may be seen in Fig. 8. It is clear that a study of the inelastic-scattering peaks corresponding to the excited states of ^{12}C (or other nuclei) can be studied by the electron-scattering method. In fact, Fig. 5 shows also the angular dependence of the scattering of the 4.43-MeV level in ^{12}C. The subject of inelastic level scattering is not relevant to our present topic and we shall not pursue this matter any further in this lecture.

One last example is shown in the case of the nucleus of the gold atom. The elastic electron scattering was studied at the four different energies shown in Fig. 6. The solid lines again show the results of theoretical calculations from

which the charge density distribution, ϱ, can be obtained. This charge distribution is shown in Fig. 8.

The electron-scattering method was employed in the manner we have described and resulted in the determination of two-parameter descriptions of nuclear charge density distributions. Studies of the charge density dis-

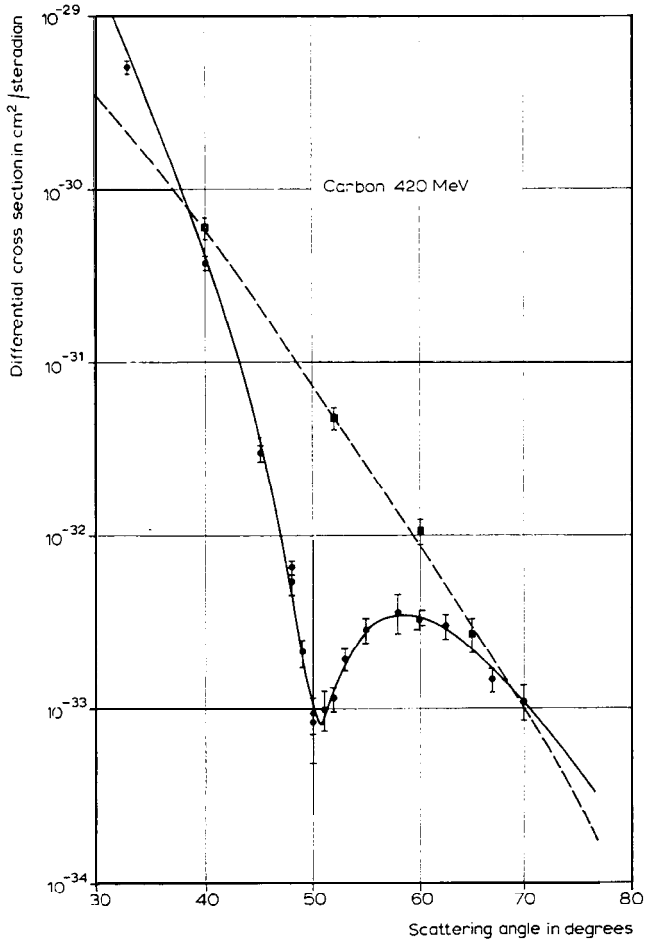

Fig. 5. This figure shows the elastic and inelastic curves corresponding to the scattering of 420-MeV electrons by ^{12}C. The solid *circles,* representing experimental points, show the elastic-scattering behavior while the *solid* squarer show the inelastic-scattering curve for the 4.43-MeV level in carbon. The *solid line* through the elastic data shows the type of fit that can be calculated by phase-shift theory for the model of carbon shown in Fig. 8.

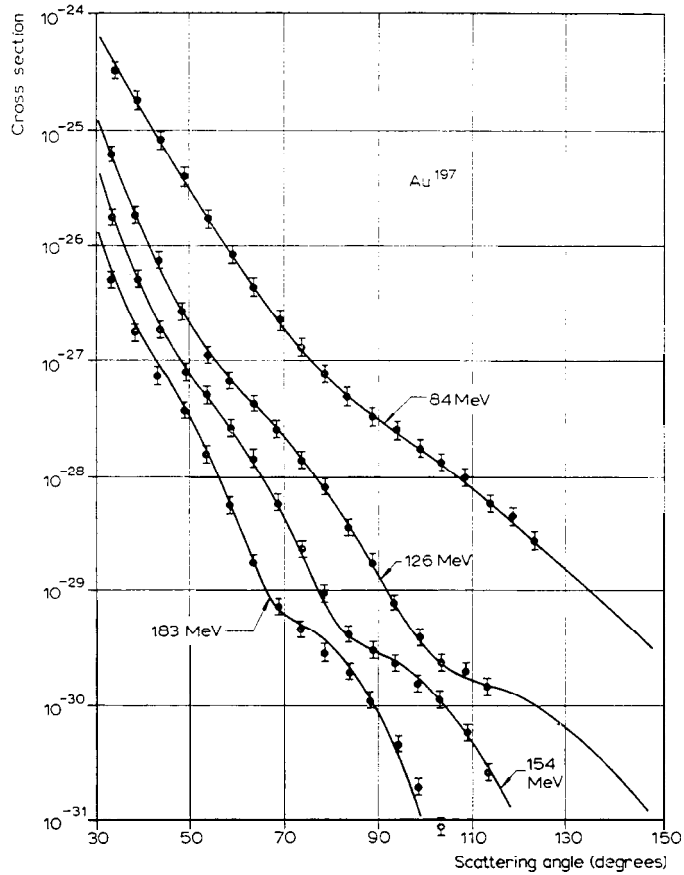

Fig. 6. The *points* represent experimental data observed by scattering electrons of the appropriate incident energies from gold nuclei[9]. The *solid lines* are calculated angular distributions for a model of the gold nucleus similar to that shown in Fig. 8.

tributions in various nuclei culminated in the evolution of a simple scheme of construction of most spherical nuclei[9]. Such nuclei could be represented by a charge density function of the type shown in Fig. 7. The exact shape of this density function is not of overriding importance; rather the distance (c) from the center of the nucleus to the 50 per cent point, and the interval (t) between the 90 per cent and 10 per cent ordinates, are the two important parameters that determine the behavior of the scattering cross sections. A trapezoidal distribution with the same values of the two parameters would also suffice to describe the experimental results in the medium and heavier nuclei when the fitting procedure is limited by the accuracy obtained in the

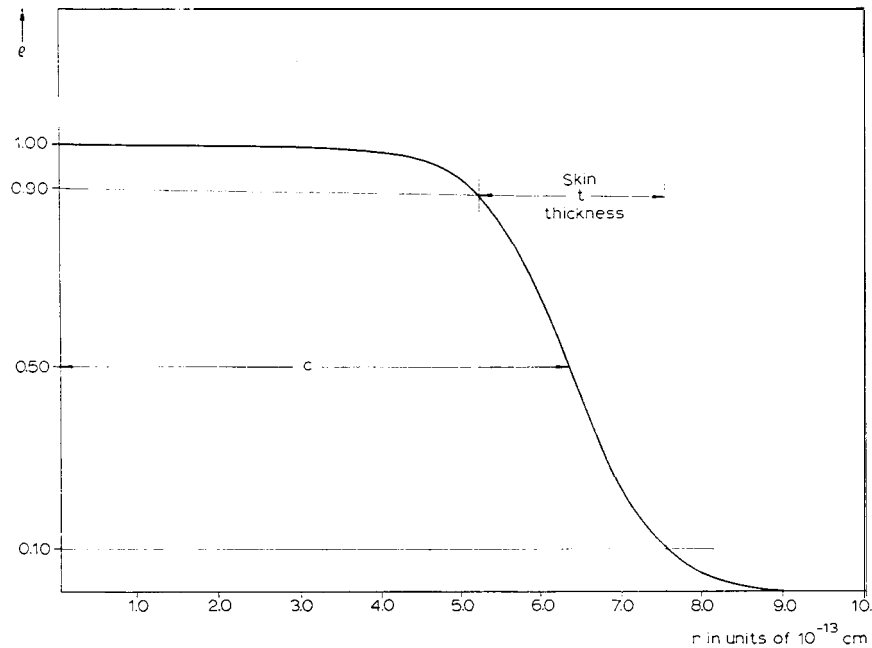

Fig. 7. The shape and parameters which describe an approximate model of the gold nucleus. This type is called the Fermi model[9].

experiments. Higher accuracy can probably distinguish between these possibilities but such studies are only beginning now.

The results of many of the above experiments covered a large range of nuclei and demonstrated9 that two simple rules can be used to summarize the scheme of construction of spherical nuclei, viz. :

$$\begin{aligned} c &= (1.07 \pm 0.02) \cdot 10^{-13} A^{\frac{1}{3}} \text{ c m} \\ t &= (2.4 \pm 0.3) \cdot 10^{-13} \text{ cm} = \text{constant} \end{aligned} \qquad (6)$$

The first equation gives the principal parameter governing the size of a nucleus and describes the behavior with increasing A of a kind of « mean » nuclear radius. The second equation states that the nuclear skin thickness is constant. The second rule implies that there is some property of nuclear matter that causes the outer nuclear regions to develop an essentially constant surface thickness. The two rules together are responsible for the approximate constancy of the central charge density of nuclei. The latter property is il-

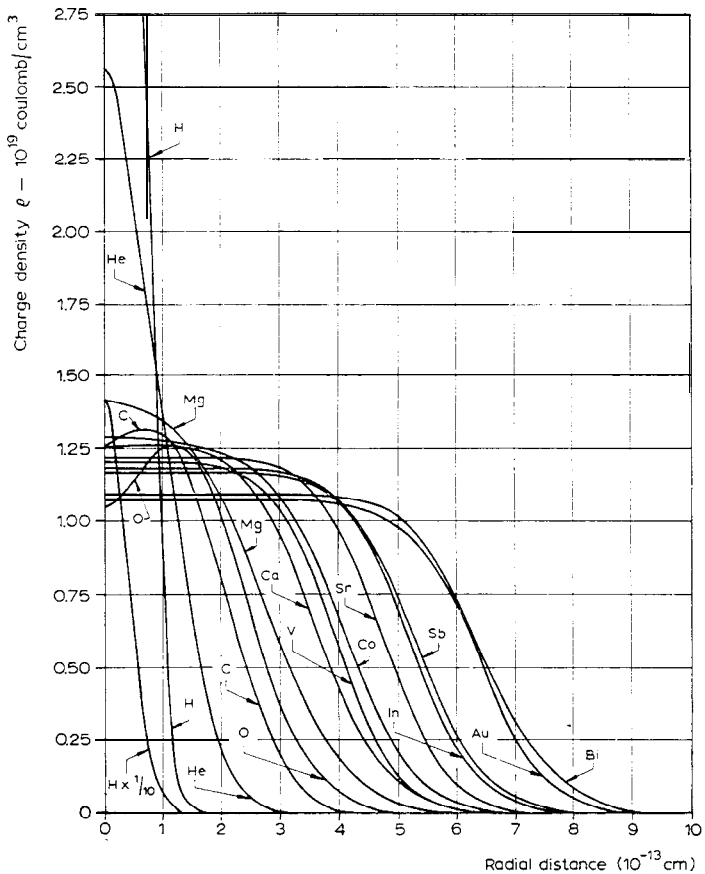

Fig. 8. This figure gives a summary of the approximate charge density distributions found for various nuclei studied by electron-scattering methods. The central densities are the least well determined positions of the curves. Note, however, the large disparity between the *average* central densities of the proton and all other nuclei. The alpha particle (^{4}He) is also a unique case and exhibits a much larger central density than all heavier nuclei.

lustrated in Fig. 8, where a summary of the charge distributions found by the electron-scattering method is presented for various nuclei. Except for the extremely light nuclei of hydrogen and helium the constancy of the central nuclear density is clearly represented in the figure.

