Physics 1989

NORMAN F RAMSEY

for the invention of the separated oscillatory fields method and its use in the hydrogen maser and other atomic clocks

HANS G DEHMELT and WOLFGANG PAUL

for the development of the ion trap technique

THE NOBEL PRIZE IN PHYSICS

Speech by Professor Ingvar Lindgren of the Royal Swedish Academy of Sciences.
Translation from the Swedish text.

Your Majesties, Your Royal Highnesses, Ladies and Gentlemen.

This year's Nobel Prize in Physics is shared between three scientists, Professor *Norman Ramsey,* Harvard University, Professor *Hans Dehmelt,* University of Washington, Seattle, and Professor Wolfgang *Paul,* University of Bonn, for *"contributions of importance for the development* of *atomic precision spectroscopy."*

The works of the laureates have led to dramatic advances in the field of precision spectroscopy in recent years. Methods have been developed that form the basis for our present definition of time, and these techniques are applied for such disparate purposes as testing Einstein's general theory of relativity and measuring continental drift.

An atom has certain fixed energy levels, and transition between these levels can take place by means of emission or absorption of electromagnetic radiation, such as light. Transition between closely spaced levels can be induced by means of radio-frequency radiation, and this forms the basis for so-called *resonance methods.* The first method of this kind was introduced by Professor I. Rabi in 1937, and the same basic idea underlies the resonance methods developed later, such as nuclear magnetic resonance (NMR), electron-spin resonance (ESR) and optical pumping.

In Rabi's method a beam of atoms passes through an oscillating field, and if the frequency of that field is right, transition between atomic levels can take place. In 1949 one of this year's laureates, Norman Ramsey, modified this method by introducing *two separate oscillatory fields.* Due to the interaction between these fields, a very sharp interference pattern appears. This discovery made it possible to improve precision by several orders of magnitude, and this started the development towards high-precision spectroscopy.

One important application of Ramsey's method is the *cesium clock,* an atomic clock on which our definition of time has been based since 1967. One second is no longer based on the rotation of the earth or its movement around the sun, but is instead defined as the time interval during which the cesium atom makes a certain number of oscillations. The cesium clock has a margin of error equivalent to one thousandth of a second in three hundred years. Compared with this clock, the earth behaves like a bobbing duck.

The dream of the spectroscopist is to be able to study a single atom or ion under constant conditions for a long period of time. In recent years, this dream has to a large extent been realized. The basic tool is here the *ion trap,* which was introduced in the 1950s by another of this year's laureates, Wolfgang Paul in Bonn. His technique was further refined by the third laureate, Hans Dehmelt, and his co-workers in Seattle into what is now known as *ion-trap spectroscopy.*

Dehmelt and his associates used this spectroscopy primarily for studying electrons, and in 1973 they succeeded for the first time in observing a *single electron* in an ion trap, and in confining it there for weeks and months. One property of the electron, its magnetic moment, was measured to 12 digits, 11 of which have later been verified theoretically. This represents a most stringent test of the atomic theory known as *quantum electrodynamics* (QED).

In a similar way, Dehmelt and others were later able to trap and study a *single ion,* which represents a true landmark in the history of spectroscopy. The technique is now being used in development of improved atomic clocks, in particular at the National Institute for Standards and Technology (formerly the National Bureau of Standards) in Boulder, Colorado.

Another technique for storing atoms and observing them for a long period of time has been developed by Ramsey and his co-workers at Harvard University, *the* hydrogen *maser*. This instrument is mainly used as a secondary standard for time and frequency with a higher stability for intermediate times than the cesium clock. It is used, for instance, for the determination of continental drift, using VLBI (Very Long Base Line Interferometry). Here, signals from a radio star are received with radio telescopes on two continents and compared by means of very accurate time settings from two hydrogen masers. Another application is the test of Einstein’s general theory of relativity. According to this theory, time elapses faster on the top of a mountain than down in the valley. In order to test this prediction, a hydrogen maser was sent up in a rocket to a height of 10,000 km and its frequency compared with that of another hydrogen maser on the ground. The predicted shift has been verified to one part in ten thousand.

The continued rapid development of the atomic clock can be foreseen in the near future. An accuracy of one *part in one billion billions* is considered realistic. This corresponds to an uncertainty of less than one second since the creation of the universe fifteen billion years ago.

Do we need such accuracy? It is clear that navigation and communication in space require a growing degree of exactness, and existing atomic clocks are already being utilized in these fields to the limit of their capacity. The new technique may be even more important for testing very fundamental principles of physics. Further tests of quantum physics and relativity theory may force us to revise our assumptions about time and space or about the smallest building blocks of matter.

Norman F. Ramsey

NORMAN F. RAMSEY

I was born August 27, 1915 in Washington, D.C. My mother, daughter of German immigrants, had been a mathematics instructor at the University of Kansas. My father, descended from Scottish refugees and a West Point graduate, was an officer in the Army Ordnance Corps. His frequently changing assignments took us from Washington, DC to Topeka, Kansas, to Paris, France, to Picatinny Arsenal near Dover, New Jersey, and to Fort Leavenworth, Kansas. With two of the moves I skipped a grade and, encouraged by my supportive parents and teachers, I graduated from high school with a high academic record at the age of 15.

My early interest in science was stimulated by reading an article on the quantum theory of the atom. But at that time I did not realize that physics could be a profession. My parents presumed that I would try to follow my father's footsteps to West Point, but I was too young to be admitted there. I was offered a scholarship to Kansas University but my parents again moved- this time to New York City. Thus I entered Columbia College in 1931, during the great depression. Though I started in engineering, I soon learned that I wanted a deeper understanding of nature than was then expected of engineers so I shifted to mathematics. By winning yearly competitive mathematics contests, I was honored in my senior year by being given the mathematics teaching assistantship normally reserved for graduate students. At the time I graduated from Columbia in 1935, I discovered that physics was a possible profession and was the field that most excited my curiosity and interest.

Columbia gave me a Kellett Fellowship to Cambridge University, England, where I enrolled as a physics undergraduate. The Cavendish Laboratory in Cambridge was then an exciting world center for physics with a stellar array of physicists: J.J. Thomson, Rutherford, Chadwick, Cockcroft, Eddington, Appleton, Born, Fowler, Bullard, Goldhaber and Dirac. An essay I wrote at Cambridge for my tutor, Maurice Goldhaber, first stimulated my interest in molecular beams and in the possiblity of later doing my Ph. D. research with I. I. Rabi at Columbia.

After receiving from Cambridge my second bachelors degree, I therefore returned to Columbia to do research with Rabi. At the time I arrived Rabi was rather discouraged about the future of molecular beam research, but this discouragement soon vanished when he invented the molecular beam magnetic resonance method which became a potent source for new fundamental discoveries in physics. This invention gave me the unique opportunity to be the first graduate student to work with Rabi and his associates, Zacharias, Kellogg, Millman and Kusch, in the new field of magnetic resonance and to share in the discovery of the deuteron quadrupole moment.

Following the completion of my Columbia thesis, I went to Washington, D. C. as a Carnegie Institution Fellow, where I studied neutron-proton and proton-helium scattering.

In the summer of 1940 I married Elinor Jameson of Brooklyn, New York, and we went to the University of Illinois with the expectation of spending the rest of our lives there, but our stay was short lived. World War II was rampant in Europe and within a few weeks we left for the MIT Radiation Laboratory. During the next two years I headed the group developing radar at 3 cm wavelength and then went to Washington as a radar consultant to the Secretary of War. In 1943 we went to Los Alamos, New Mexico, to work on the Manhattan Project.

As soon as the war ended I eagerly returned to Columbia University as a professor and research scientist. Rabi and I immediately set out to revive the molecular beam laboratory which had been abandoned during the war. My first graduate student, William Nierenberg, and I measured a number of nuclear magnetic dipole and electric quadrupole moments and Rabi and I started two other students, Nafe and Nelson, on a fundamental experiment to measure accurately the atomic hydrogen hyperfine separation.. During this period Rabi and I also initiated the actions that led to the establishment of the Brookhaven National Laboratory on Long Island, New York, where in 1946 I became the first head of the Physics Department.

In 1947 I moved to Harvard University where I taught for 40 years except for visiting professorships at Middlebury College, Oxford University, Mt. Holyoke College and the University of Virginia. At Harvard I established a molecular beam laboratory with the intent of doing accurate molecular beam magnetic resonance experiments, but I had difficulty in obtaining magnetic fields of the required uniformity. Inspired by this failure, I invented the separated oscillatory field method which permitted us to achieve the desired accuracy with the available magnets. My graduate students and I then used this method to measure in many different molecules a number of molecular and nuclear properties including nuclear spins, nuclear magnetic dipole and electric quadrupole moments, rotational magnetic moments of molecules, spin-rotational interactions, spin-spin interactions, electron distributions in molecules, etc. Although we studied a wide variety of molecules we concentrated on the diatomic molecules of the hydrogen isotopes since these molecules were most suitable for comparing theory and experiment. During this period I also consulted with various groups that were applying the separated oscillatory field method to atomic clocks and I analyzed the precautions which must be taken to avoid errors. Although our original molecular beam research was only with the magnetic resonance method, we later built a separated oscillatory fields electric resonance apparatus and used it to study polar molecules.

In an effort to attain even greater accuracy and to do so with atomic hydrogen, the simplest fundamental atom, Daniel Kleppner, a former student, and I invented the atomic hydrogen maser. We then used it for accurate measurements of the hyperfine separations of atomic hydrogen, deuterium and tritium and for determining the extent to which the hyperfine structure was modified by the application of external electric and magnetic fields. We also participated with Robert Vessot and others in converting a hydrogen maser to a clock of unprecedented stability.

While these experiments were being carried out with some of my graduate students, I worked with other students and associates to apply similar precision methods to beams of polarized neutrons. At the Institut Laue-Langevin in Grenoble, France, we measured accurately the magnetic moment of the neutron, set a low limit to the electric dipole moment of the neutron as a test of time reversal symmetry and discovered and measured the parity non-conserving rotations of the spins of neutrons passing through various materials.

Concurrently with my molecular and neutron beam research, I was also teaching and involved with other scientific activities. I was director of the Harvard Cyclotron during its construction and early operation and participated in proton-proton scattering experiments with that cyclotron. I was later chairman of the joint Harvard-MIT committee managing the construction of the 6 GeV Cambridge Electron Accelerator and used that device for various particle physics experiments including electron-proton scattering. For a year and a half I was on leave- from Harvard as the first Assistant Secretary General for Science (Science Advisor) in NATO where I initiated the NATO programs for Advanced Study Institutes, Fellowships and Research Grants. For sixteen exciting years I was on leave half time from Harvard as President of Universities Research Association which exercised its management responsibilities for the construction and operation of the Fermilab accelerator through two outstanding laboratory directors, Robert R. Wilson and Leon Lederman.

Although I am primarily an experimental physicist, theoretical physics is my hobby and I have published several theoretical papers including early discussions of parity and time reversal symmetry, the first successful theory of the NMR chemical shifts, theories of nuclear interactions in molecules and the theory of thermodynamics and statistical mechanics at negative absolute temperatures.

I officially retired from Harvard in 1986, but I have remained active in physics. For one year I was a research fellow at the Joint Institute for Laboratory Astrophysics at the University of Colorado and I now periodically revisit JILA as an Adjunct Research Fellow. Subsequent to our year in Colorado, I have been visiting professor at The University of Chicago, Williams College and the University of Michigan. I continue writing and theoretical calculations in my Harvard office and with my collaborators we are continuing our neutron experiments at Grenoble.

After Elinor died in 1983, I married Ellie Welch of Brookline, Massachusetts and we now have a combined family of seven children and six grandchildren. We enjoy downhill and cross country skiing, hiking, bicycling and trekking as well as musical and cultural events.

I have greatly enjoyed my years as a teacher and research physicist and continue to do so. The research collaborations and close friendships with my eighty-four graduate students have given me especially great pleasure. I hope they have learned as much from me as I have from them.

Books:

Experimental Nuclear *Phyics,* with E. Segrè, John Wiley and Sons, Inc. (1953) *Nuclear Moments,* John Wiley and Sons, Inc. *(1953) Molecular Beams,* Oxford University Press (1956 and 1985), and *Quick Calculus,* with D. Kleppner, John Wiley and Sons, Inc. (1965 and 1985).

Honorary D. Sc.:

Case-Western Reserve University, Middlebury College, Oxford University, The Rockefeller University, The University of Chicago, and The University of Sussex.

Honors:

E. O Lawrence Award, 1960; Trustee Carnegie Endowment for International Peace, 1962 - 86; Davisson-Germer Prize, 1974; Trustee of The Rockefeller University, 1977- ; President of the American Physical Society, 1978 - 79; Chairman Board of Governors of American Institute of Physics, 1980 - 86; President of United Chapters of Phi Beta Kappa, 1984 - 88; IEEE Medal of Honor, 1984; Rabi Prize, 1985; Rumford Premium, 1985; Chairman Board of Physics and Astronomy of National Research Council, 1985 - 1989; Compton Medal, 1986; Oersted Medal, 1988; National Medal of Science, 1988.

(added in 1991) :

Doctor of Civil Law (D.C.L.), Oxford University (1990)

D.Sc., University of Houston (1990) and Carleton College (1991)

Foreign Associate, French Academy of Science (1990)

Principal Publications:

I Magnetic Moments of Proton and Deuteron. Radiofrequency Spectrum of H_2 in Magnetic fields. With J. M. B. Kellogg, I. I. Rabi and J. R. Zacharias, Phys. Rev. 56, 728 (1939).

2. Electrical Quadruple Moment of the Deuteron. Radiofrequency Spectra of HD and D_2 Molecules in a Magnetric Field. With J. M. B. Kellogg, I. I. Rabi and J. R. Zacharias, Phys. Rev. 57, 677 (1940).
3. Rotational Magnetic Moments of H_2, D_2 and HD rnolecules. Phys. Rev. 58, 226 (1940).
4. Molecular Beam Resonance Method with Separated Oscillating Fields. Phys. Rev. 78, 695 (1950).
5. Magnetic Shielding of Nuclei in Molecules. Phys. Rev. 78, 699 (1950).
6. On the Possibility of Electric Dipole Moments for Elementary Particles and Nuclei. With E. M. Purcell, Phys. Rev. 78, 807(L) (1950).