The results obtained with heavier nuclei indicated that the electron-scattering method could also be applied to the very light nuclei and even to the proton itself. Accordingly, in early 1954 experiments were initiated on hy-

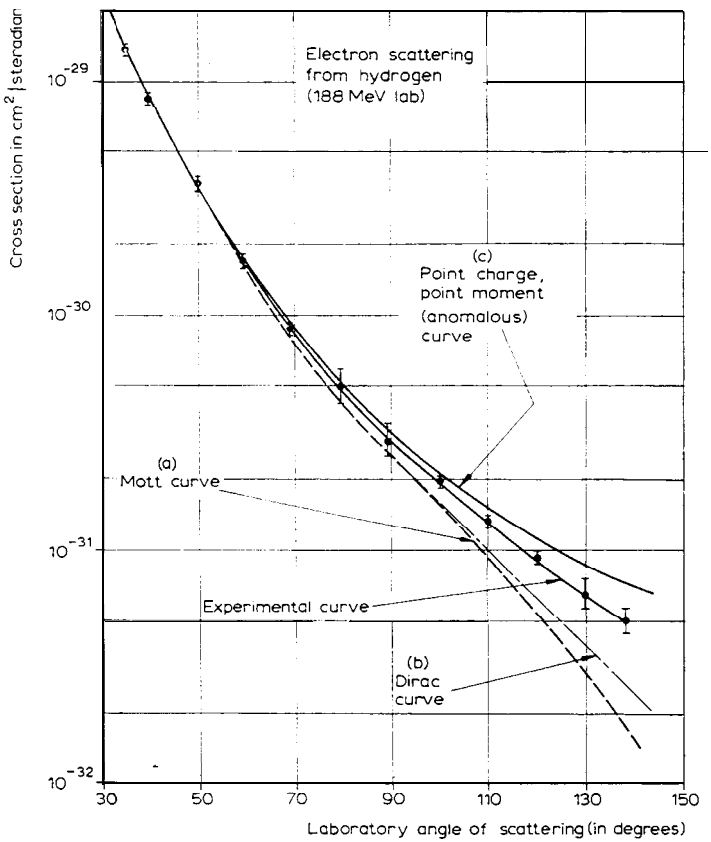

Fig. g. Electron scattering from the proton at an incident energy of 188 MeV. *Curve (a)* shows the theoretical Mott curve for a spinless point proton. *Curve (b)* shows the theoretical curve for a point proton with a Dirac magnetic moment alone. Curve (c) shows the theoretical behavior of a point proton having the anomalous Pauli contribution in addition to the Dirac value of the magnetic moment. The deviation of the experimental curve from the Curve (c) represents the effect of form factors for the proton and indicates structure within the proton. The best fit in this figure indicates an rms radius close to $0.7 \cdot 10^{-13}$ cm.

drogen and helium. The first targets employed high-pressure, thin-wall, gas chambers and were designed by the late Miss Eva Wiener. In the latter part of 1954 it was first realized that the experiments on hydrogen demonstrated that the proton was an object of finite size and not merely a point object. In fact, the size was found to be surprisingly large[10] and could be described in terms of a root-mean-square radius of value $(0.74 \pm 0.24) \cdot 10^{-13}$ cm. It is an interesting fact that more recent determinations of the rms proton charge

radius appear to converge on a value of $(0.79 \pm 0.08) \cdot 10^{-13}$ cm. Fig. 9 shows the first evidence of finite size in the proton. The figure has been drawn from Ref. 10. The first experiments leading to the above conclusions were carried out at relatively low energies (~ 190 MeV).

Now the proton is known to have a spin and a magnetic moment. The magnetic moment will affect the scattering behavior appreciably at values of q (Eq. 4) in the range equal to or larger than about $0.2\ MC$, where M is the mass of a nucleon. The magnetic type of scattering causes a leveling off in the decrease of the elastic cross section as a function of the scattering angle at high energies of the incident electrons. As we may see in Fig. 9, the experimental data fell below the expected theoretical curve for a proton possessing a point charge and a point magnetic moment. This behavior can be understood in terms of the theoretical scattering law developed by M. Rosenbluth[11] in 1950. This law described the composite effect of charge and magnetic moment scattering and is given by:

$$\frac{d\sigma}{d\Omega} = \sigma_{NS}\left\{F_1^2 + \frac{\hbar^2 q^2}{4 M^2 c^2}\left[2\,(F_1 + KF_2)^2 \tan^2 \theta/2 + K^2 F_2^2\right]\right\} \qquad (7)$$

where σ_{NS} is taken from Eq. 2 with Z = 1. In the Rosenbluth equation the quantity $F_1(q)$ is the Dirac form factor, representing the proton's charge and its associated Dirac magnetic moment. The quantity $F_2(q)$ is the Pauli form factor and represents the anomalous magnetic moment of the proton. K in the above equation indicates the static value (1.79) of the anomalous magnetic moment in nuclear magnetons.

Although one may speak qualitatively of size and shape factors of the proton in the low-energy limit it is more consistent and more desirable, from a quantitative point of view, to discuss only the two phenomenological form factors $F_1(q)$ and $F_2(q)$. Actually all the electromagnetic structure of the proton is, in principle, described by the behavior of these quantities as functions of q. Note that for the proton, $F_1(0) = F_2(0) = 1.00$. Meson theory should be able to make definite assertions about F_1 and F_2 starting from the above values. In our subsequent discussion we shall concentrate on determining the two phenomenological quantities (F_1, F_2) from the experimental data so that the form factors can be compared with theory. The experimental determinations of the form factors can be accomplished, for example, by using the method of intersecting ellipses[12] or by other equivalent methods based on the relativistic idea that each F is a function *only* of q and not of E or θ separately.

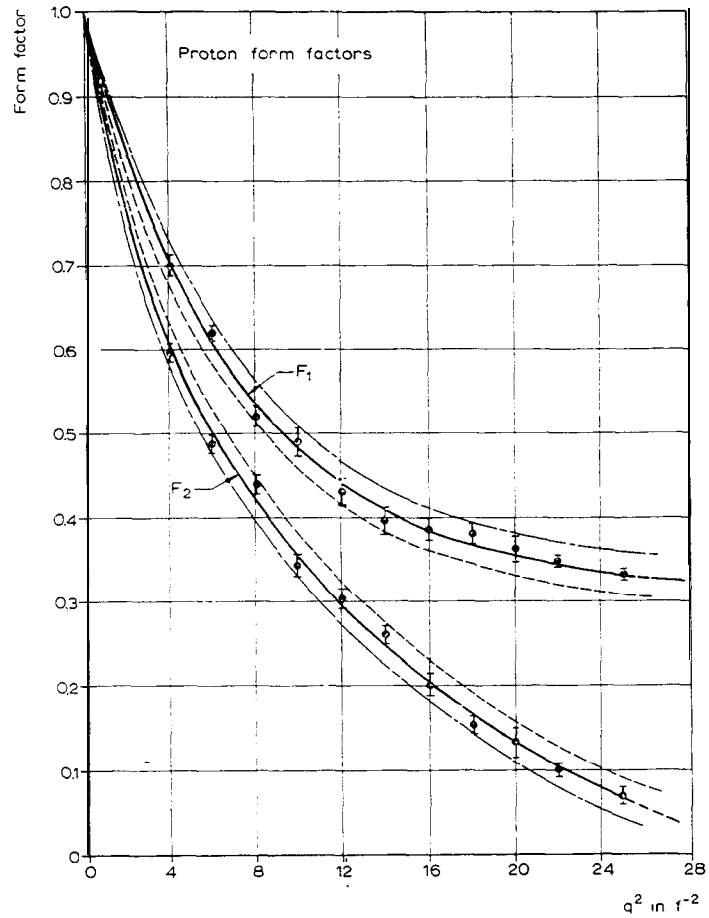

Fig. 10. The most recent Stanford experimental data on the form factors of the proton[17]. There are two dashed curves lying between the *central-value solid experimental lines*. If the error limits are correlated so that they move in opposite directions, as indicated by the *dashed lines*, the corresponding cross sections will still remain consistent with experiment. A similar statement holds for the two *small-dash long-dash curves* lying outside the F_1,F_2 central-value experimental curves. The correlated error question needs additional study but the dashed inner and outer curves are thought to give reasonable error limits of F_1 and F_2.

The early work on the proton was confirmed by subsequent studies at higher energies (~ 600 MeV)[13,14] but these energies were still low enough so that the assumption $F_1 \cong F_2$ could be employed. It was noted in the latter experiments that F_1, was slightly greater than F_2 at values of $q^2 = 4f^2$, where f = fermi = 10^{-13} cm. The value of one fermi corresponds to $(197\ \text{MeV})^{-1}$.

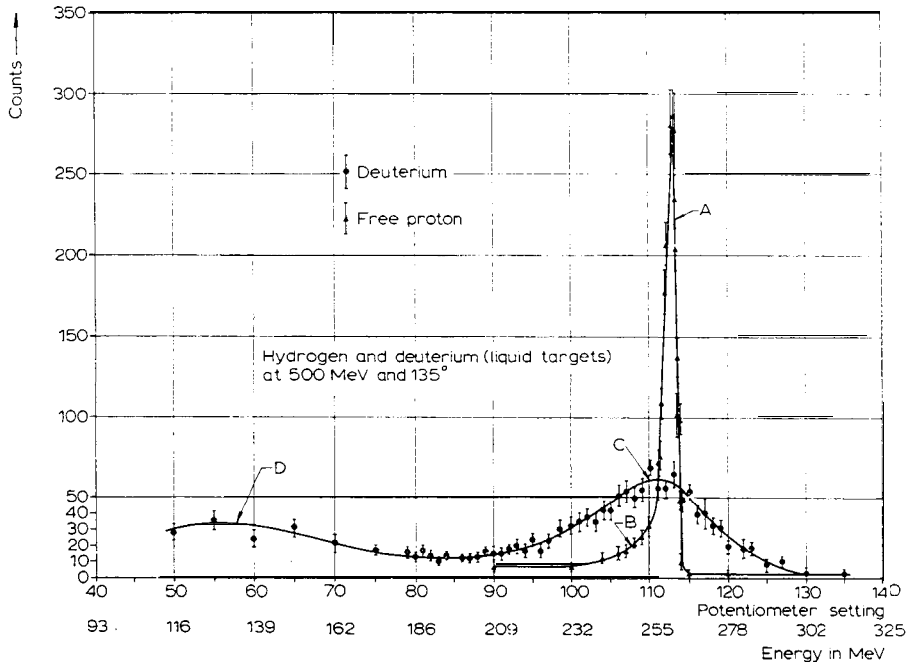

Fig. 11. The experimental comparison of the scattering from the moving proton and neutron in the deuteron (Curve C) and the scattering associated with free protons *(Curve A)*[18]. Region *B* shows the bremsstrahlung tail of the proton curve. At *D* are electrons which have been scattered after producing pions in deuterium and also other low-energy electrons. From the scattering data near C the form factors of the neutron can be obtained. The proton peak is used for comparison measurements. No correction has been applied in the figure for the different densities of liquid deuterium and liquid hydrogen.

Recently the extension of the experimental measurements to higher energies (~ 1.0 BeV) showed that indeed $F_1 > F_2$ [15,16]. The appropriate detailed behavior is shown in Fig. 10, and represents the most recent Stanford experimental data on this subject[17]. The possible theoretical significance of these results will be described below, following brief discussions of first, some tests of the Rosenbluth equation and second, the experimental determinations of the form factors of the neutron.

Various tests of the validity of the Rosenbluth equation were made in these experiments by examining whether F_1 and F_2 are really functions of q alone. In all cases studied for which q^2 was less than 25f^{-2} complete consistency in F_1,F_2 values at different energies and angles was observed so that the Rosenbluth equation was checked and found to be valid[17]. At the highest

values reached in these experiments, namely, $q^2 \cong 3$ If[2] the Stanford cross sections could not be combined with the cross sections at the same value of q in recently reported Cornell experiments[24] to give veal values of F_1 and F_2. If this observation can be confirmed, the possibility exists that quantum electrodynamics may fail at high momentum transfers or that two-proton exchange processes, heretofore neglected, are needed to correct the Rosenbluth equation; or, that some other fundamental aspect of the scattering theory needs improvement. This is an interesting question for the future to decide.

Let us now turn to the question of the neutron. According to relativistic quantum electrodynamics the neutron possesses Dirac and Pauli form factors. Proton and neutron form factors may be referred to respectively as F_{1p}, F_{2p}, F_{1n}, F_{2n}. Static values of the neutron form factors are known to be $F_{1n}(0) = o$, $F_{2n}(0) = 1.00$. F_{1n} is also known from early neutron-scattering experiments to vary as q^4 at small values of q in an expansion of F_{1n} as a function of q^2. This is commonly referred to by saying that within experimental error, the rms radius of the neutron is zero. Thus the neutron is not only a neutral body from the point of view of electric charge, but has a power expansion of F_{1n} that starts off as a function of q^2 with zero slope! Consequently, it is most difficult to determine F_{1n} (and also F_{2n}) of the neutron. The difficulty is compounded by the experimental fact that neutron targets are obtained only by using the deuteron as a neutron carrier, for free neutrons in large numbers are unobtainable in confined spaces. A neutron is in vigorous motion in the deuteron and this additional complication must be taken into account somehow. It is necessary at this point to introduce a relativistic theory of the deuteron to allow properly for the effects of the motion of the bound neutron. Of course, at the present stage of development of relativity theory, the deuteron problem can be solved only in an approximate way. Hence we can see that there are formidable difficulties which face the experimental elucidation and determination of the form factors of the neutron.

Many of these difficulties were overcome in the work of Yearian and the author who used a difference method to compare the scattering from the deuteron and the proton[18]. These investigators first showed that the neutron could not be represented as a point nucleon and that its magnetic moment was distributed in a manner similar to that of the proton. In Fig. 11, we show the type of data from which such conclusions were drawn. The spread-out deuteron peak shows the effect of the motion of the proton and neutron in

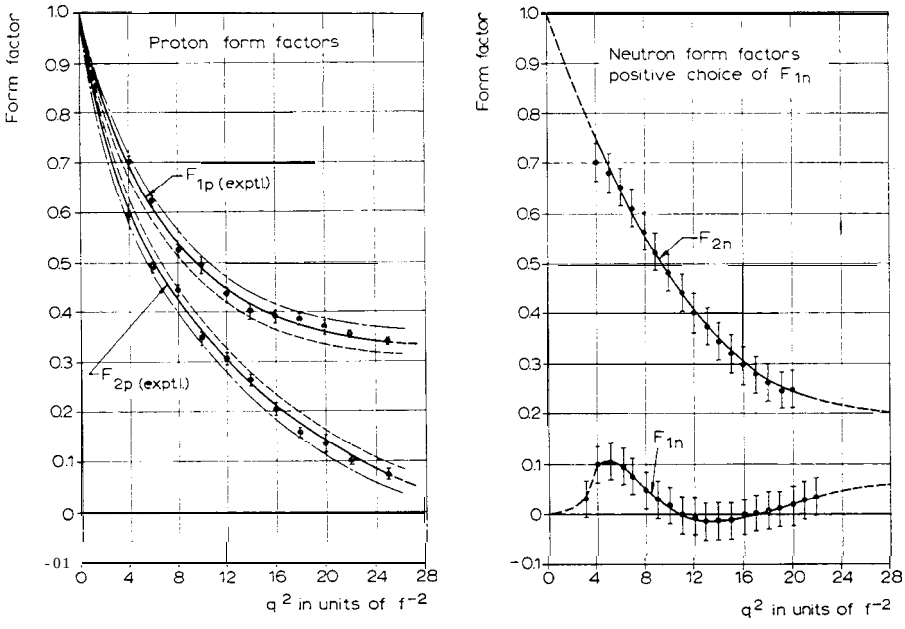

Fig. 12. This figure shows the most recent Stanford results[17,25] for both the neutron and the proton for the positive choice of sign of F_{1n}. The regularity of the neutron curves arises from the fact that the experimental deuteron curves were smoothed before putting the corresponding data into the theoretical formulae from which the form factors are deduced. The four curves of this figure can be fit approximately with dispersion theory or Clementel-Villi curves corresponding to the newly discovered heavy mesons. It is interesting that the newer neutron data agree very well with older result[18] and many of the present conclusions could have been drawn in 1958.

the deuteron and this wide peak may be compared with the sharp peak of the free proton. In the work in which the finite size of the neutron was discovered, the neutron form factor, F_{1n}, was assumed to be approximately zero and F_{2n}, had the behavior described above.

It may be noted parenthetically, that it was on the basis of the above results that Nambu[19] postulated the existence of a new heavy neutral meson, now known as π-meson. Events of the past year have brilliantly confirmed the existence of this meson[20]. A pion-pion resonance (e-meson) responsible for the magnetic behavior of the nucleon form factors was also postulated by Frazer and Fulco[21] on the basis of the above experiments. This resonance was also found recently[22].

The above conclusions about the behavior of the neutron and also the assumption that $F_{1n} \cong 0$, have been confirmed recently[23,24]. More detailed

studies[25], as yet unpublished, support the above description of the neutron form factors. These results are shown in Fig. 12. In Refs. 23 and 24, F_{1n} was found to be small and positive. However Durand[26] has recently shown that the theory of the deuteron used in the early work to derive the values of the neutron form factors can be improved. When the improved formula is employed the slightly positive values of the form factor, F_{1n}, are relatively unaffected in the low q^2 region but in the range $6f^{-2} < q^2 < 2of^{-2}$ the values of F_{1n} are reduced to approximately zero, within experimental error as in Fig. 12[25]. Because the neutron measurements are so fraught with both experimental and theoretical difficulties we must still regard these new, more accurate results, particularly for F_{1n}, as preliminary.

Fig. 12 shows the most recent Stanford results for both the proton[17] and the neutron[25]. An ambiguity exists in the choice of sign of F_{1n}. Fig. 12 shows one choice of the F_{1n} values and the corresponding F_{2n}, values. Fig. 13 shows the neutron data for the other (negative) choice of F_{1n} and the corresponding values of F_{2n} for the negative choice of F_{1n}. Theoreticians prefer the first choice, but as a purely experimental problem the negative F_{1n} values must be considered possible until proved untenable. The dashed parts of the curve refer to probable behavior at low q^2 and in the negative F_{1n} case the steep fall of F_{2n}, would be very surprising and is not expected.

If the first choice of values of F_{1n} is made, which seems much more likely, an understanding of all the proton and neutron data can be obtained along the lines of the heavy-meson or pion-resonance theory of Bergia, *et al*[27]. An interpretation of the early data in terms of Clementel-Villi form factors, using Yukawa clouds of different ranges and delta functions, was also given by the present author and Herman[23]. These initial and approximate theoretical interpretations are probably correct in principle but incomplete in detail and it now seems likely that it is necessary to add to them the effects on the form factors of a third heavy meson (η-meson)[28]. Such a particle has recently been discovered by A. Pevsner, *et al.*[29]. Its existence was also predicted by Sakurai[30].

Attempts are now being made to fit the data of Fig. 12 in terms of the heavy-meson theory in a way similar to that given in Refs. 23 and 27 but now employing three mesons (ϱ, ω, η) instead of only two. I hesitate to show the results of the studies since the exact mass values of the heavy mesons are not yet definite and small variations of these values affect the relative importance of the mesons in the form factor equations in a sensitive way. Furthermore it would not be surprising to find that new heavy mesons are

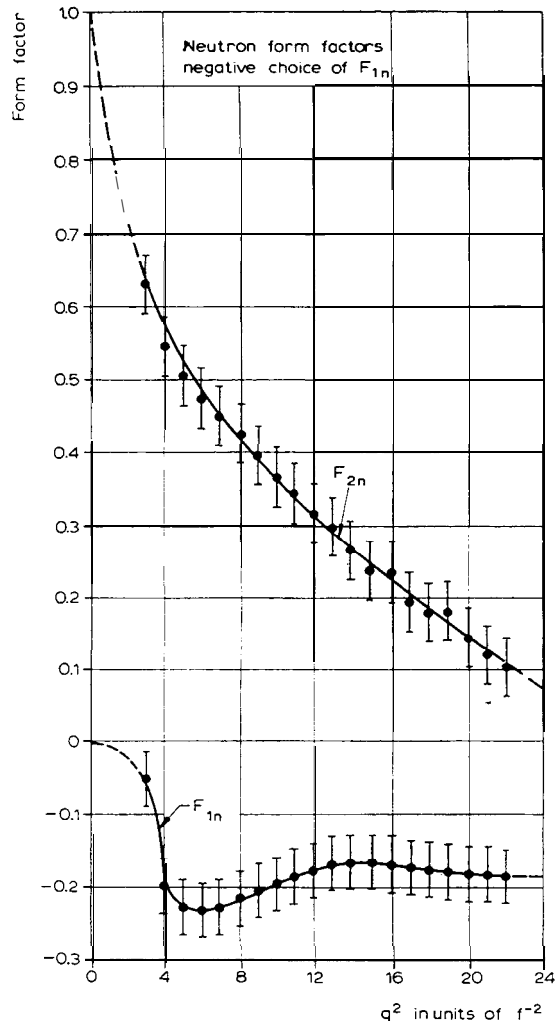

Fig. 13. This figure is similar to the right-hand side of Fig. 12 and gives the set of values of F_{1n} and F_{2n} for the negative choice of F_{1n}. It appears easier at present to fit Fig. 12 with Clementel-Villi curves than Fig. 13.

discovered in the near future, and these might also contribute to the form factors. Suffice it to say that approximate agreement with the data of Fig. 12 can be obtained with the set of three mesons (ϱ, ω, η).