7. Nuclear Audiofrequency Spectroscopy by Resonant Heating of the Nuclear Spin System. With K. V. Pound, Phys. Rev. 81, 278(I.) (1951).
8. Proton-Proton Scattering at 105 MeV and **75** MeV.. Withl K. W. Brige and U. E. Kruse, Phys. Rev. 83, 274 (1951).
9. Theory of Molecular Hydrogen and Deuterium in Magnetic. Fields. Phys. Rev. 85, 60 (1952).
IO. Chemical Effects in Nuclear Magnetic Resonance and in Diamagnetic Susceptibility. Phys. Rev. 86, 243 (1952).
11. Nuclear Radiofrequency Spectra of H_2 and D_2 in High and Low Magnetic Fields. With H. G. Kolsky, T. E. Phipps, and H. B. Silsbec, Phys. Rev. 87, 395 (1952).
12. Nuclear Radiofrequency Spectra of' D_2 and H_z in Intermediate and Strong Magnetic Fields. With N. ,J. Harrick, R. G. Barns and P. J. Bray, Phys. Rev. 90, 260 (1953).
13. Electron Coupled Interations between Nuclear Spins in Molecules. Phys. Rev. 91, 303 (1953).
14. Use of' Rotating Coordinates in Magnetic Resonance Problems. With I. I. Rabi and J. Schwinger, Rev. Mod. Phy. 26, 167 (1954).
15. Resonance Transitions Induced by Perturbations at Two or More Different Frequencies. Phys. Rcv. 100, 1191 (1955).
16. Thermodynamics and Statistical Mechanics at Negative Absolute Temperatures, Phys. Rev. 103, 20 (1956).
17. Molecular Beams, Published by Oxford University Press, England (1956).
18. Resonance Experiments in Successive Oscillatory Fields. Rev. Sci. Instr. 28, ***57(L)*** (1957).
19. Experimental Limit to the Electric Dipole Moment of' the Neutron. With ,J. H. Smith and E. M. Purcell, Phys. Rev. 108, 120 (1957).
20. Time Reversal, Charge Conjugation, Magnetic Pole Conjugation, and Parity. Phys. Rev 109, 225 (1958).
21. Molecular Beam Resonances in Oscillatory Fields of Nonuniform Amplitudcs and Phases. Phys. Rev. 109, 822 (1958).
22. Radiofrequency Spectra of Hydrogen Deuteride in Strong Magnetic- Fields. With W. F. Quinn, J. M. Baker, J. T. LaTourrctte, Phys. Rev. ***112,*** 1929 (19.X).
23. On the Significance of Potentials in Quantum Theory. With W. H. Furry, Phys. Rev. ***118, 623*** (1960).
24. Atomic Hydrogen Maser. With H. M. Goldenberg and D. Kleppner, Phys. Rev. Letters 8, 361 (1960).
25. Theory of' the Hydrogen Maser. With D. Kleppner and H. M. Goldcnberg, Phys. Rev. ***126, 603 (1962).***
26. Hyperfine Structure of Ground State of Atomic Hydrogen. With S. R. Crampton and D. Kleppner, Phys. Rev. Letters ***11, 338 (1963).***
27. Hydrogen Maser Principles and Techniques. With D. Kleppner, H. C. Berg, S. B. Crampton, R. F. C. Vessot, H. E. Peters and J. Vanier, Phys. Rev. ***138,*** A972 (1965).
28. Measurement of Proton Electromagnetic Form Factors at High Momentum Transfer. With K. W. Chcn, J. K. Dunning, Jr., A. A. Cone, J. K. Walker and Richard Wilson, Phys. Rev. ***141,*** 1267 (1966).
29. Absolute Value of' the Proton g Factor. With T. Myint, D. Kleppner and H. G. Robinson, Phys. Rev. Lett. ***17, 405*** (1966).
30. Magnetic Resonance Molecular Beam Spectra of Methane. With C. H. Anderson, Phys. Rev. ***149, 14 (1966).***
31. Hyperfinc Separation Tritium. With B. S. Mathur, S. B. Crampton, and D. Kleppner, Phys. Rev. ***158,*** 14 (1967).

32. Measurement of the Hydrogen-Deuterium Atomic Magnetic Moment Ratio and of the Deuterium Hyperfine Frequency. With D. J. Larson and P. A. Valberg, Phys. Rev. Letters 23, 1369 (1969).
33. Multiple Kegion Hydrogen Maser with Reduced Wall Shift. With E. E. Uzgiris, Phys. Rev. *AZ, 429* (1970).
34. Molecular Beam Magnetic Resonance Studies of HD and D2. With R. F. Code, Phys. Rev. *A4, 1945* (1971).
35. Atomic Deuterium Maser With D. J. Wineland, Phys. Rev. *A5, 821* (1972).
36. The Molecular Zeeman and Hyperfine Spectra of LiH and LiD by Molecular Beam High Resolution Electric Resonance. With Richard R. Freeman, Abram R. Jacobson, and David W. Johnson, J. of Chem. Physics 63, 2597 (1975).
37. The Tensor Force Between Two Protons at Long Range, Physica *96A, 285* (1979).
38. Measurement of the Neutron Magnetic Moment. With G. L. Green, W. Mampe, J. M. Pendelbury, K. Smith, W. B. Dress, P. D. Miller and P. Perrin, Phys. Rev. D20, 2139 (1979).
39. First Measurement of Parity-Nonconserving Neutron Spin Rotation: The Tin Isotopes. With M. Forte, B. R. Heckel, K. Green, and G. L. Greene, Phys. Rev. Lett. 45, 2088 (1980).
40. Search for P and T Violations in the Hyperfine Structure of Thallium Fluoride. With D. A. Wilkening and D. J. Larson, Phys. Rev. *A29, 425 (1984).*
41. Search for a Neutron Electric Dipole Moment. With J. M. Pendlebury, et al., Phys. Letters *136B, 327* (1984).
42. Neutron Magnetic Resonance Experiments. Physica *137B, 223* (1986).
43. Quantum Mechanics and Precision Measurements, IEEE Transactions on Instrumentation and Measurement *IM36, 155* (1987).
44. Precise Measurements of Time. American Scientist 76, 42 (1988).
45. The Electric Dipole Moment of the Neutron. Physica Scripta T22, 40 (1988).

EXPERIMENTS WITH SEPARATED OSCILLATORY FIELDS AND HYDROGEN MASERS

Nobel Lecture, December 8, 1989

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I am honored to receive the Nobel Prize, which I feel is also an honor to the physicists and engineers in many countries who have done beautiful experiments using the methods I shall be discussing. In particular, I am grateful to my eighty-four wonderful Ph.D. students and, to Daniel Kleppner and Daniel Larson, who were my close collaborators for a number of years.

THE METHOD OF SUCCESSIVE OSCILLATORY FIELDS

In the summer of 1937 following two years at Cambridge University, I went to Columbia University to work with I. I. Rabi. After I had been there only a few months, Rabi invented[1-4] the molecular beam magnetic resonance method so I had the great good fortune to be the only graduate student to work with Rabi and his colleagues[1-2] on one of the first two experiments to develop and utilize magnetic resonance spectroscopy, for which Rabi received the 1944 Nobel Prize in Physics.

By 1949, I had moved to Harvard University and was looking for a way to make more accurate measurements than were possible with the Rabi method and in so doing I invented the method of separated oscillatory fields.[3-6]. In this method the single oscillatory magnetic field in the center of the Rabi device is replaced by two oscillatory fields, one at the entrance and one at the exit of the space in which the properties of the atoms or molecules are studied. As I will discuss, the separated oscillatory fields method has many advantages over the single oscillatory field method and in subsequent years it has been extended to many experiments beyond those of molecular beam magnetic resonance. The device shown in Figure 1 is a molecular beam apparatus embodying successive oscillatory fields that has been used at Harvard for an extensive series of experiments.

Let me now review the successive oscillatory field method, particularly in its original and easiest to explain application - the measurement of nuclear magnetic moments. The extension to more general cases is then straightforward.

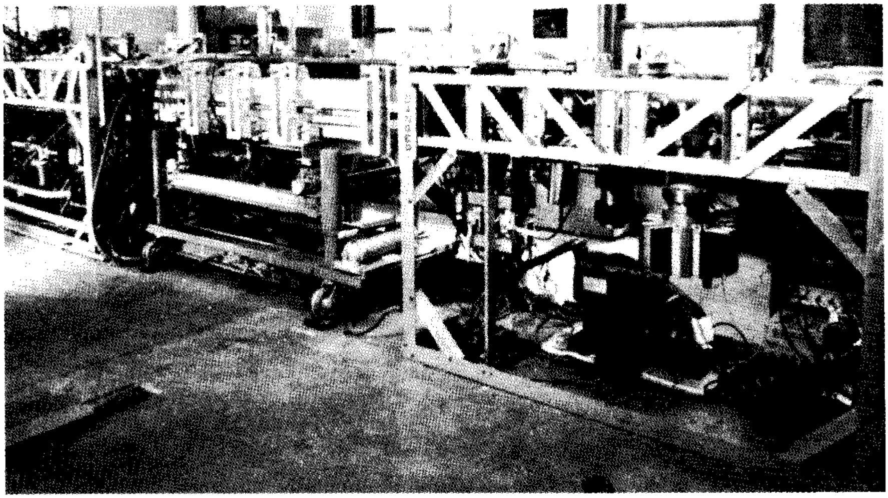


Figure I. Molecular beam apparatus with separated oscillatory fields. The beams of molecules emerges from a small source aperture in the left third of the apparatus, is focused there and passes through the middle third in an approximately parallel beam. It is focussed again in the right third to a small detection aperture. The separated oscillatory electric fields at the beginning and end of the middle third of the apparatus produce resonance transitions that reduce the focussing and therefore weaken the detected beam intensity.

The method was initially an improvement on Rabi's resonance method for measuring nuclear magnetic moments, whose principles are illustrated schematically in Figure 2. Consider a classical nucleus with spin angular momentum h**J** and magnetic moment $\mu = (\mu/J)\mathbf{J}$. Then in a static magnetic field $\mathbf{H}_0 = H_0$ k, the nucleus, due to the torque on the nuclear angular momentum, will precess like a top about $\mathbf{H}_0$ with the Larmor frequency υ_0 and angular frequency ω_0 given by

$$\omega_0 = 2\pi\, \nu_0 = \frac{\mu H_0}{\hbar J} \tag{1}$$

as shown in Figure 3. Consider an additional magnetic field $\mathbf{H}_1$ perpendicular to $\mathbf{H}_0$ and rotating about it with angular frequency ω. Then, if at any time H_1 is perpendicular to the plane of H_0 and J, it will remain perpendicular to it provided $\omega = \omega_0$. In that case, in a coordinate system rotating with Hi, J will precess about $\mathbf{H}_1$ and the angle ϕ will continuously change in a fashion analogous to the motion of a "sleeping top"; the change of orientation can be detected by allowing the molecular beam containing the magnetic moments to pass through inhomogeneous fields as in Figure 2. If ω is not equal to ω_0, $\mathbf{H}_1$ will not remain perpendicular to J; so ϕ will increase for a short while and then decrease, leading to no net change. In this fashion the Larmor precession frequency ω_0, can be detected by measuring the oscillator frequency ω at which there is maximum reorientation of the angular momentum and hence a maximum change in beam intensity for an apparatus as in Figure 2. This procedure is the basis of the Rabi molecular beam resonance method.

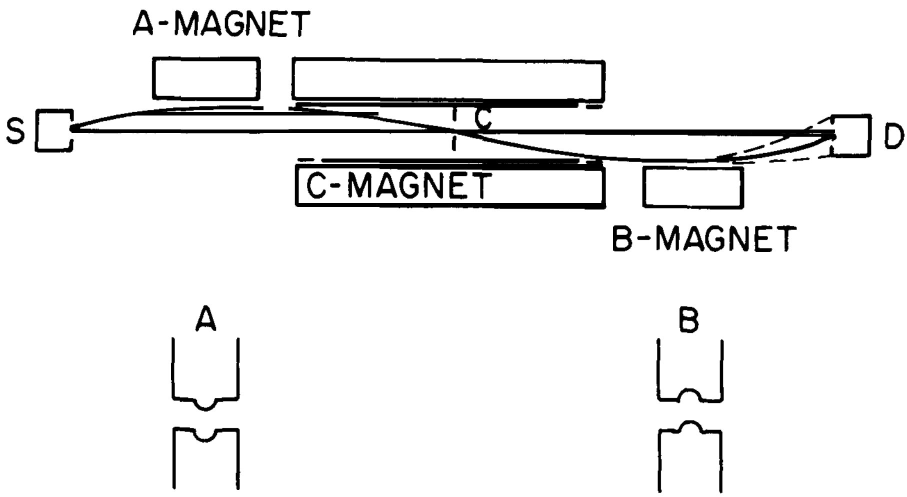


Figure 2. Schematic diagram of a molecular beam magnetic resonance apparatus. A typical molecule which can be detected emerges from the source, is deflected by the inhomogeneous magnetic field A, passes through the collimator and is deflected to the detector by the inhomogeneous magnetic field B. If, however, the oscillatory field in the C region induces a change in the molecular state, the B magnet will provide a different deflection and the beam will follow the dashed lines with a corresponding reduction in detected intensity. In the Rabi method, the oscillatory field is applied uniformly throughout the C region as indicated by the long rf lines F, whereas in the separated oscillator) field method the rf is applied only in the regions E and G.

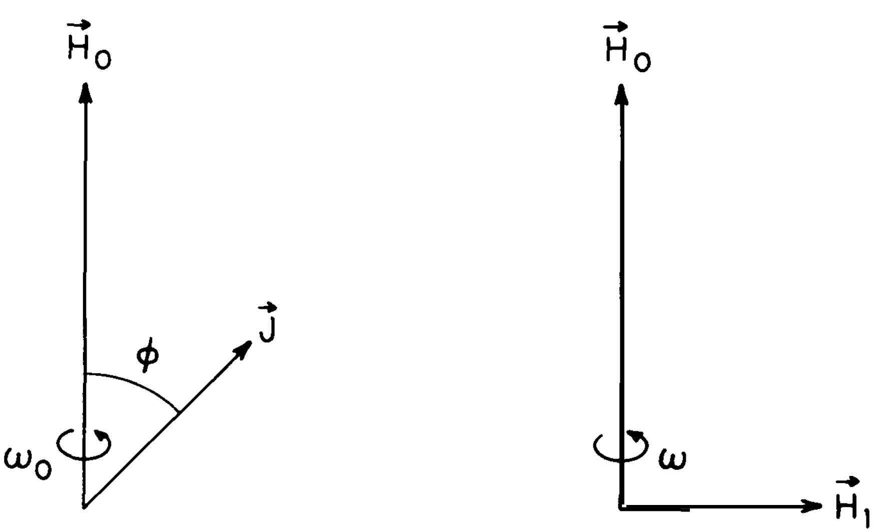


Figure 3. Precession of the nuclear angular momentum J (left) and the rotating magnetic field H, (right) in the Rabi method.

The separated oscillatory field method in this application is much the same except that the rotating field Hi seen by the nucleus is applied initially for a short time τ, the amplitude of $\mathbf{H_1}$ is then reduced to zero for a relatively long time T and then increased to H, for a time τ, with phase coherency being preserved for the oscillating fields as shown in Figure 4. This can be done, for example, in the molecular-beam apparatus of Figure 2 in which the molecules first pass through a rotating field region, then a region with no rotating field and finally a region with a second rotating field driven phase coherently by the same oscillator.

If the nuclear spin angular momentum is initially parallel to the fixed field (so that ϕ is equal to zero initially) it is possible to select the magnitude of the rotating field so that ϕ is 90° or $\pi/2$ radians at the end of the first oscillating region. While in the region with no oscillating field, the magnetic moment simply precesses with the Larmor frequency appropriate to the magnetic field in that region. When the magnetic moment enters the second oscillating field region there is again a torque acting to change ϕ. If the frequency of the rotating field is exactly the same as the mean Larmor frequency in the intermediate region there is no relative phase shift between the angular momentum and the rotating field.