If we now attempt to summarize the recent progress in nucleon structure determinations and in their interpretation, we may say that the proton and neutron are two different aspects of a single entity - the nucleon. The third

component of isotopic spin distinguishes between the two particles. Isotopic form factors can be developed in a well-known way[23] from the proton and neutron form factors. A phenomenological and qualitative interpretation of the nucleon form factors then shows that the same charged mesonic clouds appear in both the neutron and proton. In the proton the clouds add together and in the neutron the clouds cancel, more or less as given in Ref. 23.

It is a bit too early to give the final and definitive details of the mesonic clouds or of their heavy-meson compositions since, as indicated above, such details are now being worked out. However, it is possible, and even likely, that the next year or so should witness a crystallization of the « final » values of the nucleon structure parameters in terms of the models afforded by the new heavy-meson picture of the proton and neutron. The fact that new research is needed in order to clarify this picture is symptomatic of the general problem of the structure of elementary particles.

In concluding this discussion it may be appropriate to return to the theme introduced earlier in the paper and raise the question once again of the deeper, and possibly philosophical, meaning of the term « elementary » particle. As we have seen, the proton and neutron, which were once thought to be elementary particles are now seen to be highly complex bodies. It is almost certain that physicists will subsequently investigate the constituent parts of the proton and neutron - the mesons of one sort or another. What will happen from that point on? One can only guess at future problems and future progress, but my personal conviction is that the search for ever-smaller and ever-more-fundamental particles will go on as long as Man retains the curiosity he has always demonstrated.

The ideas and results presented in this paper represent the work of many individuals. Many of their names are given in the bibliography and I am indebted to them for their important contributions to the subject. I wish to acknowledge my special debt of gratitude to the following individuals who have given me not only invaluable assistance with the many theoretical concepts involved in the fascinating subjects of nuclear and nucleon structure but who have also given me support and encouragement over the last decade: L. I. Schiff, F. Bloch, D. G. Ravenhall, and D. R. Yennie.

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Biography

Robert Hofstadter, Professor of Physics at Stanford University, was born in New York, N.Y., of parents Louis Hofstadter and Henrietta Koenigsberg, on February 5, 1915.

Hofstadter attended elementary and high schools in New York City, and was graduated in 1935 from the College of the City of New York with the B.S. degree, *magna cum laude.*

On graduation from college Hofstadter received the Kenyon Prize in Mathematics and Physics, and a little later the Coffin Fellowship, awarded by the General Electric Company. He went to graduate school at Princeton University where he studied physics from 1935-1938, and received both the M.A. andPh.D. degreesin 1938 from that institution. His Ph.D. work was concerned with infrared spectra of simple organic molecules, and in particular, with the partial elucidation of the structure of the now well-known « hydrogen bond». In 1938-1939 he was awarded a Procter Fellowship at Princeton University for postdoctoral work, at which time he began a study of photoconductivity in willemite crystals. This work led to the discovery, with R. Herman, of the warm-up dark currents which demonstrated the existence oftrapping states in crystals. In 1939 Hofstadter received the Harrison Fellowship at the University of Pennsylvania where he helped to construct a large Van de Graaff machine for nuclear research. At Pennsylvania he first met L. I. Schiff, who has been a friend and colleague for many years.

During the war years Hofstadter worked first at the National Bureau of Standards and later at the Norden Laboratory Corporation. He left industry at the end of the war to become Assistant Professor of Physics at Princeton University. At Princeton he carried out research on crystal conduction counters, on the Compton effect, and on scintillation counters. In 1948 he discovered that sodium iodide, activated by thallium, made an excellent scintillation counter. In *1950,* with J. A. McIntyre, he found that well-formed crystals of this material provided remarkable energy-measuring devices for gamma rays and energetic particles and thus could be used as spectrometers in addition to gamma-ray and particle counters of high efficiency.

In 1950 Hofstadter left Princeton to become Associate Professor of Physics at Stanford University where he initiated a program on the scattering of energetic electrons from the linear accelerator, invented by W. W. Hansen, which was then under construction. While building equipment for the electron-scattering experiments, he continued working on scintillation counters and developed new detectors for neutrons and X-rays. High-speed inorganic (CsF) and useful Čerenkov (TlCl) counters were discovered at Stanford. Other studies carried out in the early years at Stanford were concerned with cosmic rays and with cascade showers generated by high-speed electrons.

After 1953 electron-scattering measurements became Hofstadter's principal interest. With students and colleagues he investigated the charge distribution in atomic nuclei and afterwards the charge and magnetic moment distributions in the proton and neutron. The electron-scattering method was used to find the size and surface thickness parameters of nuclei. Many of the principal results on the proton and neutron were obtained in the years 1954-1957. Since 1957 emphasis in the research program has been placed on making more precise studies of the nucleon form factors. This work is still in progress.

Hofstadter was elected to the National Academy of Sciences (U.S.A.) in *1958* and was named California Scientist of the Year in *1959.* He has also been a Guggenheim Fellow *(I958-1959)* and spent one year at CERN in Geneva, Switzerland, on sabbatical leave.

In *1942* he married Nancy Givan of Baltimore, Maryland, and they have a son, Douglas, and two daughters, Laura and Mary.

RUDOLF L. MÖSSBAUER

Recoilless nuclear resonance absorption of gamma radiation

Nobel Lecture, December 11, 1961

It is a high distinction to be permitted to address you on the subject of recoilless nuclear resonance absorption of gamma radiation. The methods used in this special branch of experimental physics have recently found acceptance in many areas of science. I take the liberty to confine myself essentially to the work which I was able to carry out in the years 1955 to 1958 at the Max Planck Institute in Heidelberg, and which finally led to establishment of the field of recoilless nuclear resonance absorption. Many investigators shared in the preparations of the basis for the research we are concerned with in this lecture. As early as the middle of the last century Stokes observed, in the case of fluorite, the phenomenon now known as fluorescence - namely, that solids, liquids, and gases under certain conditions partially absorb incident electromagnetic radiation which immediately is reradiated. A special case is the so-called resonance fluorescence, a phenomenon in which the re-emitted and the incident radiation both are of the same wavelength. The resonance fluorescence of the yellow D lines of sodium in sodium vapour is a particularly notable and exhaustively studied example. In this optical type of resonance fluorescence, light sources are used in which the atoms undergo transitions from excited states to their ground states (Fig. 1). The light quanta emitted in these transitions $(A \rightarrow B)$ are used to initiate the inverse process of resonance absorption in the atoms of an absorber which are identical with the radiating atoms. The atoms of the absorber undergo a transition here from the ground state (B) to the excited state (A), from which they again return to the ground state, after a certain time delay, by emission of fluorescent light.

As early as 1929, Kuhn[1] had expressed the opinion that the resonance absorption of gamma rays should constitute the nuclear physics analogue to this optical resonance fluorescence. Here, a radioactive source should replace the optical light source. The gamma rays emitted by this source should be able to initiate the inverse process of nuclear resonance absorption in an absorber composed of nuclei of the same type as those decaying in the source.

Again, the scheme of Fig. 1 would hold here, but the radiative transitions would now take place between nuclear states. Nevertheless, all attempts in the next two decades to find this nuclear resonance absorption proved fruitless. Before I can approach the subject of my talk, it is appropriate to consider the reasons why the discovery of nuclear resonance absorption was so long delayed.

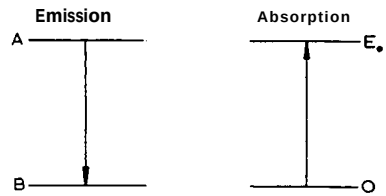

Fig. 1. Scheme of resonance absorption.

For simplicity, we shall first consider a nuclear transition of a free nucleus at rest. The gamma quantum emitted in the transition AfiB imparts a recoil momentum $\vec{p}$ to the emitting nucleus and consequently a kinetic energy DE, which is given by

$$AE = \vec{p}^2/2M = E_o^2/2Mc^2 \qquad (1)$$

where M is the mass of the nucleus and c is the velocity of light. The energy liberated in this nuclear transition is divided, in accordance with the law of conservation of momentum, the larger part being carried away by the emitted quantum, the other part going to the emitting nucleus in the form of recoil energy. This recoil-energy loss of the quantum has the consequence that the emission line does not appear at the position of the transition energy E_o but is displaced to lower energy by an amount DE (Fig. 2). The absorption line, on the contrary, is displaced to a higher energy by the same amount DE, because in order for the process of resonance absorption to occur, a quantum must provide, in addition to the transition energy E_o, the amount of energy DE which is taken up by the absorbing nucleus in the form of a recoil kinetic energy. Typical values for the line shifts DE lie in the range from 10^{-2} eV to 10^{2} eV; they are therefore very small in comparison with the energies of the gamma quanta, which frequently are of the order of magnitude of millions of electron volts.