Consequently, if the magnitude of the second rotating field and the length of time of its application are equal to those of the first region, the second rotating field has just the same effect as the first one - that is, it increases ϕ by another $\pi/2$, making $\phi = \pi$, corresponding to a complete reversal of the direction of the angular momentum. On the other hand, if the field and the Larmor frequencies are slightly different, so that the relative phase angle between the rotating field vector and the precessing angular momentum is changed by π while the system is passing through the intermediate region, the second oscillating field has just the opposite effect to the first one; the result is that f is returned to zero. If the Larmor frequency and the rotating field frequency differ by an amount such that the relative phase shift in the intermediate region is exactly an integral multiple of 2π, ϕ will again be left at π just as at exact resonance.

In other words if all molecules had the same velocity, the transition probability would be periodic as in Figure 5. However, in a molecular beam resonance experiment one can easily distinguish between exact resonance and the other cases. In the case of exact resonance, the condition for no change in the relative phase of the rotating field and of the precessing angular momentum is independent of the molecular velocity. In the other cases, however, the condition for integral multiple of 2π relative phase shift is velocity dependent, because a slower molecule is in the intermediate region longer and so experiences a greater shift than a faster molecule. Consequently, for the non-resonance peaks, the reorientations of most molecules are incomplete so the magnitudes of the non-resonance peaks are smaller than at exact resonance and one expects a resonance curve similar to that shown in Figure 6, in which the transition probability for a particle of spin 1/2 is plotted as a function of frequency.

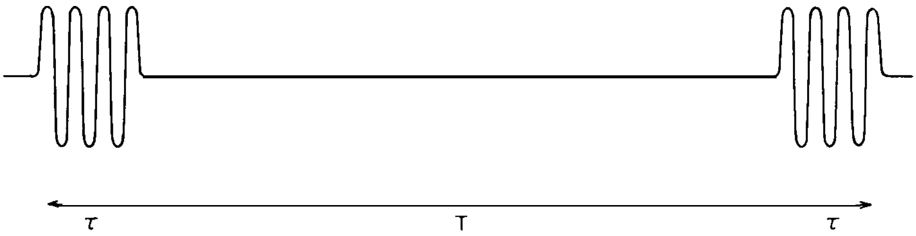


Figure 4. Two separated oscillatory fields, each acting for a time τ, with zero amplitude oscillating field acting for time T. Phase coherency is preserved between the two oscillatory fields so it is as if the oscillation continued, but with zero amplitude for time T.

Although the above description of the method is primarily in terms of classical spins and magnetic moments, the method applies to any quantum mechanical system for which a transition can be induced between two energy states W, and W_f which are differently focussed. The resonance frequency ω_0. is then given by

$$\omega_0 = (W_i - W_f)/\hbar \tag{2}$$

and one expects a resonance curve similar to that shown in Figure 6, in which the transition probability for a particle of spin l/2 is plotted as a function of frequency.

From a quantum-mechanical point of view, the oscillating character of the transition probability in Figures 5 and 6 is the result of the cross term in the calculation of the transition probability from probability amplitudes. Let C_{iif} be the probability amplitude for the nucleus to pass through the first oscillatory field region with the initial state i unchanged but for there to be a transition to state ϕ in the final field, whereas C_{iff} is the amplitude for the alternative path with the transition to the final state ϕ being in the first field with no change in the second. The cross term C_{iff} produces an interference pattern and gives the narrow oscillatory pattern of the transition probability shown in the curves of Figures 5 and 6. Alternatively the pattern can in part be interpreted as resulting from the Fourier spectrum of an oscillating field which is on for a time τ, off for T and on again for τ, as in Figure 4,. However, the Fourier interpretation is not fully valid since with finite rotations of J, the problem is a non-linear one. Furthermore, the Fourier interpretation obscures some of the key advantages of the separated oscillatory field method. I have calculated the quantum mechanical transition probabilities[3,6,7,8] and these calculations provide the basis for Figure 6.

The separated oscillatory field method has a number of advantages including the following:

(1) The resonance peaks are only 0.6 as broad as the corresponding ones with the single oscillatory field method. The narrowing is somewhat analogous to the peaks in a two slit optical interference pattern being

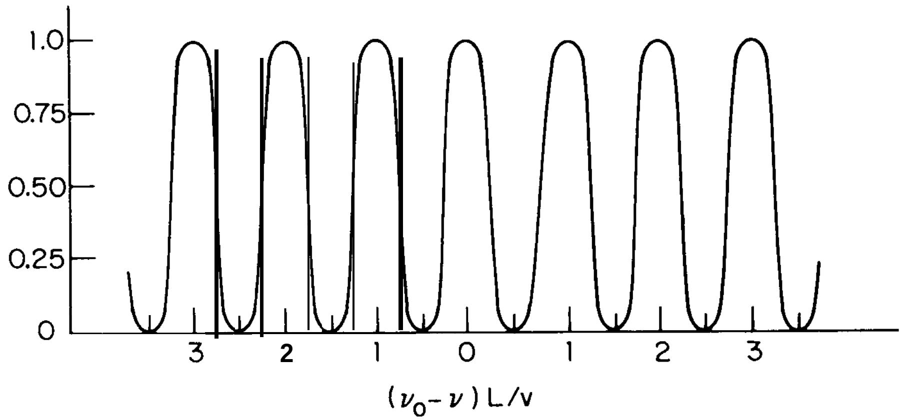


Figure 5. Transition probability as a function of the frequency $\nu = \omega/2\pi$ that would be observed in a separated oscillatory field experiment if all the molecules in the beam had a single velocity.

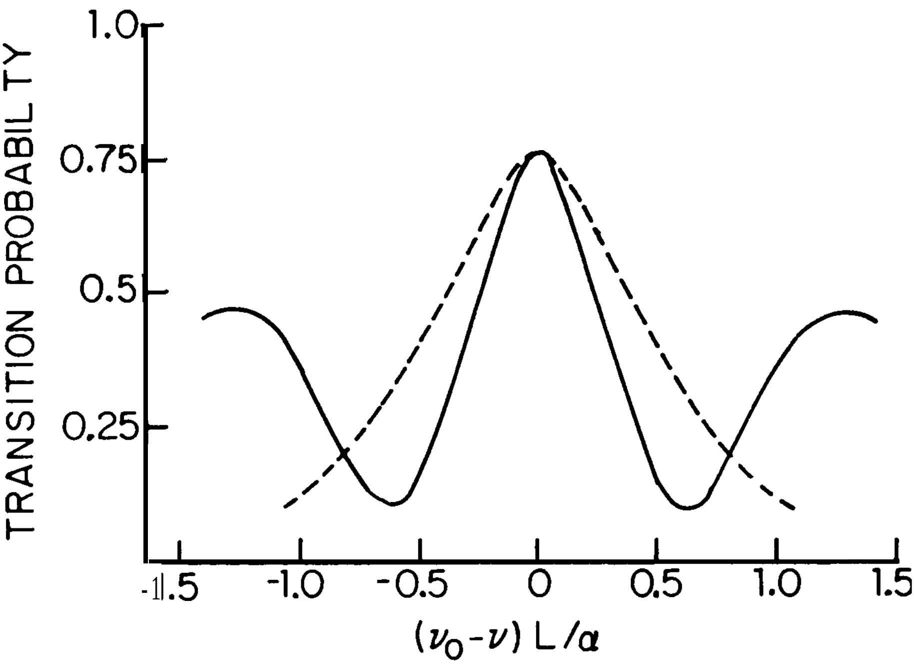


Figure 6. When the molecules have a Maxwellian velocity distribution, the transition probability is as shown by the full line for optimum rotating field amplitude. (L is the distance between oscillating field regions, α is the most probable molecular velocity and ν is the oscillatory frequency $= \omega/2\pi$). The dashed line represents the transition probability with the single oscillating field method when the total duration is the same as the time between separated oscillatory field pulses.

narrower than the central diffraction peak of a single wide slit whose width is equal to the separation of the two slits.

(2) The sharpness of the resonance is not reduced by non-uniformities of the constant field since both from the qualitative description and from the theoretical quantum analysis, it is only the space average value of the energies along the path that enter Eq. (2) and are important.

(3) The method is more effective and often essential at very high frequencies where the wave length of the radiation used may be comparable to or smaller than the length of the region in which the energy levels are studied.

(4) Provided there is no unintended phase shift between the two oscillatory fields, first order Doppler shifts and widths are eliminated.

(5) The method can be applied to study energy levels in a region into which an oscillating field can not be introduced; for example, the Larmor precession frequency of neutrons can be measured while they are inside a magnetized iron block.

(6) The lines can be narrowed by reducing the amplitude of the rotating field below the optimum, as shown by the dotted curve in Figure 6. The narrowing is the result of the low amplitude favoring slower than average molecules.

(7) If the atomic state being studied decays spontaneously, the separated oscillatory field method permits the observation of narrower resonances than those anticipated from the lifetime and the Heisenberg uncertainty principle provided the two separated oscillatory fields are sufficiently far apart; only states that survive sufficiently long to reach the second oscillatory field can contribute to the resonance. This method, for example, has been used by Lundeen and others' in precise studies of the Lamb shift.

The advantages of the separated oscillatory field method have led to its extensive use in molecular and atomic beam spectroscopy. One of the best known is in atomic cesium standards of frequency and time which will be discussed later.

Although in most respects, the separated oscillatory field method offers advantages over a single oscillatory field, there are sometimes disadvantages. In studying complicated overlapping spectra the subsidiary maxima of Figure 6 can cause confusion. Furthermore, it is sometimes difficult at the required frequency to obtain sufficient oscillatory field strengths with two short oscillatory fields, whereas adequate field strength may be achieved with a weaker, longer oscillatory field. Therefore for most molecular beam resonance experiments, it is best to have both separated oscillatory fields and a single long oscillatory field available so the most suitable method under the circumstances can be used.

As in any high precision experiment, care must be exercised with the separated oscillatory field method to avoid obtaining misleading results. Ordinarily these potential distortions are more easily understood and eliminated with the separated oscillatory field method than are their counterparts in most other high-precision spectroscopy. Nevertheless, the effects are important and require care in high-precision measurements. I have discussed the various effects in detail elsewhere[3,7,8,10] but I will briefly summarize them here.

Variations in the amplitudes of the oscillating fields from their optimum values may markedly change the shape of the resonance, including the replacement of a maximum transition probability by a minimum. However, symmetry about the exact resonance frequency is preserved, so no measurement error need be introduced by such amplitude variations.[7,8]

Variations of the magnitude of the fixed field between, but not in, the oscillatory field regions do not ordinarily distort a molecular beam resonance provided the average transition frequency (Bohr frequency) between the two fields equals the values of the transition frequencies in each of the two oscillatory field regions alone. If this condition is not met, there can be some shift in the resonance frequency.[7,8]

If, in addition to the two energy levels between which transitions are studied, there are other energy levels partially excited by the oscillatory field, there will be a pulling of the resonance frequency as in any spectroscopic study and as analyzed in detail in the literature.[3,7,8]

Even in the case when only two energy levels are involved, the application of additional rotating magnetic fields at frequencies other than the resonance frequency will produce a net shift in the observed resonance frequency, as discussed elsewhere.[3,7,8] A particularly important special case is the effect identified by Bloch and Siegert[11] which occurs when oscillatory rather than rotating magnetic fields are used. Since an oscillatory field can be decomposed into two oppositely rotating fields, the counter-rotating field component automatically acts as such an extraneous rotating field. Another example of an extraneously introduced rotating field is that which results from the motion of an atom through a field $\mathbf{H}_0$ whose direction varies in the region traversed. The theory of the effects of additional rotating fields at arbitrary frequencies has been developed by Ramsey,[7,8,10,12] Winter,[10] Shirley,[13] Code,[12] and Greene.[14]

Unintended relative phase shifts between the two oscillatory field regions will produce a shift in the observed resonance frequency.[13,14,15] This is the most common source of possible error, and care must be taken to avoid it either by eliminating such a phase shift or by determining the shift - say by measurements with the molecular beam passing through the apparatus first in one direction and then in the opposite direction.

A number of extensions to the separated oscillatory field method have been made since its original introduction:

(1) It is often convenient to introduce phase shifts deliberately to modify the resonance shape.[15] As discussed above, unintended phase shifts can cause distortions of the observed resonance, but some distortions are useful. Thus, if the change in transition probability is observed when the relative phase is shifted from $+\pi/2$ to $-\pi/2$ one sees a dispersion curve shape[15] as in Figure 7. A resonance with the shape of Figure 7 provides maximum sensitivity for detecting small shifts in the resonance frequency.

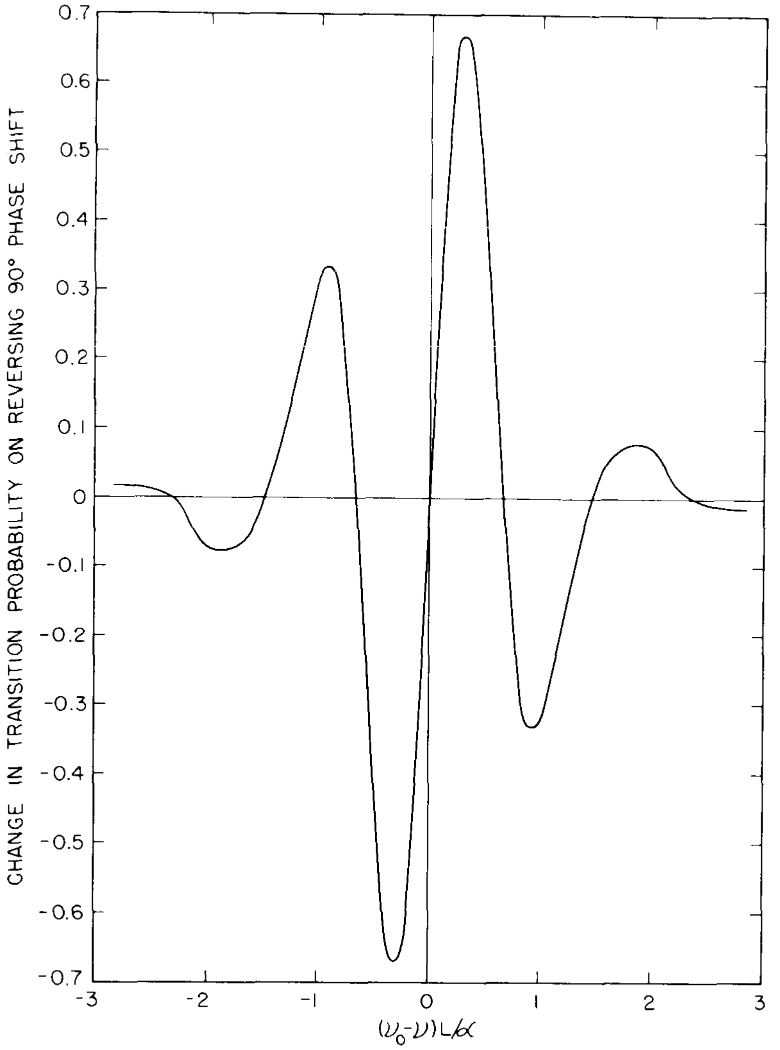


Figure 7. Theoretical change in transition probability on reversing a $\pi/2$ phase shift. At the resonance frequency there is no change in transition probability, but the curve at resonance has the steepest slope.

(2) For most purposes the highest precision can be obtained with just two oscillatory fields separated by the maximum time, but in some cases it is better to use more than two separated oscillatory fields[4] The theoretical resonance shapes[7] with two, three, four and infinitely many oscillatory fields are given in Figure 8. The infinitely many oscillatory field case, of course, by definition becomes the same as the single long oscillatory field if the total length of the transition region is kept the same and the infinitely many oscillatory fields fill in the transition region continuously as we assumed in

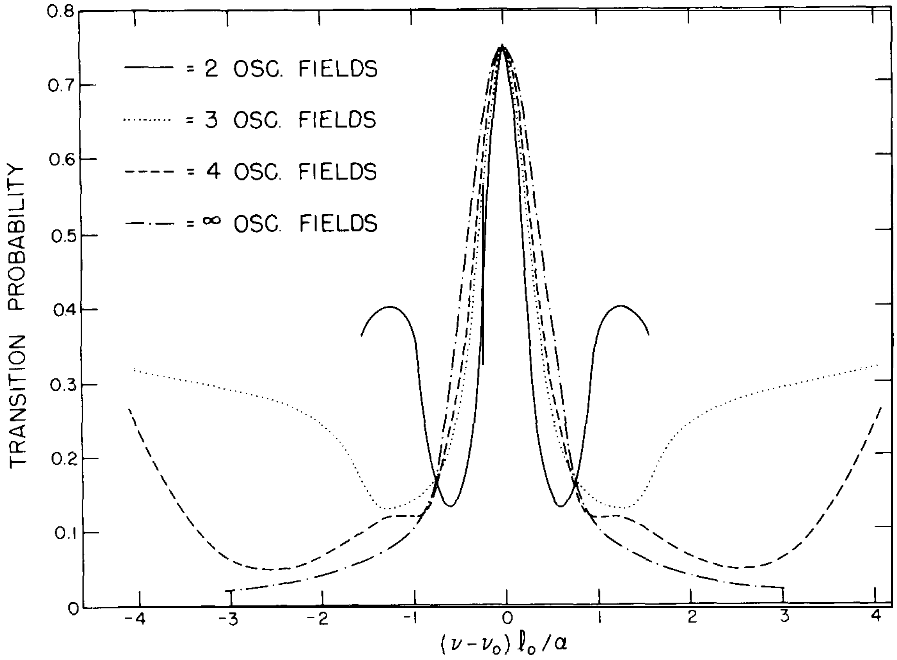


Figure 8. Multiple oscillatory fields. The curves show molecular beam resonances with two, three, four and infinitely many successive oscillating fields. The case with an infinite number of oscillating fields is essentially the same as Rabi's single oscillatory field method.

Figure 8. For many purposes this is the best way to think of the single oscillatory field method, and this point of view makes it apparent that the single oscillatory field method is subjected to complicated versions of all the distortions discussed in the previous section. It is noteworthy that, as the number of oscillatory field regions is increased for the same total length of apparatus, the resonance width is broadened; the narrowest resonance is obtained with just two oscillatory fields separated the maximum distance apart. Despite this advantage, there are valid circumstances for using more than two oscillatory fields. With three oscillatory fields the first and largest side lobe is suppressed, which may help in resolving two nearby resonances; for a larger number of oscillatory fields additional side lobes are suppressed, and in the limiting case of a single oscillatory field there are no side lobes. Another reason for using a large number of successive pulses can be the impossibility of obtaining sufficient power in a single pulse to induce adequate transition probability with a small number of pulses.

(3) The earliest use of the separated oscillatory field method involved two oscillatory fields separated in space, but it was early realized that the method with modest modifications could be generalized to a method of successive oscillatory fields with the separation being in time, say by the use of coherent pulses.[16]

(4) If more than two successive oscillatory fields are utilized it is not necessary to the success of the method that they be equally space in time;[4] the only requirement is that the oscillating fields be coherent - as is the case if the oscillatory fields are all derived from a single continuously running oscillator. In particular, the separation of the pulses can even be random,[16] as in the case of the large box hydrogen maser[17] discussed later. The atoms being stimulated to emit move randomly into and out of the cavities with oscillatory fields and spend the intermediate time in the large container with no such fields.

(5) The full generalization of the successive oscillatory field method is excitation by one or more oscillatory fields that vary arbitrarily with time in both amplitude and phase.[7,8]

(6) V. F. Ezhov and his colleagues,[6,18] in a neutron-beam experiment, used an inhomogeneous static field in the region of each oscillatory field region such that initially when the oscillatory field is applied conditions are far from resonance. Then, when the resonance condition is slowly approached, the magnetic moment that was originally aligned parallel to $\mathbf{H}_0$ will adiabatically follow the effective magnetic field on a coordinate system rotating with $\mathbf{H}_0$ until at the end of the first oscillatory field region the moment is parallel to H_1. This arrangement has the theoretical advantage that the maximum transition probability can be unity even with a velocity distribution, but the method may be less well adapted to the study of complicated spectra.

(7) I emphasized earlier that one of the principal sources of error in the separated oscillatory field method is that which arises form uncertainty in the exact value of the relative phase shift in the two oscillatory fields. Jarvis, *et* al. [19] have pointed out that this problem can be overcome with a slight loss in resolution by driving the two cavities at slightly different frequencies so that there is a continual change in the relative phase. In this case the observed resonance pattern will change continuously from absorption to dispersion shape. The envelope of these patterns, however, can be observed and the position of the maximum of the envelope is unaffected by relative phase shifts. Since the envelope is about twice the width of a specific resonance there is some loss of resolution in this method, but in certain cases this loss may be outweighed by the freedom from phase-shift errors.

(8) The method has been extended to electric as well as magnetic transitions and to optical laser frequencies as well as radio- and microwave-frequencies. The application of the separated oscillatory field method to optical frequencies requires considerable modifications because of the short wave lengths, as pointed out by Blaklanov, Dubetsky and Chebotsev[20] Successful applications of the separated oscillatory field method to lasers have been made by Bergquist,[21] Lee," Ha11,[21] Salour,[22] Cohen-Tannoudji,[22] Bordé,[23] Hansch,[24] Chebotayev[25] and many others.[25]

(9) The method has been extended to neutron beams and to neutrons stored for long times in totally reflecting bottles.

(10) In a recent beautiful experiment, S. Chu and his associates.[26] have

successfully used the principle of separated oscillatory fields with a fountain of atoms that rises up slowly, passes through an oscillating field region, falls under gravity and passes again through the same oscillatory field region. This fountain experiment was attempted many years ago by J. R. Zacharias and his associates,[3] but it was unsuccessful because of the inadequate number of very slow atoms. Chu and his collaborators used laser cooling[27,28,29] to slow the atoms to a low velocity and obtained a beautifully narrow separated oscillatory fields resonance pattern.

THE ATOMIC; HYDROGEN MASER

The atomic hydrogen maser grew out of my attempts to obtain even greater accuracy in atomic beam experiments. By the Heisenberg uncertainty principle (or by the Fourier transform), the width of a resonance in a molecular beam experiment cannot be less than approximately the reciprocal of the time the atom is in the resonance region of the apparatus. For atoms moving through a 1 m long resonance region at 100 m/s this means that the resonance width is about 100 Hz wide. To decrease this width and hence increase the precision of the measurements required an increase in this time. To increase the time by drastically lengthening the apparatus or selecting slower molecules would decrease the already marginal beam intensity or greatly increase the cost of the apparatus. I therefore decided to plan an atomic beam in which the atoms, after passing through the first oscillatory field would enter a storage box with suitably coated walls where they would bounce around for a period of time and then emerge to pass through the second oscillatory field. My Ph.D. student, Daniel Kleppner,[30] undertook the construction of this device as his thesis project. The original configuration required only a few wall collisions and was called a broken atomic beam resonance experiment. Initially the beam was cesium and the wall coating was teflon. The experiment[30] was a partial success in that a separated oscillatory field pattern for an atomic hyperfine transition was obtained, but it was weak and disappeared after a few wall collisions. The results improved markedly when paraffin was used for the wall coating and a hyperfine resonance was eventually obtained after 190 collisions giving a resonance width of 100 Hz, but with the resonance frequency shifted by 150 Hz.

To do much better than this, we decided we would have to use an atom with a lower mass and a lower electric polarizability to reduce the wall interactions. Atomic hydrogen appeared ideal for this purpose, but atomic hydrogen is notoriously difficult to detect. We, therefore, calculated the possibility of detecting the transitions through their effects on the electromagnetic radiations. Townes[31] had a few years earlier made the first successful maser (acronym for microwave amplifier by stimulated emission of radiation) but no one had previously made a maser based on a magnetic dipole moment or on a frequency as low as that of an atomic hyperfine transition. We concluded, however, that if the resonance could be made narrow enough by multiple wall collisions, we should be able to obtain

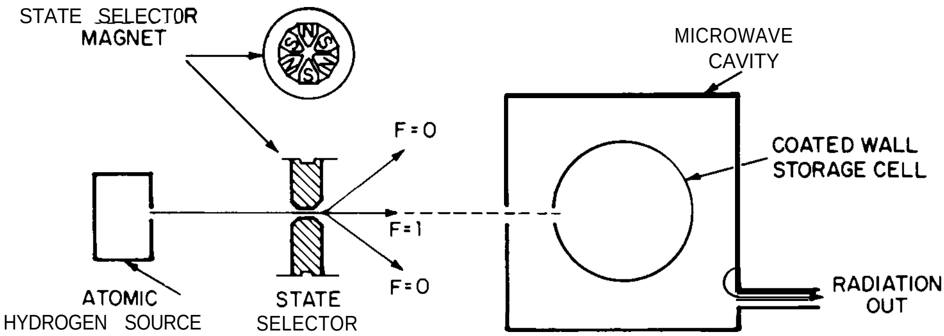


Figure 9. Schematic diagram of atomic hydrogen maser. Only the paths of the m=0 atoms are shown since the m=1 atoms are not involved in the $\Delta m=0$ transitions studied.

maser oscillations. The apparatus was designed and constructed by Goldenberg, Kleppner and myself[32] and after a few failures we obtained maser oscillations at the atomic hydrogen hyperfine frequency. Both the proton and the electron have spin angular momenta I and J as well as magnetic moments. The atomic hyperfine transitions are those for which there is a change of the relative orientation of these two magnetic moments between the initial and final states in Eq. (2). We studied H atoms in the $1^2S_{1/2}$ ground electronic state and mostly observed the transitions (F=1, m=O $\rightarrow$ F=0, m=O) where F is the quantum number of the total angular momentum F = I + J and m is the associated magnetic quantum number.

The principles of an atomic hydrogen maser are shown schematically in Figure 9. An intense electrical discharge in the source converts commercially available molecular hydrogen (H_2) into atomic hydrogen (H). The atoms emerge from the source into a region that is evacuated to 10^{-6} torr and enter a state selecting magnet which has three north poles alternating in a circle with three south poles. By symmetry, the magnetic field is zero on the axis and increases in magnitude away from the axis. Since the energy of a hydrogen atom in the F=l m=0 state increases with energy and since mechanical systems are accelerated toward lower potential energy, an atom in F=l state that is slightly off axis will be accelerated toward the axis, i.e. the F= 1 state will be focussed onto the small aperture of the 15 cm diameter storage cell whereas the F=0 state is defocussed. As a result, if the atomic beam flows steadily, the storage bottle in equilibrium will contain more high energy F=l atoms than low. If these atoms are exposed to microwave radiation at the hyperfine frequency, more atoms are stimulated to go from the higher energy state to the lower one than in the opposite direction. Energy is then released from the atoms and makes the microwave radiation stronger. Thus the device is an amplifier or maser. If the storage cell is placed inside a tuned cavity, an oscillation at the resonance frequency will increase in magnitude until an equilibrium value is reached. At this level the oscillation will continue indefinitely, with the energy to maintain the oscillation coming from the continuing supply of hydrogen atoms in the high energy hyperfine state. The device then becomes a free running maser oscillator at the atomic hyperfine frequency.

The atomic hydrogen maser oscillator has unprecedented high stability due to a combination of favorable features. The atoms typically reside in the storage cell for 10 seconds, which is much longer than in an atomic beam resonance apparatus so the resonance line is much narrower. The atoms are stored at low pressure so they are relatively free and unperturbed while radiating. The first order Doppler shift is removed, since the atoms are exposed to a standing wave and since the average velocity is extremely low for atoms stored for 10 seconds. Masers have very low noise levels, especially when the amplifying elements are isolated atoms. Over periods of several hours the hydrogen maser stability is better than 1×10^{-15}.

The major disadvantage of the hydrogen maser is that the atoms collide with the walls at intervals, changing slightly the hyperfine frequency and giving rise to wall shifts of 1×10^{-11}. However, the wall shifts can be experimentally determined by measurements utilizing storage bottles of two different diameters or with a deformable bulb whose surface to volume ratio can be altered. As in all precision measurements, care must be taken in adjusting and tuning the hydrogen maser to avoid misleading results. These limitations and precautions are discussed in a series of publications by various authors.[32,33,34] The designs of hydrogen masers have been modified in many ways either for special purposes or for increased stability and reliability. For example different hyperfine transitions have been used and masers have been operated in relatively strong magnetic fields. A hydrogen maser has also been operated” with a storage bottle that is much larger than the wave length of the stimulating radiation by confining the microwave power to two small cavities so that it functions as a separated oscillatory field device. As shown in Figure 10 the atoms that are stimulated to emit radiation move randomly into and out of the two oscillatory field cavities and spend the intermediate time in the large container where there is no oscillatory field. Due to the larger size of the storage box there are longer storage times and less frequent wall collisions, so the resonances are narrower and the wall shifts are smaller than for a normal hydrogen maser.

PRECISION SPECTROSCOPY

Now that I have discussed extensively the principles of the separated oscillatory field method and of the atomic maser, I shall give some illustrations as to their value. One major category of applications is to precision spectroscopy, especially at radio and microwave frequencies. Another category of applications is to atomic clocks and frequency standards.

It is difficult to summarize the spectroscopic applications since there are so many of them. Many beautiful experiments have been done by a large number of scientists in different countries, including Sweden. I shall, therefore use just a few illustrations from experiments in which I have been personally involved.