Since there is an uncertainty in the energies of the individual excited states

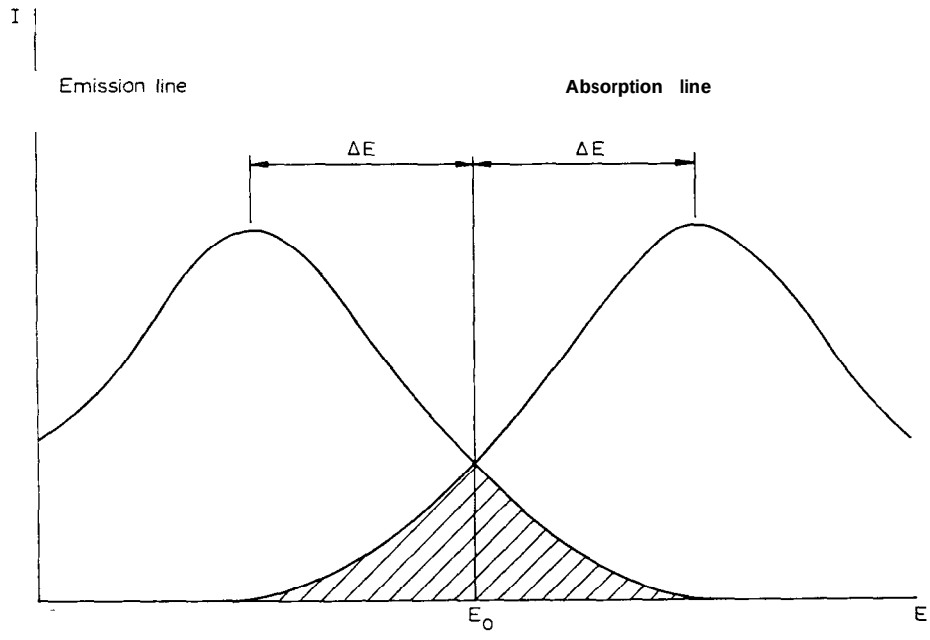

Fig. 2. Position and shape of the emission and absorption lines of a free nucleus (shown in the case of the I29-keV transition in ^{191}Ir for T = 300°K).

of the nuclei, the lines associated with transitions between an excited state and the ground state have a certain minimum width. This so-called natural width Γ is, according to the Heisenberg uncertainty principle, connected with the lifetime τ of an excited nuclear state by the relation $\Gamma\tau$ = h. The usual values for the lifetimes τ of the low-lying excited nuclear states lie in the range from 10^{-7} to 10^{-11} second, corresponding to an interval of 10^{-8} to 10^{-4} eV for the natural line widths appearing in ground-state transitions. Such extraordinarily sharp lines exhibiting the natural line width are normally not observed. Rather, a series of side effects always exist, which lead to considerable broadening such that the line widths ordinarily associated with low-energy gamma transitions exceed the natural minimum width by many orders of magnitude. The most important broadening mechanism is the thermal motion of the nuclei in the source and in the absorber; this leads to Doppler shifts in the energy of the gamma quanta and therefore produces corresponding line broadenings. Even a temperature drop to absolute zero does not extinguish this thermal broadening, since the existence of zero-point energy at absolute zero frequently produces, at least in solids, line

widths of the same order of magnitude as the ones existing at room temperature.

Usually the line shifts DE are large in comparison to the thermal line widths, and they are also always very large in comparison to the natural line widths associated with the low-energy nuclear transitions we are concerned with here. As a consequence, the energy of an emitted quantum is usually too small for the inverse process of resonance absorption to be carried out, or in other words, the probability of occurrence of nuclear resonance absorption is so small that the process escapes detection. Therefore the long and unsuccessful search for nuclear resonance absorption is to be blamed on the high recoil-energy losses of the gamma quanta.

On the other hand, entirely different conditions hold for optical resonance absorption. There, because of the much lower energies of the light quanta, the recoil-energy losses produced by light quanta are small in comparison with the line widths. Emission and absorption lines therefore overlap in an ideal manner, the resonance condition is satisfied, and the optical effect is, at least in principle, easily observable.

The unsatisfactory situation with respect to nuclear resonance absorption first changed in 1951, when Moon[2] succeeded in demonstrating the effect for the first time, by an ingenious experiment. The fundamental idea of his experiment was that-of compensating for the recoil-energy losses of the gamma quanta: the radioactive source used in the experiment was moved at a suitably high velocity toward the absorber or scatterer. The displacement of the emission line toward higher energies achieved in this way through the Doppler effect produced a measurable nuclear fluorescence effect.

After the existence of nuclear resonance fluorescence had been experimentally proved, a number of methods were developed which made it possible to observe nuclear resonance absorption in various nuclei. In all these methods for achieving measurable nuclear resonance effects the recoil-energy loss associated with gamma emission or absorption was compensated for in one way or another by the Doppler effect.

At this point, let me speak of my esteemed teacher, Heinz Maier-Leibnitz, who in 1953 directed my attention to this newly advancing field of nuclear resonance fluorescence, and who stimulated me to turn to this area of research. He was, also, the one who made it possible for me to conduct my research throughout the years 1955 to 1958 at the Heidelberg Max Planck Institute, in an undisturbed and fruitful atmosphere - research which finally led to the discovery of recoilless nuclear resonance absorption. I want to express

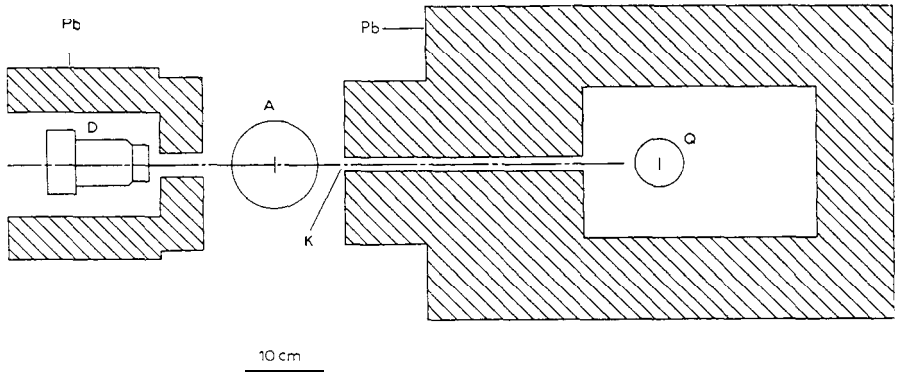

Fig. 3. Experimental arrangement. *A*, absorber-cryostat; *Q*, cryostat with source; *D*, scintillation detector; *K*, lead collimator.

my warmest thanks to my esteemed teacher for his efforts on my behalf.

The method which I shall now proceed to discuss differs fundamentally from the methods described above in that it attacks the problem of recoil-energy loss at its root in a manner which, in general, insures the complete elimination of this energy loss. The basic feature of this method is that the nuclei in the source and absorber are bound in crystals. The experiments described in the following paragraphs exclusively employed radioactive sources which emitted the 129-keV gamma line leading to the ground state in ^{191}Ir.

The first experiments aimed at measuring the lifetime of the 129-keV state in ^{191}Ir by utilizing methods of nuclear resonance absorption known at that time. The experimental set-up used for this purpose is shown schematically in Fig. 3. A method first employed by Malmfors[4] appeared to be especially suitable for the planned measurement. In this method, a broadening of the emission or absorption line, leading to a corresponding increase in the degree of overlap of the two lines, is achieved by increasing the temperature. If the relative shift of the emission and the absorption lines resulting from the recoil-energy losses is only of the order of magnitude of the line widths, a temperature increase leads, under favourable conditions, to a measurable nuclear absorption effect. In the case of the 129-keV transition in ^{191}Ir, there is considerable overlap of the two lines even at room temperature as a consequence of the small energies of the quanta and the small line shifts resulting therefrom (see Fig. 2). In this case, not only an increase but also a decrease in temperature can result in a measurable change in the nuclear absorption.

My decision between these two possibilities was made in favour of a temperature decrease. It was motivated essentially by the consideration that at low temperature, effects of chemical binding would be more likely than at elevated temperatures. This hypothesis was vindicated in an unexpected way during the course of the experiments. The simultaneous cooling of the source and the absorber with liquid air led to inexplicable results, for which I first blamed effects associated in some way with the cooling of the absorber. In order to eliminate these unwanted side effects, I finally left the absorber at room temperature and cooled only the source. In very tedious experiments, which demanded extremely stable apparatus, a small decrease in the absorption with respect to the value at room temperature was in fact obtained - a result consistent with my expectations. The evaluation of these measurements finally led to the determination of the lifetime sought for.

In a second series of experiments I attempted to explain the side effects which had appeared in the simultaneous cooling of the source and the absorber during the earlier experiments. The result of this attempt was striking :

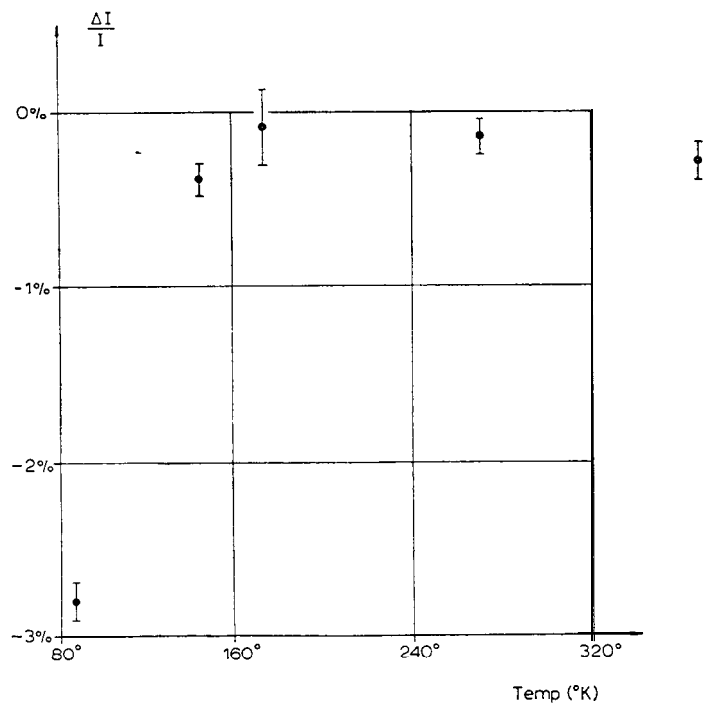

Fig. 4. Temperature dependence of the absorption. Relative intensity change $\Delta I/I$ in comparison with that of a non-resonant absorber.

instead of the decrease expected, a strong increase in the absorption clearly manifested itself when the absorber was cooled. This result was in complete contradiction to the theoretical expectation. The observed temperature dependence of this absorption is shown in Fig. 4.

In considering the possible sources of the anomalous resonance effect, I now began to subject the hypothesis of the existing theory to a critical examination.

The views originally held as to the shape and energy of the emission and absorption lines were based on the assumption that the emitting and absorbing nuclei can be treated as free particles. It was therefore natural to modify this assumption, taking into account the fact that source and absorber were each used in crystalline form. Therefore, I first attempted to explain the observed anomalous resonance absorption by assuming that the recoil momentum was not transferred to the single nucleus. It should rather be transferred to an assembly of nuclei or atoms which include nearest or next-nearest neighbours surrounding the nucleus under consideration. After the failure of this and other attempted explanations, based on a purely classical point of view, I turned my attention to a quantum-mechanical treatment of the problem.