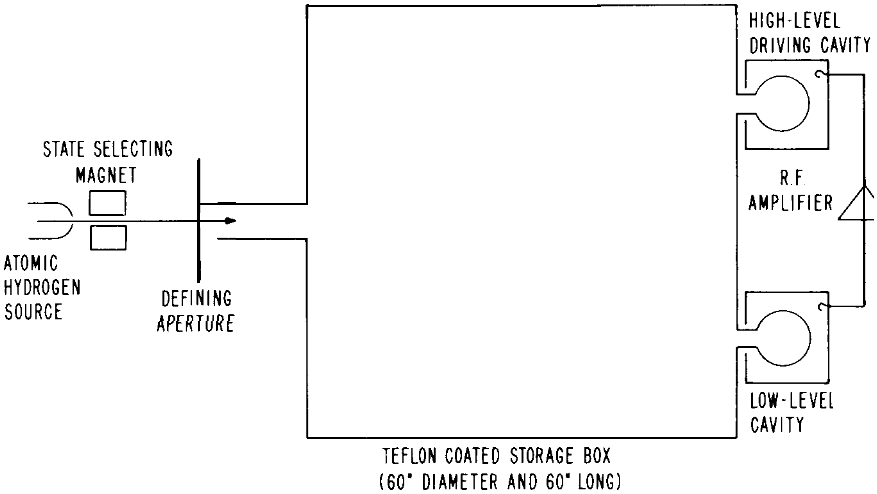


Figure 10. Schematic diagram of a large box hydrogen maser. The two cavities on the right act as two separated oscillating fields with that of the high level cavity being obtained by amplification from the low.

My graduate students have made precision measurements of the radiofrequency spectra of different molecules in various rotational states. For each of these states more than seven different molecular properties can be inferred and thus the variations of the properties with changes in the rotational and vibrational quantum numbers can be determined. These properties include nuclear and rotational magnetic moments, nuclear quadrupole interactions, nuclear spin-spin magnetic interactions, spin rotational interactions, etc. I shall illustrate the accuracy and significance of the measurements with a single example. With both D_2 and LiD we have accurately measured[35,36] the deuteron quadrupole interaction eqQ where e is the proton electric charge, q is the gradient of the molecular electric field at the deuteron and Q is the deuteron quadrupole moment which measures the shape of the deuteron and in particular its departure from spherical symmetry. These measurements were made with a high resolution molecular beam apparatus based on the method of separated oscillatory fields. We found for eqQ the value + 225,044 ± 20 Hz in D_2 and + 34,213 ± 33 Hz in LiD. Since q has been calculated[37,38] for each of these quite different molecules, two independent values of Q can be calculated. The results agree to within 1.5% which confirms the validity of the difficult calculation; with it we find $Q = 2.9\times10^{-27}$ c m^2.

In an experiment with collaborators[39] at the Institut Laue-Langevin at Grenoble, France, we have used the separated oscillatory field method with a beam of slow neutrons to make an accurate measurement of the neutron magnetic moment and found[37,40] it to be - 1.91304275 ± 0.00000045 nuclear magnetons. In a somewhat different experiment with neutrons moving so slowly that they can be bottled for more than 80 s in a suitable storage vessel, we have used the method of successive oscillatory fields with the two coherent radiofrequency pulses being separated in time rather than space. In this manner and as a fundamental test of time reversal symmetry, we have recently set a very low upper limit for the neutron electric dipole moment by finding[41] its value to be $(-3 \pm 5) \times 10^{-26}$ e cm.

The atomic hydrogen maser gives very accurate data on the microwave spectrum of the ground electronic state of the hydrogen atom. The hyperfine frequency $\Delta\nu$ for atomic hydrogen has been measured in our laboratory and in a number of other laboratories. The best value[42,43] is

$$\Delta\nu_H = 1{,}420{,}405{,}751.7667 \pm 0.0009 \text{ Hz}$$

This value agrees with present quantum electromagnetic theory[44] to within the accuracy of the theoretical calculation and can be used to obtain information on the proton structure. Similarly accurate values have been found for atomic deuterium and tritium and the dependence[45] of these results on the strengths of externally applied electric fields have been measured. With a modified form of the hydrogen maser designed to operate at high magnetic fields, the ratio of magnetic moment of the electron to that of the proton is found[40,46] to be -658.210688 ± 0.000006. Incidentally when this result is combined with the beautiful electron measurements from Professor Dehmelt's labortory[40,47,48] we obtain the best values for the free proton magnetic moment in both Bohr and nuclear magnetons.

ATOMIC CLOCKS

In the past 50 years there has been a major revolution in time keeping with accuracy and reproducibility of the best clocks at the end of that period being approximately a million times those at the beginning. This revolution in time keeping and frequency control is due to atomic clocks.

Any clock or frequency standard depends on some regular periodic motion such as the pendulum of the grandfather's clock. In the case of atomic clocks the periodic motion is internal to the atoms and is usually that associated with an atomic hyperfine structure as discussed in the section on atomic hydrogen maser.

In the most widely used atomic clocks, the atom whose internal frequency provides the periodicity is cesium and the usual method of observing it is with a separated oscillatory field magnetic resonance apparatus as in Figure 2. The first commercial cesium beam clock was developed in 1955 by a group led by J. R. Zacharias[4] and in the same year L. Essen and V. L. Parry[4] constructed and operated the first cesium beam apparatus that was extensively used as an actual frequency standard. Subsequently many scientists and engineers throughout the world contributed to the development of atomic clocks, as discussed in greater detail elsewhere.[4]

Cesium atomic clocks now have an accuracy and stability of about 10^{-13} which was so far superior to all previous clocks that in 1967 the internationally adopted definition of the second was changed from one based on motion of the earth around the sun to 9,192,631,770 periods of the cesium atom.

For many purposes even greater stability is required over shorter time intervals. When such stability is needed the hydrogen maser is frequently used with a stability of 10^{-15} over periods of several hours.

Atomic clocks based on the above principles have for a number of years provided clocks of the greatest stability and accuracy and these are sufficiently great that further improvements might seem to neither be desirable nor feasible. But as we shall see in our final section, there are applications that already push atomic clocks to their limits and there are many current developments with great promise for the future. These include improvements to the existing devices, use of higher frequency, use of lasers, electromagnetic traps for storing both ions and atoms, laser cooling, etc.

APPLICATIONS FOR ACCURATE CLOCKS

Accurate atomic clocks are used for so many different purposes that a list of them all is tediously long so I shall here just briefly mention a few that push clock technology to its limit.

In radio astronomy one looks with a parabolic reflector at the radio waves coming from a star just as in optical astronomy one looks with an optical telescope at the light waves coming from a star. Unfortunately, in radio astronomy the wavelength of the radiation is about a million times longer than the wavelength of light. The resolution of the normal radio telescope is therefore about a million times worse since the resolution of a telescope depends on the ratio of the wave length to the telescope aperture. However, if there are two radio telescopes on opposite sides of the earth looking at the same star and if the radio waves entering each are matched in time, it is equivalent to a single telescope whose aperture is the distance between the two telescopes and the resolution of such a combination exceeds that of even the largest single optical telescope. However, to do such precise matching in time each of the two radio telescopes needs a highly stable clock, usually an atomic hydrogen maser.

One of the exciting discoveries in radio astronomy has been the discovery of pulsars, that emit their radiation in short periodic pulses. Precision clocks have been needed to measure the pulsar periods and the changes in the periods with time; these changes sometimes occur smoothly and sometimes abruptly. Of particular interest from the point of view of time measurements, are the millisecond pulsars which have remarkable constancy of period, rivaling the stability of the best atomic clocks.[49] Another millisecond pulsar is part of a rapidly rotating binary star that is slowly changing its period of rotation.[49] This slow change in rotation can be attributed to the loss of energy by the radiation of gravity waves - the first experimental evidence for the existence of gravity waves.

Time and frequency can now be measured so accurately that wherever possible other fundamental measurements are reduced to time or frequency measurements. Thus the unit of length by international agreement has recently been defined as the distance light will travel in a specified time and voltage will soon be represented in terms of frequency measurements.

Accurate clocks have provided important tests of both the special and general theories of relativity. In one experiment, a hydrogen maser was shot in a rocket to a 6,000 mile altitude and its periodic rate changed with speed and altitude just as expected by the special and general theories of relativity.[50] In other experiments, observers have measured the delays predicted by relativity for radio waves passing near the sun.

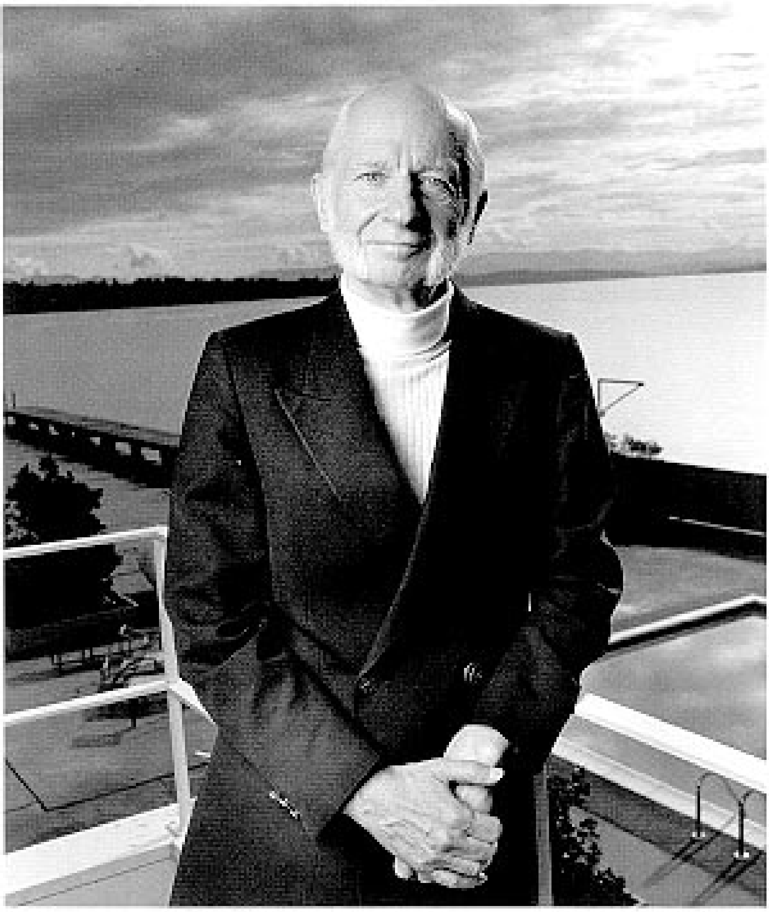
Precision clocks make possible an entirely new and more accurate navigational system, the global positioning system or GPS. A number of satellites containing accurate atomic clocks transmit signals at specific times so any observer receiving and analyzing the signals from four such satellites can determine his position to within ten yards and the correct time within one hundredth of a millionth of a second (10^{-8} s).

A particularly fascinating navigation feat dependent on accurate clocks was the recent and highly successful tour of the Voyager spacecraft to Neptune. The success of this mission depended upon the ground controllers having accurate knowledge of the position of the Voyager. This was accomplished by having three large radio telescopes at different locations on the earth, each of which transmitted a coded signal to Voyager which in turn transmitted the signals back to the telescopes. The distances from each telescope to Voyager could be determined from the elapsed times and thus Voyager could be located. To achieve the required timing accuracy, two hydrogen masers were located at each telescope. Due to the rotation of the earth in the eight hours required for the electromagnetic wave to travel from the earth to Voyager and back again at the speed of light, the telescope transmitting the signal in some cases had to be different from the one receiving; this placed an additional stringent requirement on the clocks. Thus, the spectacular success of the Voyager mission was depended on the availability of highly stable clocks.

REFERENCES

1. I. I. Rabi, J. R. Zacharias, S. Millman and P. Kusch, Phys. Rev. 53, 318 (1938) and 55, 526 (1939).
2. J. M. B. Kellogg, I. I. Rabi, N. F. Ramsey and J. R. Zacharias, Phys. Rev. 55, 729 (1939); 56, 728 (1939) and 57, 677 (1940).
3. N. F. Ramsey, *Molecular* Beams, Oxford Press (1956 and 1985).
4. N. F. Ramsey, *History of Atomic* Clocks, Journal of Research of NBS 88, 301 (1983). This paper contains an extensive list of references.
5. N. F. Ramsey, Phys. Rev. 76, 996 (1949) and 78, 695 (1950).
6. N. F. Ramsey, Physics Today 33 (7), 25 (July 1980).
7. N. F. Ramsey, Phys. Rev. *109, 822* (1958).
8. N. F. Ramsey, Jour. Phys. et Radium 19, 809 (1958).
9. S. R. Lundeen, P. E. Jessop and F. M. Pipkin, Phys. Rev. Lett. 34, 377 and 1368 (1975).
10. N. F. Ramsey, Phys. Rev. 100, 1191 (1955).
11. F. Bloch and A. Siegert, Phys. Rev. 57, 522 (1940).
12. R. F. Code and N. F. Ramsey, Phys. Rev. *A4,* 1945 (1971).
13. J. H. Shirley, J. Appl. Phys. 34, 783 (1963).
14. G. Greene, Phys. Rev. A18, 1057 (1970).
15. N. F. Ramsey and H. B. Silsbee, Phys. Rev. 84, 506 (1951).
16. N. F. Ramsey, Rev. Sci. Inst. 28, 57 (1957).
17. E. Uzgiris and N. F. Ramsey, Phys. Rev. *Al, 429* (1970).
18. V. F. Ezhov, S. N. Ivanov, I. M. Lobashov, V. A. Nazarenko, G. D. Porsev, A. P. Serebrov and R. R. Toldaev, Sov. Phys. - JETP 24, 39 (1976).
19. S. Jarvis, D. J. Wineland and H. Hellwig, J. Appl. Phys. 48, 5336 (1977).
20. Y. V. Blaklanov, B. V. Dubetsky and V. B. Chebotsev, Appl. Phys. 9, 171 (1976).
21. J. C. Bergquist, S. A. Lee and J. I.. Hall, Phys. Rev. Lett. 38, 159 (1977) and Laser Spectroscopy *III, 142* (1978).
22. M. M. Salour, C. Cohen-Tannoudji, Phys. Rev. Lett. 38, 757 (1977); Laser Spectroscopy *III,* 149 (1978), Appl. Phys. 15, 119 (1978) and Phys. Rev. *Al 7,* 614 (1978).
23. C. J. Bordé., C. R. Acad. Sri. Paris 284B, 101 (1977).
24. T. W. Hansch, Laser Spectroscopy *III, 149* (1978).
25. V. P. Chebotayev, A. V. Shishayev, B. Y. Yurshin, L. S. Vasilenko, N. M. Dyuba and M. 1. Skortsov, Appl. Phys. *15,* 43, 219 and 319 (1987).
26. M. Kasevich, E. Riis, S. Chu and R. S. DeVoe, Phys. Rev. Lett. 63, 612 (1989).
27. D. Wineland and H. Dehmelt, Bull. Am. Phys. Soc. *18,* 1521 (1973) and 20, 60, 61, 637 (1975).
28. T. W. Hansch and A. L. Schawlow Opt. Commun. *13,* 68 (1975) and review by V. S. Letokhow, Comments on Atomic and Molecular Physics 6, 119 (1977).
29. D. J. Wineland and W. M. Itano, Physics Today 40, (6) 34 (June 1987).
30. D. Kleppner, N. F. Ramsey and P. Fjelstadt, Phys. Rev. Lett. I, 232 (1958).
31. J. P. Gordon, H. Z. Geiger and C. H. Townes, Phys. Rev. 95, 282 (1954) and 99, 1264 (1955).
32. H. M. Goldenberg, D. Kleppner and N. F. Ramsey, Phys. Rev. Lett. 5, 361 (1960) and Phys. Rev. *126, 603* (1962).
33. D. Kleppner, H. C. Berg, S. B. Crampton, N. F. Ramsey, R. F. C. Vessot, H. E. Peters and J. Vanier, Phys. Rev. *138,* A972 (1965).
34. J. M. V. A. Koelman, S. B. Crampton, H. T. C. Luiten and B. J. Verhaar, Phys. Rev. *A38,* 3535 (1988). This paper contains an extended series of references to other papers on hydrogen maser limitations, principles and practices.
35. R. F. Code and N. F Ramsey, Phys. Rev. A4, 1945 (1971).