Let me here introduce some concepts from crystal physics, by means of which I will develop the reasoning that finally led to a solution of the problem. All the internal motions of the particles forming the crystal lattice can be described in terms of a superposition of a large number of characteristic vibrations whose distribution is called the frequency spectrum of the crystal. The nature of the binding of the particles forming the crystal determines the structure of the lattice vibrational spectrum, this spectrum often being very complicated. Nevertheless, the substitution, for the true vibrational spectrum of the lattice, of a much simpler frequency distribution often suffices for qualitative considerations.

This first, still purely classical picture of the internal motions in a crystal corresponds, in the quantum-mechanical description, to a system of uncoupled harmonic oscillators with quantized energy states. While the vibrational spectrum describes only the distribution of the fundamental frequencies of these oscillators, the temperature determines the so-called occupation numbers of these crystal oscillators; these occupation numbers simply tell which of the possible energy states the particular oscillators occupy.

The recoil energy appearing in the emission or absorption of a quantum by a nucleus bound in a crystal is taken up by the crystal partly in the form

of translational energy and partly in the form of internal energy. The resultant increase in translational energy is always negligible because of the enormous mass of the crystal as a whole in comparison to the mass of a single nucleus. An increase in the internal energy leads to changes in the occupation numbers of the individual crystal oscillators. Because of the quantization of the oscillator energies, the crystal can absorb the recoil energy only in discrete amounts. The nuclear transitions of the bound nuclei are normally accompanied by simultaneous transitions of the crystal oscillators. Thus, for example, a gamma quantum can be emitted and simultaneously one of the crystal oscillators can undergo a transition to a neighbouring energy state. Likewise, a gamma emission process can be accompanied by simultaneous transitions of two crystal oscillators, and so forth. As a consequence of the quantization of the oscillators, there also exists in principle the possibility that the gamma transition takes place with none of the crystal oscillators changing their states.

The problem now was to compute the probabilities of the various processes. Significant was the calculation of the probability of nuclear transitions leaving the lattice state unchanged - that is, transitions in which no recoil energy is transferred to the lattice in the form of internal energy. Similar problems had already been solved much earlier. The coherent scattering of X-rays from crystals had been known for decades; in that case a momentum transfer to the reflecting lattice takes place without simultaneous transfer of internal energy to the crystal. And for a long time the analogous problem of the elastic scattering of slow neutrons from crystals had been thoroughly studied, both experimentally and theoretically. Lambs had, as early as 1939, developed a theory for the resonance capture of slow neutrons in crystals. This theoretical work was somewhat premature, inasmuch as Lamb assumed considerably smaller values for the widths of the neutron lines than were observed in later experiments. For this reason, this extraordinarily beautiful work was of no practical significance in the area of application originally intended. It remained only to apply this Lamb's theory to the analogous problem of the resonance absorption of gamma radiation. This indeed enabled me to show that under the conditions chosen in the experiments described above there exists a high probability of nuclear transitions with no simultaneous change of the lattice state. Since these nuclear transitions are not associated with any energy losses caused by recoil phenomena, I shall in the following discussion characterize these particular transitions as « recoilless » transitions, and the lines associated with such transitions, as « recoilless

lines>>. In such a recoilless emission process, the entire excitation energy is therefore transferred to the emitted quantum, and the corresponding situation holds for the recoilless absorption. Here the notation <<recoilless>> relates only to recoil energy transferred in a nuclear transition, and not to the transferred momentum. The value of this transferred momentum is determined by the energy of the gamma quantum and is essentially a constant, independent of any change in the internal state of motion of the crystal. This momentum is, therefore, transferred to the lattice in all emission or absorption processes, even in the recoilless processes. It is always taken up by the crystal as a whole, and therefore the corresponding translational velocity is negligibly small.

What are the conditions under which the recoilless nuclear resonance absorption can be observed? In answering this question, I wish to develop here, without presenting the mathematical formulation of the theory, a detailed picture of the processes which take place in radiative transitions in nuclei bound in crystals. The recoil-energy loss that occurs in a nuclear transition of a free nucleus is given by Eq. (1). It can be shown that in a transition of a nucleus bound in a crystal, Eq. (1) is no longer valid for the individual process but holds in the means over many processes; that is, instead of Eq. (1), we now have

$$\overline{\Delta E} = E_0^2/2Mc^2 \tag{2}$$

Let us now consider a very simple model, in which we describe the vibrational state of the crystal by a single frequency ω, the so-called Einstein frequency. It is instructive to consider the two limiting cases, in which the mean recoil energy is either large or small in comparison to the transition energy of the Einstein oscillator:

$$\overline{\Delta E} > \hbar\omega \quad \text{(case 1)}$$
$$\overline{\Delta E} < \hbar\omega \quad \text{(case 2)}$$

In case 1, many oscillator transitions are required to take up the energy contribution $\overline{\Delta E}$ in the lattice. The nuclear processes will therefore in general be accompanied by simultaneous transitions of many oscillators. The probability of a nuclear transition taking place without any oscillator transition - that is, the probability of a recoilless process - is correspondingly small. The situation is entirely different in case 2. Here it is immediately evident that

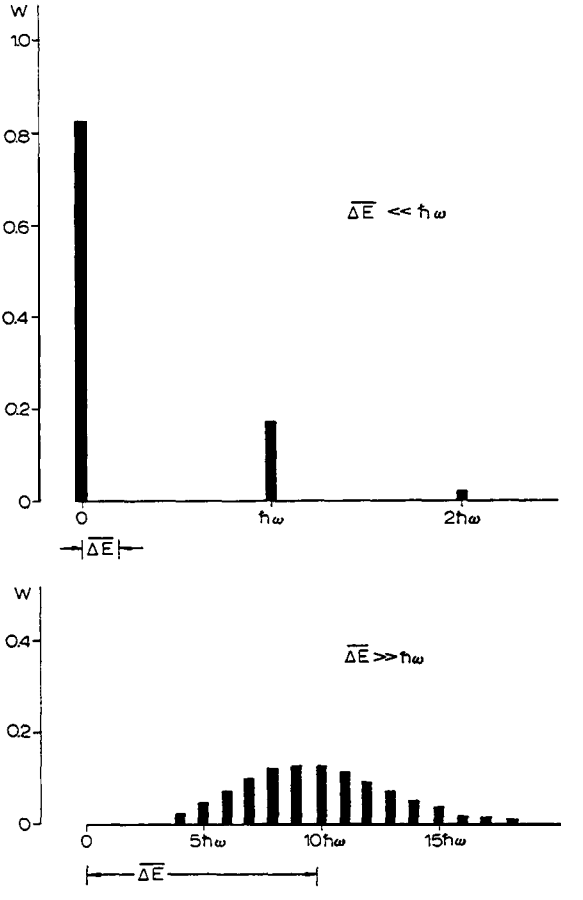

Fig. 5. Relative probability for a gamma transition associated with simultaneous transitions of 0, 1, 2, . . . n crystal oscillators, for two different values of $\overline{\Delta E}$ for the temperature $T = 0°K$.

a nuclear transition which is accompanied by an oscillator transition occurs relatively seldom, leading under these circumstances to a high probability for recoilless processes. The probabilities, under these conditions, for the occurrence of gamma emission processes accompanied by 0, 1, 2, . . . n oscillator transitions are shown in Fig. 5 for these two cases.

For qualitative considerations this simple picture can well be applied to the case of the real crystal. The frequency spectrum of the real crystal exhibits an increasingly high oscillator density at high frequencies. It is sufficient, for this simplified consideration, to replace the Einstein frequency by the upper frequency of the vibrational spectrum of the real crystal. This

limiting frequency ω_g is related, approximately, to the characteristic temperature θ of the crystal by the equation $\hbar\omega_g = k\theta$.

The essential condition for a high probability of recoilless nuclear transitions now has the form

$$E_0^2/2Mc^2 < k\theta \qquad (3)$$

The condition given here is quite restrictive because it limits the observation of recoilless resonance absorption to nuclear transitions of relatively low energy; the upper limit lies at about 150 keV.

If $\Delta E = E_0^2/2Mc^2$ is small in comparison to the upper energy limit of the frequency spectrum, the percentage of recoilless processes that occur is high even at room temperature. However, if $\overline{DE}$ is about equal to the upper energy limit of the frequency spectrum, then the probability of transitions of the crystal oscillators must be correspondingly reduced by the use of low temperatures in order to arrive at measurable effects.

After the appearance of the observed strong resonance absorption in ^{191}Ir had been traced back to the phenomenon of recoilless nuclear resonance absorption, the next step was to compute the probability of the effect in a general form. This probability, also known as the Debye-Waller factor, in analogy with the terminology used in X-ray scattering, is, as I have already pointed out, strongly dependent on the temperature and the energy of the nuclear transition. This dependence is illustrated in Fig. *6* by two examples.

The shape and location of the emission and absorption lines, as shown in Fig. 2 for the case of a free nucleus, are modified considerably by the influence of the chemical binding. While the centres of the lines as given by Eq. (2) are retained, each of them shows a complicated structure which reflects different single and multiple oscillator transitions, hence the notion « line » is applied here in a more generalized sense.

The most interesting prediction of the theory is the appearance of a strong line with the natural line width appearing in the structure of both « lines » at the position of the transition energy E_o. This line represents the recoilless processes. The strong prominence of these lines with the natural line width within the total line structure is not so surprising when one considers that all the recoilless processes in the emission and absorption spectra appear within an energy range of the order of magnitude of the natural line width. The gamma transitions associated with the oscillator transitions appear, on the other hand, in an energy range of the order of magnitude of the Debye

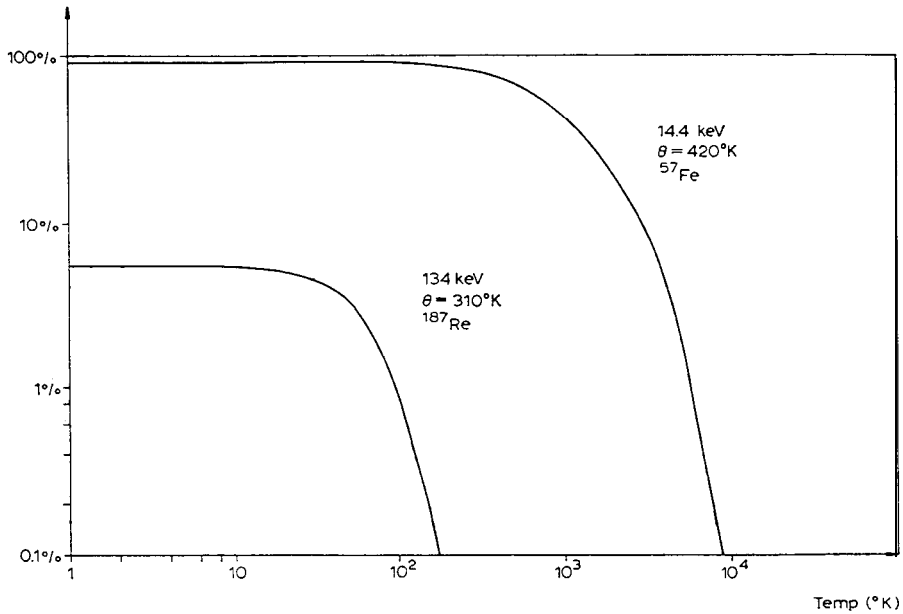

Fig. 6. Fractions of recoil-free nuclear transitions (Debye-Waller factors) in ^{57}Fe and ^{187}Re, shown as functions of the temperature.

temperature of the crystal; this energy range is always broader than the natural line width by many orders of magnitude.