36. R. R. Freeman, A. R. Jacobson, D. W. Johnson and N. F. Ramsey, Jour. Chem. Phys. 63, 2597 (1975).
37. R. V. Reid and M. L. Vaida, Phys. Rev. A7, 1841 (1973).
38. K. K. Docken and R. R. Freeman, J. Chem. Phys. 61, 4217 (1974).
39. G. L. Green, N. F. Ramsey, W. Mampe, J. M. Pendlebury, K. Smith, W. B. Dress, P. D. Miller and P. Perrin, Phys. Rev. D20, 2139 (1979).
40. E. R. Cohen and B. Taylor, Rev. Mod. Phys. 59, 1121 (1987).
41. K. F. Smith, N. Crampin, J. M. Pendlebury, D. J. Richardson, D. Shiers, K. Green, A. 1. Kilvington, J. Moir, H. B. Prosper, D. Thompson, N. F. Ramsey, B. R. Heckel, S. K. Lamoreaux, P. Ageron, W. Mampe and A. Steyerl, Phys. I,ett. 136B, 327 (1984) and Phys. Lett. 234, 191 (1990).
42. H. Hellwig, R. F. Vessot, M. Levine, P. W. Zitzewitz, D. W. Allan and D. T. Glaze, IEEE Trans. Instruments and Measurements *IM-19, 200* (1970).
43. L. Essen, M. J. Donaldson, M. J. Bangham and E. G. Hope, Nature 229, 110 (1971).
44. G. L. Baldwin and D. R. Yennie, Phys. Rev. *D37,* 498 (1988).
45. P. C. Gibbons and N. F. Ramsey, Phys. Rev. *A5, 73* (1972).
46. P. F. Winkler, D. Kleppner, T. Myint and F. G. Walther, Phys. Rev. *A5, 83* (1972) and E. Cohen and B. Taylor, Phys. Lett. B204 (April 1988).
47. R. S. van Dyck, P. B. Schwinberg and H. Dehmelt, Atomic Physics 9, 53 (1984) (World Scientific, Singapore).
48. R. S. van Dyck, F. L. Moore, D. L. Farnum and P. B. Schwinberg, Bull. Am. Phys. Soc. *31, 244* (1986) and Atomic Physics 9, 75 (1984) (World Scientific, Singapore)
49. J. Taylor, et al., Nature 277, 437 (1979) and 315, 547 (1985).
50. R. F. C. Vessot, et al., Phys. Rev. Lett. 45, 2081 (1980).



Hans Dehmelt

HANS G. DEHMELT

My father, Georg, had studied law at the Universität Berlin for some years, and in the first World War had been an artillery officer. He was of a philosophical bend of mind and a man of independent opinions. In the depth of the depression he just managed to make a living in real estate. When the family fortunes had shrunk to ownership of a heavily mortgaged apartment building located in an overwhelmingly Communist part of Berlin, it seemed reasonable to move into one of the apartments ourselves as nobody paid any rent. Cannons were deployed on the streets on occasion and the class war had entered the class rooms. After a few bloody noses administered by a burly repeater, I shifted my interests from roaming the streets more towards playing with rudimentary radio receivers and noisy and smelly experiments in my mother's kitchen. In the spring of 1933 my mother, a very energetic lady, saw to it that, at the age of ten, I entered the Gymnasium zum Grauen Kloster, the oldest Latin school in Berlin, which counted Bismarck amongst its Alumni. This involved a stiff entrance examination and I was admitted on a scholarship. My father at that time expressed the opinion that I probably would be happier as a plumber. However, he apparently didn't quite believe this himself. Thus, in years before, he had bought me an erector set and books on the lives of famous inventors and Greek mythology, and when I was ill he had given me the encyclopedia to read. I supplemented the school curriculum with do-it-yourself radio projects until I had hardly any time left for my class work. Only tutoring from my father rescued me from disaster. Reading popular radio books deepened my interest in physics. While physics was taught at the Kloster only in the later grades, in the public library I read books with titles such as "Umsturz im Weltbild der Physik" and learned about the Balmer series and Bohr's energy levels of the hydrogen atom. My teachers at the Kloster were excellent, I remember in particular Dr. Richter, who taught Latin and Greek, and Dr. Splettstoesser, who taught biology and physics. Richter liked to expand on the classical works, which we were reading in class. I spent most of the ample breaks in related intense discussions with a group of classmates, Heppke, Hübner, Landau and Leiser while others engaged in boxing matches. Splettstoesser was a working scientist who spent Summers as a visitor with a marine biology institute on the Adriatic. I jumped a term and graduated in the spring of 1940.

Having received a notice from the draft board, I found it wise to volunteer for the anti-aircraft artillery and a motorized unit. I was not able to serve as a radio man but was assigned to a gun crew and never rose above the rank of senior private. Sent to relieve the German armies at Stalingrad, my battery was extremely lucky to escape the encirclement. A few months later I was even more lucky to be ordered back to Germany to study physics under an army program at the Universitat Breslau in 1943. After one year of study, I was sent to the Western Front and captured in the Battle of the Bulge. I spent a year in an American prisoner of war camp in France and was released early in 1946. Supporting myself with the repair and barter of prewar radios, I took up my study of physics again at the Universitat Göttingen. Here I attended lectures by Pohl, Richard Becker, Hans Kopfermann and Werner Heisenberg; Max v. Laue and Max Planck attended the physics colloquia. At the funeral of Planck I was chosen to be one of the pall bearers. At the university, I greatly enjoyed repeating the Frank-Hertz experiment, the Millikan oil drop, Zeemann effect, Hull's magnetron, Langmuir's plasma tube and other classic modem physics experiments in an excellent laboratory class run by Wolfgang Paul. In one of his Electricity & Magnetism classes Becker drew a dot on the blackboard and declared "Here is an electron ..." Having heard in another class that the wave function of an electron at rest spreads out over all of space, and having read about ion trapping in radio tubes in my teens set me to wonder how one might realize Becker's localization feat in the laboratory. However, that had to wait a while. In 1948, in Kopfermann's Institute, which was heavily oriented towards hyperfine structure studies, I completed an experimental Diplom-Arbeit (master's thesis) on a Thomson mass spectrograph under Peter Brix. The results were published in "Die photographischen Wirkungen mittelschneller Protonen II," the first paper of which I was a (co)author. Soon thereafter, I began work on my doctoral thesis under Hubert Kruger in the same Institute. Well prepared by a series of excellent Institute seminars on the NMR work of Bloch and of Purcell, we were able to successfully compete with workers at Harvard University. In 1949 we discovered Nuclear Quadrupole Resonance and reported it in our paper "Kernquadrupolfrequenzen in festem Dichloraethylen." My doctoral thesis had the title "Kernquadrupolfrequenzen in kristallinen Jodverbindungen." This work led to an invitation to join Walter Gordy's well known microwave laboratory at Duke University as postdoctoral associate.

At Duke I had the pleasure of making the acquaintance of James Frank, Fritz London, Lothar Nordheim and Hertha Sponer. I advised Hugh Robinson, a graduate student of Gordy's in an NQR experiment, did my own research and also contributed some NMR expertise to an experiment by Bill Fairbank and Gordy on spin statistics in $^3He/^4He$ mixtures, gaining some very useful low temperature experience in this brief collaboration. Through Gordy's and Nordheim's good offices I was able to receive a visiting assistant professor appointment at the University of Washington with a charge to advise Edwin Uehling's students during his sabbatical and to do independent research. I had built my first electron impact tube during a brief interlude in 1955 in George Volkoff s laboratory at the University of British Columbia. Prior to that I had attempted a paramagnetic resonance experiment on free atoms in Göttingen and succeeded in doing so at Duke. During seminars at Göttingen on the magnetic resonance techniques of Rabi and of Kastler, it had occurred to me that because of the analogy between an atom and a radio dipole antenna, (a), *alignment* of the atom should show up in its optical absorption cross section, and (b), electron impact should produce *aligned* excited atoms. I put these two ideas to good use in 1956 in Seattle in an experiment entitled "Paramagnetic Resonance Reorientation of Atoms and Ions Aligned by Electron Impact." In this paper I first pointed out the usefulness of ion *trapping for high resolution spectroscopy* and mentioned the 1923 Kingdon trap as a suitable device. This work also brought me into close contact with spin exchange between electron and target atom, which gave me the idea for my 1958 experiment "Spin Resonance of Free Electrons Polarized by Exchange Collisions." However, first I had to learn how to produce polarized atoms, which could then transfer their orientation to trapped electrons. Falling back on buffer gas techniques developed in my 1955 Duke paper "Atomic Phosphorus Paramagnetic Resonance Experiment," I quickly demonstrated in my 1956 Seattle paper "Slow Spin Relaxation of Optically Polarized Sodium Atoms" how to efficiently produce and monitor a polarized atom cloud. Trapping the electrons in a neutralizing ion cloud slowly diffusing in the buffer gas, I was able to carry out the spin resonance experiment. My optical transmission monitoring scheme proved also very useful in the development of rubidium vapor magnetometers and frequency standards by Earl Bell and Arnold Bloom at Varian Associates, in which I acted as a consultant. The rubidium frequency standard is still the least expensive, smallest and most widely used commercial atomic frequency standard. The thesis "Experimental Upper Limit for the Permanent Electric Dipole Moment of Rb^{85} by Optical Pumping Techniques" of my first graduate student, Earl Ensberg, also made use of these novel optical pumping schemes and was finished in 1962. These early results were improved orders of magnitude by my doctoral student Philip Ekstrom in his 1971 thesis "Search for Differential Linear Stark Shift in Cs^{133} and Rb^{85} Using Atomic Light Modulation Oscillators."

I was not satisfied with the plasma trapping scheme used for the electrons and asked my student, Keith Jefferts, to study ion trapping in an electron beam traversing a field free vacuum space between two grids. Also, I began to focus on the magnetron/Penning discharge geometry, which, in the Penning ion gauge, had caught my interest already at Göttingen and at Duke. In their 1955 cyclotron resonance work on photoelectrons in vacuum Franken and Liebes had reported undesirable frequency shifts caused by accidental electron trapping. Their analysis made me realize that in a pure electric quadrupole field the shift would not depend on the location of the electron in the trap. This is an important advantage over many other traps that I decided to exploit. A magnetron trap of this type had been briefly discussed in J. R. Pierce's 1949 book, and I developed a simple description of the axial, magnetron, and cyclotron motions of an electron in it. With the help of the expert glassblower of the Department, Jake Jonson, I built my first high vacuum magnetron trap in 1959 and was soon able to trap electrons for about 10 sec and to detect axial, magnetron and cyclotron resonances. About the same time, my Göttinger colleague, Otto Osberghaus, sent me a research report on the Paul rf ion cage. This trap had very desirable properties for atomic ions and it did not require a magnetic field. Therefore, I asked my student, Fouad Major, to experiment with a simplified cylindrical version of such a trap in the hope that it might be useful in hfs resonance experiments on hydrogenic helium ions. The early results were very encouraging and Jefferts also switched to the Paul trap. In 1962, Jefferts and Major both finished their Doctoral Theses entitled respectively "Alignment of Trapped H_2^+ Molecular Ions by Selective Photodissociation" and "The Orientation of Electrodynamically Contained He^4 Ions." As a continuation of the latter, a new postdoc, Norval Fortson, Major and I published the 1966 paper "Ultrahigh Resolution AF=0 ± 1 $^3He^+$ HFS Spectra by an Ion Storage - Exchange Collision Technique." My own attempts to detect the polarization of the electrons acquired from a polarized beam of alkali atoms in my Penning (magnetron) trap, described in a 1961 research report to the NSF "Spin Resonance of Free Electrons," were not so quickly successful. However in this work I was much impressed by *seeing* the beam of sodium atoms traversing my glass apparatus in the reflected light from a sodium vapor street lamp adapted as illuminating light source. Only a later concerted effort by Gräff and Werth at Bonn, reinforced by Major and Fortson, as visitors, made a similar spin resonance experiment work in 1968.

In the 1966 paper with Fortson and Major, I also proposed to develop an infrared laser based on ions in an rf trap. To this end my student, David Church, completed a thesis in 1969 entitled "Storage and Radiative Cooling of Light Ion Gases in RF Quadrupole Traps." In this work we demonstrated a race-track-shaped trap and cooled the ions by coupling to a resonant LC circuit. In parallel work my student, Stephan Menasian, in 1968, with some help from G. R. Huggett, succeded in cooling Hg^+ ions in a race-track-trap with a helium buffer gas and in detecting them by optical absorption. Jefferts' research on hfs spectra of H_2^+ was continued in Seattle by my postdoc Charles Richardson and later by Menasian in his 1973 doctoral thesis "High Resolution Study of the (1, ½, ½,) - (1, $^1/_2$,) HFS Transition in H_2^+." The resolution in the $^3He^+$ hfs work was greatly enhanced in work with my colleague Fortson and my postdoc Hans Schuessler. Realizing in 1961 that precision measurements of the electron magnetic moment would require a large magnetic field and that Becker's electron localization feat might be approximated in a Penning trap, I began to consider other avenues for magnetic resonance experiments. Some success in the electron work, achieved with the help of my new student, Fred Walls, was described in our 1968 paper "Bolometric" Technique for the RF Spectroscopy of Scored Ions." I reviewed the work on ions and electrons up to 1968 in two articles "Radiofrequency Spectroscopy of Stored Ions."