All these considerations provided a very plausible explanation of the origin of the observed resonance absorption in ^{191}Ir at low temperatures. The agreement between the experimentally observed temperature dependence of the absorption (Fig. 4) and the theoretically computed dependence was satisfactory when one considered that in the first calculation the Debye approximation was used for the frequency spectrum because the actual frequency spectra of the crystals used were not known. Notwithstanding this qualitative agreement between experiment and theory, the situation still appeared to be somewhat unsatisfactory. The theory predicted that under the prescribed conditions lines of natural width should appear in the structure of the emission and absorption lines at the value of the transition energy E_o.

While the assumption of the existence of these lines made it possible to explain the experiments thus far carried out, the keystone was evidently still missing - namely, direct experimental proof of the existence of these lines and, especially, a demonstration that their widths were indeed the natural

line widths. It was necessary to find a detector which had the necessary energy resolution to measure the profiles of these extremely sharp lines. The use of conventional detectors was excluded from the start. For example, the scintillation detectors frequently used for gamma-ray measurements in the relevant energy region have resolutions of the order of magnitude of 10^{4} eV, while the natural line widths of the observed lines were only about 10^{-6} eV. The possibility of using the atomic nuclei themselves as detectors was suggested as a way out of this situation. As was shown above, an essential prediction of the theory was that the recoilless lines in both the emission and the absorption spectra should appear at the same position - that is, at the value of the transition energy.

Both lines would, therefore, overlap completely, this being the reason for the strong absorption effect. If one could succeed in partially removing the perfect overlap by a relative displacement of the lines, the absorption effect of the recoilless lines should disappear correspondingly.

In the experiment carried out to test the validity of this prediction, the idea was to accomplish the relative shift of the lines by means of the Doppler effect, so that a relative velocity would be imparted to the nuclei of the source with respect to the nuclei of the absorber. Here we had a sort of reversal of the experiment carried out by Moon. Whereas in that experiment the resonance condition destroyed by the recoil-energy losses was regained

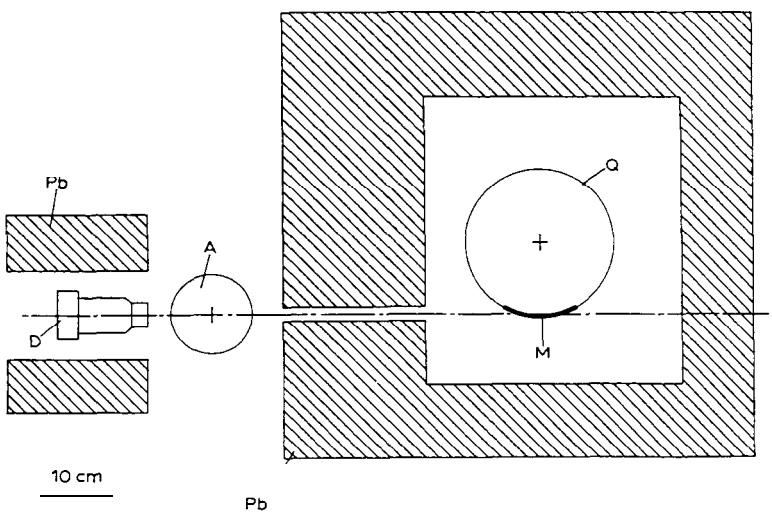

Fig. 7. Experimental arrangement. A, absorber-cryostat; Q, rotating cryostat with source; *D*, scintillation detector.

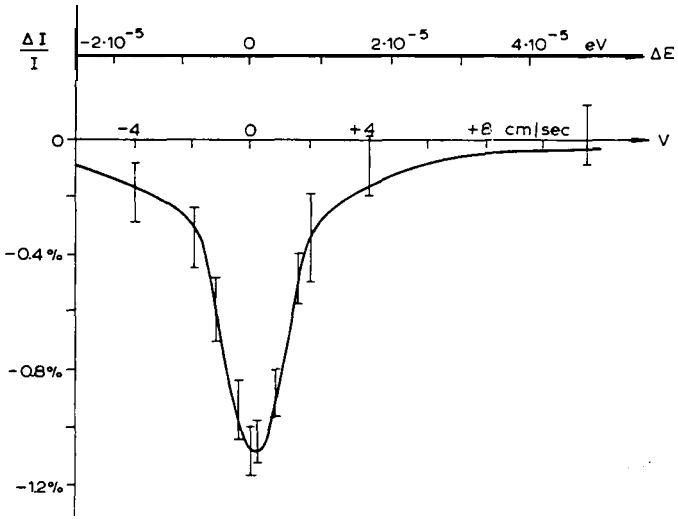

Fig. 8. Relative intensity ratio $\Delta I/I$ of gamma radiation measured behind the resonant iridium absorber, in comparison with intensities measured behind a nonresonant absorber.

by the application of an appropriate relative velocity, here the resonance condition fulfilled in the experiment was to be destroyed through the application of a relative velocity. And yet there was an essential difference between this and Moon's experiment. There, the width of the lines that were displaced relative to one another was determined by the thermal motion of the nuclei in the source and absorber; here, the line widths were sharper by four orders of magnitude. This made it possible to shift them by applying velocities smaller by four orders of magnitude. The indicated velocities were in the region of centimeters per second.

Fig. 7 shows the experimental arrangement[6]. For simplicity, I decided to move the source by means of a turn-table. Only the part of the rotational motion marked by the heavy line in Fig. 7 was used for the measurement - namely, that part in which the source was moving relative to the absorber with approximately constant velocity. The intensity at the detector was measured as a function of the relative velocity between the source and the absorber. Since the preparation of the conical-gear assembly necessary for adjusting the various velocities caused a disagreeable delay in this experiment which was so exciting for me, I took advantage of the existence in Germany of a highly developed industry for the production of mechanical toys. A

day spent in the Heidelberg toy shops contributed materially to the acceleration of the work.

Fig. 8 shows the result of this experiment, a result which was just what had been expected. As the figure demonstrates, a maximum resonance absorption was actually present at zero relative velocity as a result of the complete superposition of the recoilless emission and absorption lines; therefore, minimal radiation intensity passing through the absorber was observed in the detector. With increasing relative velocity the emission line was shifted to higher or lower energies, the resonance absorption decreased, and the observed intensity correspondingly increased. The necessary relative velocities were manifestly only of the order of centimeters per second. Since the experiment consisted essentially of producing a shift of an emission line of width Γ relative to an absorption line of width Γ, the observed line possessed a width which, with a small correction, was equal to 2Γ. It was especially satisfying that the line width thus obtained agreed with the width determined in the first experiment3 under much more difficult conditions. While absorption effects of the order of 1 per cent were observed in the second experiment, an effect of the order of a hundredth of 1 per cent had been achieved in the earlier work. Thus, direct proof of the existence of recoilless absorption was achieved.

The significance of the new method was immediately apparent, although not all of its consequences were immediately realized. With 4.6×10^{-6} eV the line width observed in the 129 keV gamma transition of ^{191}Ir was already smaller than the usual thermal line widths by many orders of magnitude. Let us define the energy resolving power $E/\delta E$ by the ratio of the energy E_o of the nuclear transition and the natural width Γ of the line; that is, $E/\delta E = E_o/\Gamma$. Then we obtain in the present case $E/\delta E = 2.8 \times 10^{10}$. The actual energy resolution achieved was already much greater in this experiment, since energy shifts amounting to a small fraction of the natural line width were actually observed. Since then, it has become possible, by utilizing other nuclear isotopes, to improve the obtainable energy resolution once more by several orders of magnitude. It is this property of the recoilless nuclear resonance absorption - namely, that it is possible by this means to measure extraordinarily small energy differences between two systems - which gave the method its significance and opened up a broad field of possible applications.

Thus, the extraordinary sharpness of the recoilless gamma lines brought direct investigation of the hyperfine structure of nuclear transitions within

the range of possibility. As a rule, atomic nuclei possess electric and magnetic moments in their various excited states. The interaction of these moments with internal or external fields leads to a splitting of nuclear levels into a number of states that are very close to one another. This hyperfine structure normally remains hidden in gamma lines, since the thermal width of a gamma line is always very large in comparison to the spacing of the hyperfine levels of the nuclear state. When the distances between the individual hyperfine components are larger than the natural widths of the gamma lines, as is frequently the case, and when the conditions necessary for the observation of recoilless absorption are fulfilled, this method makes possible direct measurements of the hyperfine structure of both participating nuclear states. Instead of a single line with the natural line width, a whole set of lines now appears in the emission spectrum, corresponding to recoilless transitions between the hyperfine levels of the nuclear excited and ground states. The same situation holds for the absorption spectrum. Studies of this type yield predictions on the magnetic dipole and electric quadrupole moments of the nuclear states involved, as well as predictions on the magnetic fields and gradients of the electric field prevailing at the site of the nucleus. The special promise of such measurements lies primarily in the possibility of obtaining information on the hyperfine splitting of excited nuclear states. In fact, several moments of excited nuclear states have been determined in this way in various laboratories. However, in our laboratory and in laboratories of many others now working in this region, this method is used mainly for studying the internal fields existing at the site of the nucleus; such studies have already led to a series of interesting results.

In addition to measurement of the fields located in crystals at nuclear sites and to measurement of the moments of excited nuclear states, studies of a number of important effects have been made during the past two years in a large number of laboratories. The observation of these effects was made possible by means of even sharper nuclear transitions, especially that of the 14.4-keV transition in ^{57}Fe.

Particular mention should be made here of the beautiful measurements of the energy shift of radiation quanta in the gravitational field of the earth', the observation of the second-order Doppler effect, and the measurements of the isomeric shift. However, discussion of these and of a whole series of other effects which have been studied by means of the method of recoilless nuclear resonance lies outside the framework of this address.

The interpretation of the formalism which underlies the quantitative de-

scription of recoilless nuclear resonance absorption has led to extremely active discussions. The question particularly raised has been whether the effect can be explained classically and, in this connection, whether the momentum transfer takes place as a continuous process during the lifetime τ of the excited nuclear state or as a spontaneous process in the sense of quantum electrodynamics. The question raised here is closely connected with the problems encountered in the dualistic description of radiation as a wave process or as a stream of free particles. Notwithstanding the fact that many details of the recoilless resonance absorption can be described by classical models, I should characterize this effect as a specifically quantum-mechanical one. In particular, it can be shown by the mathematical formulation of the theory that the momentum transfer takes place spontaneously. This can be demonstrated experimentally, not by an individual process but, rather, by the measurement of certain integral quantities, as, for example, the Debye-Waller factor.

In conclusion, let me now say a few words on the limits of the methods described. An upper limit for the usable natural line widths has certainly been given when the widths approach the width of the vibrational spectrum of the crystal oscillators.

In this particular case it becomes impossible to distinguish clearly between nuclear processes which are simultaneously accompanied by oscillator transitions and those which are not. However, this would require nuclear lifetimes of less than 10^{-13} second, which do not occur in the nuclear levels available for this type of experiment. Therefore this upper limit is both uninteresting and unrealistic.

More difficult is the question of a lower limit for the available line widths. To go beyond the limit so far attained of about 10^{-8} eV for the natural line widths is quite possible in principle. There are, however, a number of factors which have delayed extension of the method into the region of higher sensitivity. On the one hand, there are very few nuclei of stable isotopes whose first excited states possess the desired lifetime of greater than 10^{-7} second. On the other hand, all the previously mentioned side effects of such sharp lines play a dominant role; small disturbances of the crystal symmetry and small contaminations quickly lead to individual shifts in the nuclear states, and these shifts, as a group, produce a very considerable broadening of the extremely sharp lines. In this way the resonance condition is so far violated that the lines are not observed. However, there is a well-founded view that still more sharply defined nuclear transitions will be available before long.

These should lead to multiplication of the possibilities for applying the method of recoilless absorption. We may therefore hope that this young branch of physics stands only at its threshold, and that it will be developed in the future, not only to extend the application of existing knowledge but to make possible new advances in the exciting world of unknown phenomena and effects.

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7. R. V. Pound and G. A. Rebka, Jr., *Phys. Rev. Letters, 4* (1960) 337. A complete bibliography of all pertinent researches is included in H. Frauenfelder, *The Mössbauer Effect,* to be published *in* the series *Frontiers in Physics,* Benjamin, New York.

Biography

Rudolf Ludwig Mössbauer was born in Munich on the 31st of January 1929, the son of Ludwig Mössbauer and his wife Erna, *née* Ernst. He was educated at the « Oberschule » (non-classical secondary school) in Munich-Pasing and left after matriculating in 1948. After working for one year in industrial laboratories, he started reading physics at the Technical University (Technische Hochschule) in Munich in 1949 and passed his intermediate degree examinations in 1952. During the years 1953 and 1954 he completed his thesis at the Laboratory for Applied Physics at the Technical University in Munich, at the same time acting as assistant lecturer at its Institute of Mathematics. From 1955 to 1957 he worked on his thesis for the doctorate and carried out a series of investigations at the Institute for Physics of the Max Planck Institute for Medical Research in Heidelberg, in the course of which he carried out the first experimental observation of the phenomenon of Recoilless Nuclear Resonance Absorption. In January 1958 he received his degree under Professor Maier-Leibnitz at the Technical University in Munich. In 1958, again at the Max Planck Institute in Heidelberg, he provided the direct experimental evidence of the existence of Recoilless Nuclear Resonance Absorption. For the year 1959 he was appointed scientific assistant at the Technical University in Munich. He accepted an invitation by the California Institute of Technology in Pasadena, U.S.A., in 1960 and there continued his investigations of gamma absorption, at first as Research Fellow and later as Senior Research Fellow. He was appointed Professor of Physics at the California Institute of Technology in 1961.

From the year 1953 onwards his main work was directed towards the study of absorption of gamma rays in matter, in particular the study of nuclear resonance absorption. This led to the discovery of Recoilless Nuclear Resonance Absorption and its theoretical interpretation. During the last few years he has been investigating problems of nuclear physics and of solid state physics by applying already previously established methods.

His work in the field of Recoilless Nuclear Resonance Absorption has been rewarded by the following prizes: Prize of the Research Corporation

New York (1960); Röntgen Prize of the University of Giessen (1961); Elliot Cresson Medal, Franklin Institute (1961).

He is married to Elisabeth, *née* Pritz, and has two children, Peter and Regine.

Physics 1962

LEV DAVIDOVIČ LANDAU

« *for his pioneering theories for condensed matter, especially liquid helium* »

Physics 1962

Presentation Speech by Professor I. Waller, member of the Swedish Academy of Sciences

Your Majesties, Your Royal Highnesses, Ladies and Gentlemen.

The winner of this year's Nobel Prize in Physics, Professor Lev Davidovič Landau at Moscow University, was born in Baku, 1908. His mathematical talents appeared at a very early age and at the age of 14 he began his studies at the University of Leningrad. After finishing them he spent one and a half years abroad, in particular with the well-known atomic physicist Niels Bohr in Copenhagen. He made a strong impression during this time thanks to his brilliant intellect and great outspokenness.

In 1930 Landau published a quantum theoretical investigation concerning the behaviour of free electrons in a magnetic field which immediately gave him international fame. This work turned out to be essential for the understanding of the properties of metals. Starting from new fruitful ideas Landau found after his return home, often in collaboration with his pupils, important results concerning the structure of magnetic substances and supraconductors and advanced fundamental theories for phase transformations and thermodynamical fluctuations.

Landau's ability to see the core of a problem and his unique physical intuition appear clearly in his investigations on liquid helium which he started after having been attached in 1937 to the Institute for Physical Problems in Moscow. The head of this institute was the famous physicist Kapitza who then performed interesting experiments on liquid helium. The natural helium gas had earlier been liquefied by cooling to about four degrees above the absolute zero of temperature and subsequent research had shown that this fluid when further cooled about two degrees was transformed to a new state which has quite strange properties. According to a term introduced by Kapitza it is superfluid which means that it can easily flow through very fine capillaries and slits which almost completely prevent the flow of all other liquids.

The originality in Landau's attack on the problem of explaining these phenomena was that he considered the quantized states of motion of the whole liquid instead of the states of the single atoms as other scientists had

done earlier. Landau started by considering the state of the fluid at the absolute zero temperature which is its ground state. He described the excited states of the liquid by the motion of certain fictive particles called quasi-particles. Landau combined experimental results with his calculations and deduced in this way the mechanical properties of the quasi-particles. These results, from which the properties of the fluid could be calculated, were later directly confirmed by investigations on the scattering of neutrons in liquid helium. Such experiments were first performed at Atomic Energy Ltd. in Stockholm in 1957. Landau further found that there exists in liquid helium besides ordinary sound waves also waves of a « second sound ». He inspired thereby a Russian scientist to confirm this phenomenon experimentally.

Natural helium consists of an isotope of atomic weight 4 apart from about one millionth of another isotope of atomic weight 3. The lighter isotope has been studied in the liquid state since about 1950. This kind of liquid helium has properties which are quite different from those of the heavier isotope because the helium nuclei of atomic weights 3 and 4 are essentially different. A satisfactory theory for the lighter helium liquid was first given by Landau in 1956-1958 and has many formal similarities with his above-mentioned theory for the heavier isotope. The new theory is valid only at very low temperatures, less than one tenth of a degree above absolute zero. This is, however, the most interesting temperature range. Due to the difficulty of making measurements at these low temperatures the theory was not experimentally tested until very recently. These tests have been the more favourable for the theory the more the measuring technique has been refined. Landau has also predicted a new kind of wave propagation for this liquid and has called it zero sound. He has thereby stimulated experimental scientists to great efforts aiming to detect zero sound.

The importance of Landau's investigations are apparent when one considers that an important goal of physics research is to explain the properties of liquids as completely as it has been possible to explain the properties of crystals and of rarefied gases. In their efforts to attain this goal the scientists have in general met with insurmountable difficulties. An essential exception is Landau's theories of liquid helium which therefore are an achievement of great and profound importance.

Besides his investigations on condensed matter, i.e. matter in the solid and liquid state for which he is now awarded the Nobel Prize, Landau has also made contributions of the utmost importance to other parts of physics, in

particular to the theories of quantized fields and of elementary particles. He has by his original ideas and masterly investigations exercised far-reaching influence on the evolution of the atomic science of our time.

Professor Landau has unfortunately not yet fully recovered from the severe accident which he sustained at the beginning of this year. He is therefore not here to receive his Nobel Prize which is instead handed to him today by the Ambassador of Sweden in Moscow. On behalf of the Swedish Academy of Sciences I wish to express the hope that Professor Landau will soon completely recover.

No Lecture was delivered by Professor L. D. Landau

Biography

Lev Davidovič Landau was born in Baku on January 22, 1908, as the son of an engineer and a physician.

After graduating from the Physical Department of Leningrad University at the age of 19, he began his scientific career at the Leningrad Physico-Technical Institute. The years 1929-1931 he spent abroad, partly as a Rockefeller Foundation Fellow, working in Germany, Switzerland, England and, especially, in Copenhagen under Niels Bohr.

During 1932-1937 he was head of the Theoretical Department of the Ukrainian Physico-Technical Institute at Kharkov, and since 1937 he has been the head of the Theoretical Department of the Institute for Physical Problems of the Academy of Sciences of the U.S.S.R. in Moscow. Simultaneously he taught constantly as a professor of theoretical physics in the Kharkov and Moscow State Universities.

Landau's work covers all branches of theoretical physics, ranging from fluid mechanics to quantum field theory. A large portion of his papers refers to the theory of the condensed state. They started in 1936 with a formulation of a general thermodynamical theory of the phase transitions of the second order. After P. L. Kapitza's discovery, in 1938, of the superfluidity of liquid helium, Landau began extensive research which led him to the construction of the complete theory of the « quantum liquids » at very low temperatures. His papers of 1941-1947 are devoted to the theory of the quantum liquids of the « Bose type », to which the superfluid liquid helium (the usual isotope ^{4}He) refers. During 1956-1958 he formulated the theory of the quantum liquids of the « Fermi type », to which liquid helium of isotope ^{3}He refers.

In 1946 he was elected to the membership of the Academy of Sciences of the U.S.S.R. The U.S.S.R. State Prize was awarded to him several times, and in 1962 he received, jointly with E. M. Lifshitz, the Lenin Science Prize for their *Course of Theoretical Physics.*

Landau is a Foreign Member of the Royal Society (London), of the Danish Royal Academy of Sciences, of the Netherlands Royal Academy of Sciences, Foreign Associate of the National Academy of Sciences of the

U.S.A., Honorary Member of the American Academy of Arts and Sciences, of the Physical Society (London), and of the Physical Society of France. In 1961, he received the Max Planck Medal and the Fritz London Prize.

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