The able assistance of two postdocs, David Wineland and my former student Phil Ekstrom, made the isolation of a single electron become a reality in 1973 with our paper "Monoelectron Oscillator." Measuring its magnetic moment was another story. At Göttingen in the late forties I had attended a seminar given by Helmut Friedburg, a doctoral Student of Wolfgang Paul, on focussing spins with a magnetic hexapole. This may be viewed as a refinement of the Stern-Gerlach effect. In subsequent discussions with fellow students a rumor of a Stern-Gerlach experiment for electrons was brought up, and also Bohr's and Pauli's thesis that such experiments were impossible in principle. Though it greatly piqued my interest, I could not understand this thesis. Stimulated by a 1927 paper of Brillouin on the subject, I followed another of the guiding principles formulated by Bohr: "In my Institute we take nothing absolutely serious, including this statement." In 1973 I proposed, together with Ekstrom, to monitor spin and cyclotron quantum numbers of the lone electron by means of the "continuous Stern-Gerlach effect" in an abstract "Proposed $g\text{-}2/\delta\nu_z$ Experiment on Stored Single Electron or Positron." My new postdoc Robert Van Dyck, Philip Ekstrom and myself reported the first such experiment in our 1976 paper "Axial, Magnetron, and Spin-Cyclotron Beat Frequencies Measured on Single Electron Almost at Rest in Free Space (Geonium)." This work also already made use of the important technique of *side band cooling* of the electron. The demonstration of sideband cooling had eluded us in earlier attempts undertaken together with Walls and later with Wineland. Encouraged by the success of the monoelectron oscillator I had also published in 1973 an abstract "Proposed $10^{14}\Delta\nu < \nu$ Laser Fluorescence Spectroscopy on Tl^{+} Mono-Ion Oscillator." Unfortunately, this proposal infuriated one of the agencies funding our research to the degree that they terminated their support almost immediately. I was rescued by a prize from the Humboldt Foundation and an invitation by Gisbert zu Putlitz to initiate the proposed laser spectroscopy project in his Institute at the Universität Heidelberg. As the fruit of these efforts a paper "Localized visible Ba^{+} mono-ion oscillator" by Neuhauser, Hohenstatt, Toschek and myself appeared in 1980.

In 1981 Van Dyck, my doctoral student Paul Schwinberg and myself extended the electron work to its antiparticle in our paper "Preliminary Comparison of the Positron and Electron Spin Anomalies" and I reviewed it in an article "Invariant Frequency Ratios in Electron and Positron Geonium Spectra Yield Refined Data on Electron Structure." In 1986 we published a detailed paper "Electron Magnetic Moment from Geonium Spectra: Early Experiments and Background Concepts" and in 1987 our collaboration reported a 4 parts in 10^{12} resolution in the g factor for electron and positron in "New High-Precision Comparison of Electron and Positron g Factors." A very promising scheme to detect cyclotron excitation through the small relativistic mass increase accompanying it was published in a 1985 paper "Observation of Relativistic Bistable Hysteresis in the Cyclotroil Motion of a Single Electron" together with my postdoc, Gerald Gabrielse, and William Kells, a visitor from Fermi Lab.

Two years after the Heidelberg pioneering work an individual magnesium ion was isolated in Seattle with my postdoc Warren Nagourney and my student Gary Janik. The latter's thesis bore the title "Laser Cooled Single Ion Spectroscopy of Magnesium and Barium." "Shelved optical electron amplifier: Observation of quantum jumps," was published in 1986 with my colleague Nagourney, and Jon Sandberg, an exceptional undergraduate assistant. The paper introduced a new technique which has made optical spectroscopy on an individual ion possible with record resolution and reproducibility. To date the best resolution has been realized at NIST by a group headed by my former collaborator Wineland. Peter Toschek who had made important contributions to the visible ion work in Heidelberg has built up a thriving laboratory for monoion-spectroscopy at the Universität Hamburg. With Herbert Walther a collaboration almost came off in 1974. Walther, with his large staff and excellent facilities in Munich, has since developed his own expertise in the field and made outstanding contributions to it. Gabrielse, now a full professor at Harvard, has assembled a large group and is trapping and cooling antiprotons at CERN.

In the 1988 paper "A Single Atomic Particle Forever Floating at Rest in Free Space: New Value for Electron Radius" I have surveyed the field and suggested new avenues for its extension. More precise measurements of the g factor of the electron may well be the most promising approach to study its structure. No less important, a trapped individual atomic ion may reveal itself as a timekeeping element of unsurpassed reproducibility. The research effort in Seattle continues on both projects. The National Science Foundation has supported my research since 1958 without interruption. Initially the Army Office of Ordnance Research and the Office of Naval Research did also provide support for many years.

I am married to Diana Dundore, a practicing physician. I have a grown son, Gerd, from an earlier marriage to Irmgard Lassow who is deceased.

I do regular hatha yoga exercises, enjoy waltzing, hiking in the foothills, reading, listening to classical music, and watching ballet performances.

SELECTED PUBLICATIONS

"Die photographischen Wirkungen mittelschneller Protonen II", P. Brix and H. Dehmelt, Z. Physik 126; 728 (1949)

"Kernquadrupolfrequenzen in festem Dichloraethylen", H. Dehmelt and H. Krueger, Naturwissenschaften 37, 111 (1950)

"Nuclear Quadrupole Resonance", H. Dehmelt, Am. J. Phys. 22, 110 (1954)

"Atomic Phosphorus Paramagnetic Resonance Experiment", H. Dehmelt, Phys. Rev. 99,527 (1955)

"Paramagnetic Resonance Reorientation of Atoms and Ions Aligned by Electron Impact" H. Dehmelt, Phys. Rev. 103, 1125 (1956)

"Slow Spin Relaxation of Optically Polarized Sodium Atoms", H. Dehmelt, Phys. Rev. 105, 1487 (1957)

"Modulation of a Light Beam by Precessing Absorbing Atoms" H. Dehmelt, Phys. Rev. 105, 1924 (1957)

"Spin Resonance of Free Electrons Polarized by Exchange Collisions", H. Dehmelt, Phys. Rev. 109, 381 (1958)

"Spin Resonance of Free Electrons", H. Dehmelt, 1958-61 Progress Report for NSF Grant NSF-G 5955

"Alignment of the H_2^+ Molecular Ion by Selective Photodissociation", H. Dehmelt and K. Jefferts, Phys. Rev. 125, 1318 (1962)

"Orientation of He Ions by Exchange Collisions with Cesium Atoms", H. Dehmelt and F. Major, Phys. Rev. Lett. 8, 213 (1962)

"Ultrahigh Resolution AF=0, ±1 ^{3}He+ HFS Spectra by an Ion Storage - Exchange Collision Technique", N. Fortson, F. Major and H. Dehmelt, Phys. Rev. Lett. ***16,*** 221 (1966)

"Radiofrequency Spectroscopy of Stored Ions, H. Dehmelt, Adv. At. Mol. Phys. 3, 53 (1967) and 5, 109 (1969)

"Alignment of the H_2^+ Molecular Ion by Selective Photodissociation II: Experiments on the RF Spectrum," Ch. Richardson, K. Jefferts and H. Dehmelt, Phys. Rev. 165, 80 (1968)

'Bolometric' Technique for the RF Spectroscopy of Stored Ions", H. Dehmelt and F. Walls, Phys. Rev. Lett. ***21,*** 127 (1968)

"Radiative ***Cooling*** of an Electrodynamically Confined Proton Gas", D. Church and H. Dehmelt, J. Appl. Phys. 40, 3421 (1969)

"Proposed $g\text{-}2/\delta\nu_z$ Experiment on Stored Single Electron or Positron", H. Dehmelt and P. Ekstrom, Bull. Am. Phys. Soc. ***18, 727*** (1973)

"Monoelectron Oscillator", D. Wineland, P. Ekstrom and H. Dehmelt, Phys. Rev. Lett. ***31,*** 1279 (1973)

"Proposed 10^{14} **Av** < v Laser Fluorescence Spectroscopy on Tl^+ Mono-Ion Oscillator", H. Dehmelt, Bull. Am. Phys. Soc. ***18,*** 1521 (1973)

"Principles of the Stored Ion Calorimeter" D. Wineland and H. Dehmelt, J. Appl. Phys. 46, 919 (1975)

"Proposed $10^{14}\Delta\nu < \nu$ Laser Fluorescence Spectroscopy on Tl^+ Mono-Ion Oscillator II (spontaneous quantum jumps)", H. Dehmelt, Bull. Am. Phys. Soc. 20, 60 (1975)

"Proposed 10^{14} Av < v Laser Fluorescence Spectroscopy on Tl^+ Mono-Ion Oscillator III (side band cooling)", D. Wineland and H. Dehmelt, Bull. Am. Phys. Soc. 20, 637 (1975)

"Axial, Magnetron, Cyclotron and Spin-Cyclotron Beat Frequencies Measured on Single Electron Almost at Rest in Free Space (Geonium)", Van Dyck, Jr., R. S., Ekstrom, P., and Dehmelt, H., Nature 262, 776 (1976)

"Entropy Reduction by Motional Side Band Excitation", Dehmelt, H., Nature 262, 777 (1976)

"A Progress Report on the g-2 Resonance Experiments", H. Dehmelt, in ***Atomic Musses and Fundamental*** Constants, Volume 5 (eds. J. H. Sanders, and A. H. Wapstra), p. 499. Plenum New York, 1976

"Precise Measurement of Axial, Magnetron, Cyclotron and Spin-Cyclotron Beat Frequencies on an Isolated 1-meV Electron", Van Dyck, Jr., R. S., Ekstrom, P., and Dehmelt, H., Phys. Rev. Lett. 38, 310 (1977)

"Electron Magnetic Moment from Geonium Spectra", Van Dyck, Jr., R. S., Schwinberg, P. B. & Dehmelt, H. ***G.,*** in New ***Frontiers in High Energy Physics*** (Eds. B. Kursunoglu, A. Perlmutter, and L. Scott), Plenum New York, 1978

"Optical Sideband Cooling of Visible Atom Cloud Confined in Parabolic Well", Neuhauser, W., Hohenstatt, M., Toschek, P. E., and Dehmelt, H. G., Phys. Rev. Lett. ***41, 233*** (1978)

"Single Elementary Particle at Rest in Free Space I-IV", Dehmelt, H., Van Dyck, Jr., R. S., Schwinberg, P. B., Gabrielse, G., Bull. Am. Phys. Soc. 24, 757 (1979)

"Localized visible Ba^+ mono-ion oscillator", Neuhauser, W., Hohenstatt, M., Toschek, P. E., and Dehmelt, H. G., Phys. Rev. ***A22,*** 1137 (1980)

"Preliminary Comparison of the Positron and Electron Spin Anomalies", P. B. Schwinberg, R. S. Van Dyck, Jr., and H. G. Dehmelt, Phys. Rev. Lett. 47, 1679 (1981)

"Invariant Frequency Ratios in Electron and Positron Geonium Spectra Yield Refined Data on Electron Structure", Hans Dehmelt, ***in Atomic Physics 7,*** D. Kleppner & F. Pipkin Eds., Plenum, New York, 1981

"Mono-Ion Oscillator as Potential Ultimate Laser Frequency Standard", Hans Dehmelt, IEEE Transactions on Instrumentation & Measurement, ***IM-31, 83*** (1982)

"Stored Ion Spectroscopy", Hans Dehmelt, in ***Advances in Laser spectroscopy,*** F. T. Arecchi, F. Strumia & H. Walther, Eds., Plenum, New York, 1983

"Geonium Spectra and the Finer Structure of the Electron", R. Van Dyck, P. Schwinberg, G. Gabrielse & Hans Dehmelt, Bulletin of Magnetic Resonance 4, 107 (1983)

"g-Factor of Electron Centered in Symmetric Cavity", Hans Dehmelt, Proc. Natl. Acad. Sci. USA ***81, 8037*** (1984); Erratum ibidem 82, 6366 (1985)

"Observation of Relativistic Bistable Hysteresis in the Cyclotron Motion of a Single Electron", G. Gabrielse, H. Dehmelt & W. Kells, Phys. Rev. Letters 54, 537 (1985).

"Doppler-Free Optical Spectroscopy on the Ba^+ Mono-Ion Oscillator", G. Janik, W. Nagourney, H. Dehmelt, J. Opt. Soc. Am. B2, 1251-1257 (1985)

"Single Atomic Particle at Rest in Free Space: New Value for Electron Radius", Hans Dehmelt, Annales de Physique (Paris) ***10, 777 - 795*** (1985)

"Observation of Inhibited Spontaneous Emission", G. Gabrielse and H.Dehmelt, Phys. Rev. Lett. 55, 67 (1985)

"Electron Magnetic Moment from Geonium Spectra: Early Experiments and Background Concepts", Van Dyck, Jr., R. S., Schwinberg, P. B. & Dehmelt, H. G., Phys. Rev. D 34, 722 (1986)

"Continuous Stern Gerlach Effect: Principle and idealized apparatus", Hans Dehmelt, Proc. Natl. Acad. Sci. USA 83, 2291 (1986), and 83, 3074 (1986)

"Shelved optical electron amplifier: Observation of quantum lumps", Warren Nagourney, Jon Sandberg, and Hans Dehmelt, Phys. Rev. Letters 56, 2797 (1986)

"New High Precision Comparison of Electron/Positron g-Factors", Van Dyck, Jr, R. S., Schwinberg, P. B. Dehmelt, H. G., Phys. Rev. Letters 59, 26 (1987)

"Single Atomic Particle at Rest in Free Space: Shift-Free Suppression of the Natural Line Width?", Hans Dehmelt, in ***Laser Spectroscopy VIII,*** S. Svanberg and W. Persson editors, 1987 (Springer, New York)

"Single Atomic Particle Forever Floating at Rest in Free Space: New Value for Electron Radius", Hans Dehmelt, Physica Scripta T22, 102 (1988)

"New Continuous Stern Gerlach Effect and a Hint of 'The' Elementary Particle", Hans Dehmelt, Z. Phys. D 10, 127-134 (1988)

"Coherent Spectroscopy on a Single Atomic System at Rest in Free Space III", Hans Dehmelt, in ***Frequency Standards and Metrology,*** A. de Marchi Ed. (Springer, New York, 1989). p. 15

"Triton, electron, cosmon .: An infinite regression? Hans Dehmelt, Proc. Natl. Acad. Sri. USA 86, 8618-8619 (1989)

"Miniature Paul-Straubel ion trap with well-defined deep potential well", Nan Yu, Hans Dehmelt, and Warren Nagourney, Proc. Natl. Acad. Sci. USA 86, 5672 (I 989)

EXPERIMENTS WITH AN ISOLATED SUBATOMIC PARTICLE AT REST

Nobel Lecture, December 8, 1989

bY

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"You know, it would be sufficient to really understand the electron."
Albert Einstein

The 5th century B.C. philosopher's Democritus' smallest conceivable indivisible entity, the a-tomon (the un-cuttable), is a most powerful but not an immutable concept. By 1920 it had already metamorphosed twice: from something similar to a molecule, say a slippery atomon of water, to Mendeleyev's chemist's atom and later to electron and to proton, both particles originally assumed to be of small but finite size. With the rise of Dirac's theory of the electron in the late twenties their size shrunk to mathematically zero. Everybody "knew" then that electron and proton were indivisible Dirac point particles with radius R = 0 and gyromagnetic ratio g = 2.00. The first hint of cuttability or at least compositeness of the proton came from Stern's 1933 measurement of proton magnetism in a Stern-Gerlach molecular beam apparatus. However this was not realized at the time. He found for its normalized dimensionless gyromagnetic ratio not g = 2 but

$$g = (\mu/A)(2M/q) \approx 5,$$

where μ, A, M, q are respectively magnetic moment, angular momentum, mass and charge of the particle. For comparison the obviously composite $^4He^+$ ion, also with spin ½, according to the above formula has the $|g|$ value 14700, much larger than the Dirac value 2. Also, along with this large $|g|$ value went a size of this atomic ion about 4 orders of magnitude larger than an a-particle. And indeed, with Hofstadter's high energy electron scattering experiments in the fifties the proton radius grew again to R = 0.86 x 10^{-15} m. Similar later work at still higher energies found 3 quarks inside the "indivisible" proton. Today everybody "knows" the *electron* is an indivisible atomon, a Dirac point particle with radius R = 0 and g = 2.00.... But is it? Like the proton, it could be a composite object. History may well repeat itself. This puts a high premium on precise measurements of the g factor of the electron.

GEONIUM SPECTROSCOPY

The metastable pseudo-atom geonium (Van Dyck et al. 1978 and 1986) has been expressly synthesized for studies of the electron g factor under optimal conditions. It consists of an individual electron permanently confined in an ultrahigh vacuum Penning trap at 4K. The trap employs a homogeneous magnetic field $B_0 = 5T$ and a weak electric quadrupole field. The latter is produced by hyperbolic electrodes, a positive ring and two negative caps spaced $2Z_0 = 8$ mm apart, see Fig. 1. The potential, with A a constant, is given by

$$\phi(xyz) = A(x^2 + y^2 - 2z^2),$$

with an axial potential well depth

$$D = e[\phi(000) - \phi(00Z_0)] = 2eAZ_0{}^2 = 5eV.$$

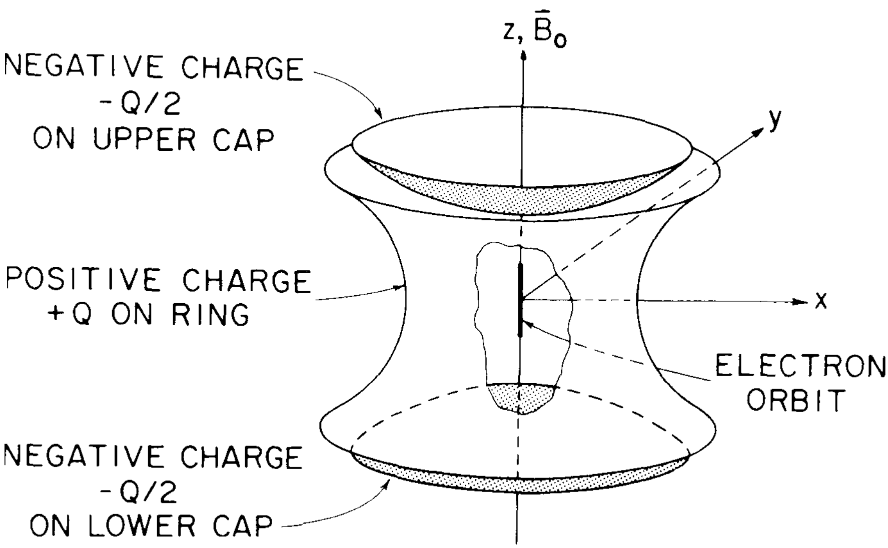

Figure I. Penning trap. The simplest motion of an electron in the trap is along its symmetry axis, along a magnetic field line. Each time it comes too close to one of the negatively charged caps it turns around. The resulting harmonic oscillation took place at about 60 MHz in our trap. Reproduced from (Dehmelt 1983) with permission, copyright Plenum Press.

The trapping is mostly magnetic. The large magnetic field dominates the motion in the geonium atom. The energy levels of this atom shown in Figure 2 reflect the cyclotron motion, at frequency $v_c = eB_0/2nm = 141$ GHz, the spin precession, at v_c, v_c, the anomaly or g-2 frequency $v_a = v_s - v_c = 164$ MHz, the axial oscillation, at $v_z = 60$ MHz, and the magnetron or drift motion at frequency v_m, = 13 kHz. The electron is continuously monitored by exciting the v_z-oscillation and detecting via radio the 10^8-fold enhanced spontaneous 60 MHz emission. A corresponding signal appears in Figure 3.

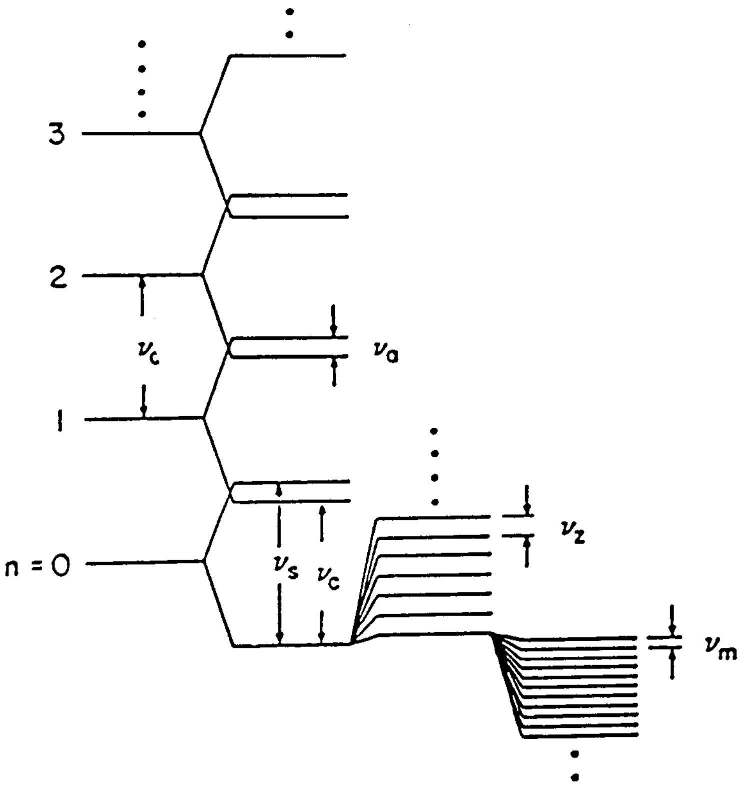

Figure 2. Energy levels of gconium. Each of the cyclotron lcvcls labeled n is split first by the spin magnetic field interaction. The resulting sublevels are further split into the oscillator levels and finally the manifold of magnetron levels extending downwards. Reproduced from (Van Dyck et al. 1978) with permission, copyright Plenum Press.

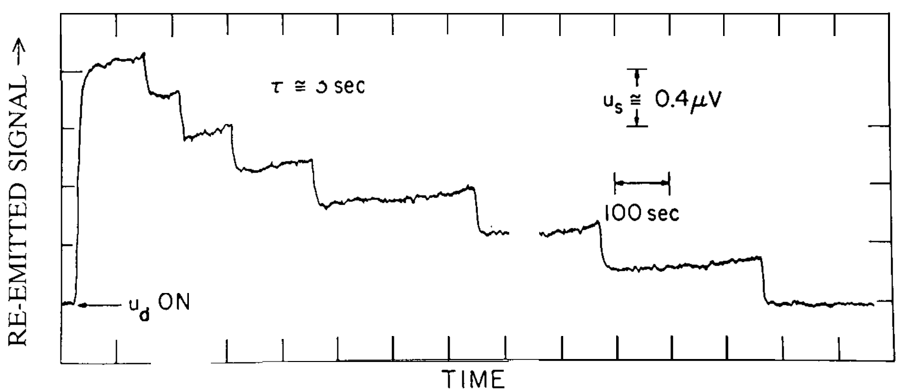

Figure 3. Rf signal produced by trapped electron. When the electron is driven by an axial rf field, it emits a 60 MHz signal, which was picked up by a radio receiver. The signal shown was for a very strong drive and an initially injected bunch of 7 electrons. One electron after the other was randomly "boiled" out of the trap until finally only a single one is left. By somewhat reducing the drive power, this last electron could be observed indefinitely. Reproduced from (Wineland et al. 1973) with permission, copyright American Institute of Physics.

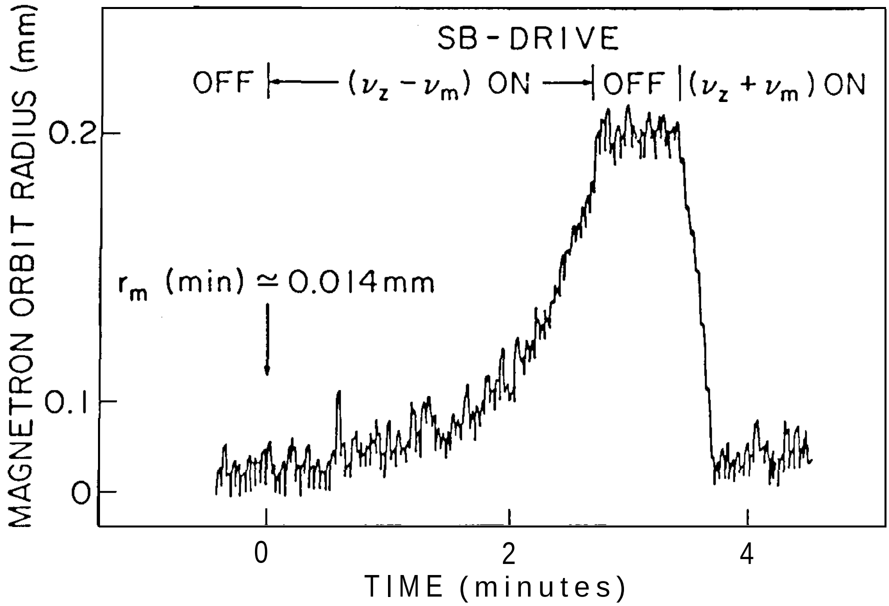

Figure 4. Side-band "cooling" of the magnetron motion at v_m. By driving the axial motion not on rcsonancc at v_z but on the lower side-band at v_z-v_m it is possible to force the metastable magnetron motion to provide the energy balance hv_m, and thereby expand the magnetron orbit radius. Conversely, an axial drive at $v_z + v_m$ shrinks the radius. The roles of upper and lower side-bands arc reversed here from the case of a particle in a well where the energy increases with amplitude because the magnetron motion is metastable and the total energy of this motion decreases with radius. Reproduced from (Van Dyck et al. 1978) with permission, copyright Plenum Press.

Side band cooling has made continuous confinement in the trap center of an electron for 10 months (Gabrielse et al. 1985) possible. This process makes the electron absorb rf photons deficient in energy and supply the balance from energy stored in the electron motion to be cooled. The corresponding shrinking of the radius of the magnetron motion is displayed in Figure 4. Extended into the optical region, the cooling scheme is most convincingly demonstrated in Figure 5. The transitions of primary interest at v_c, v_a, v_m are much more difficult to detect than the v_z oscillation. Nevertheless the task may be accomplished by means of the continuous Stern-Gerlach effect (Dehmelt 1988a), in which the geonium atom itself is made to work as a 10^8-fold amplifier. In the scheme a single v_a-photon of only ≈ 1μeV energy gates the absorption of ≈ 100 eV of rf power at v,. The continuous effect uses an inhomogeneous magnetic field in a similar way as the classic one. However, the field takes now the form of a very weak Lawrence cyclotron trap or magnetic bottle shown in Figure 6. The bottle adds a minute monitoring well, only

$$D_m = (m + n + \tfrac{1}{2})\, 0.1\mu eV$$

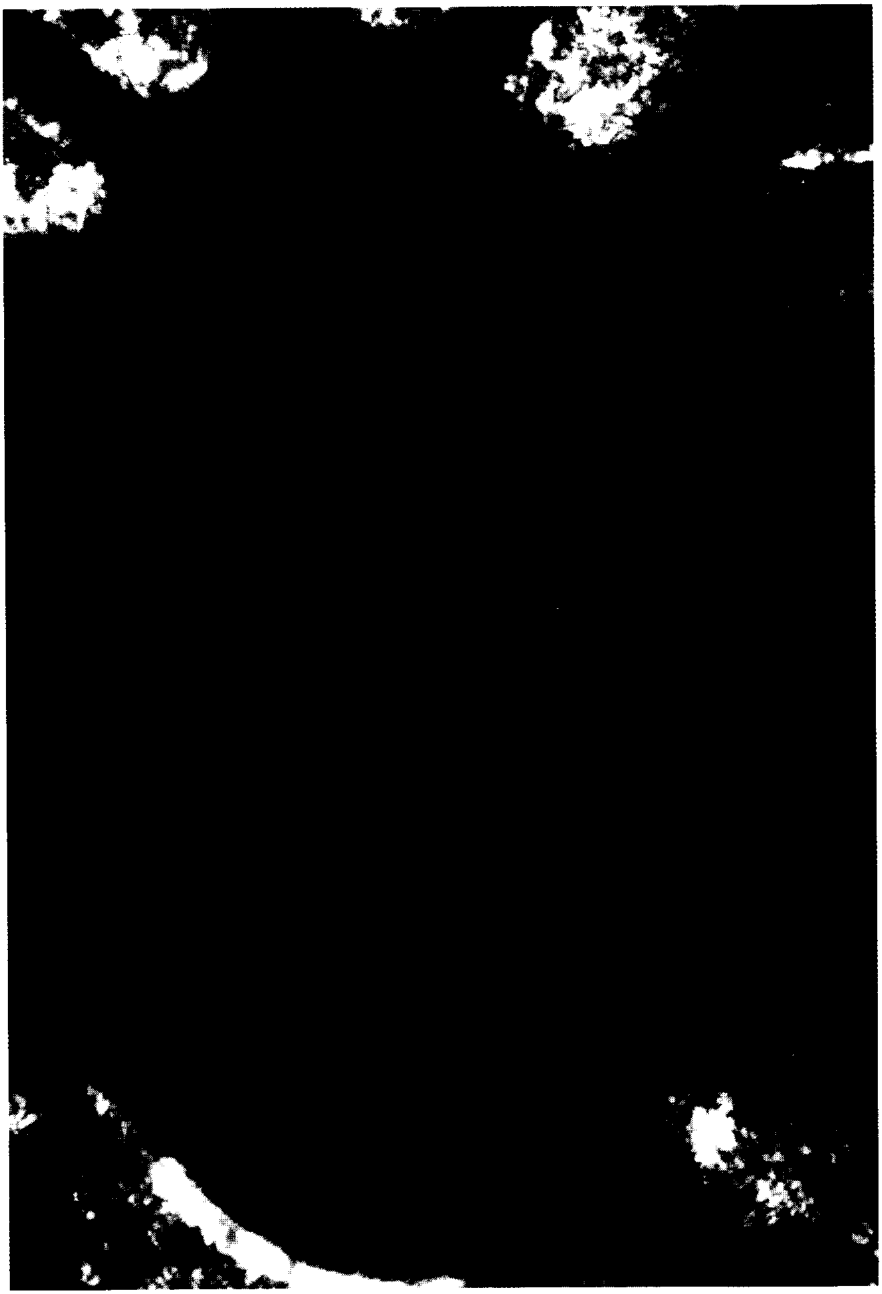

Figure 5. Visible blue (charged) barium atom Astrid at rest in center of Paul trap photographed in natural color. Thc photograph strikingly demonstrates the close localization, < 1 μm, attainable with geonium techniques. Stray light from the lasers focussed on the ion also illuminate\ the ring electrode of the tiny rf trap of about 1 mm internal diameter. Reproduced from (Dehmelt 1988) with permission, copyright the Royal Swedish Academy of Sciences.

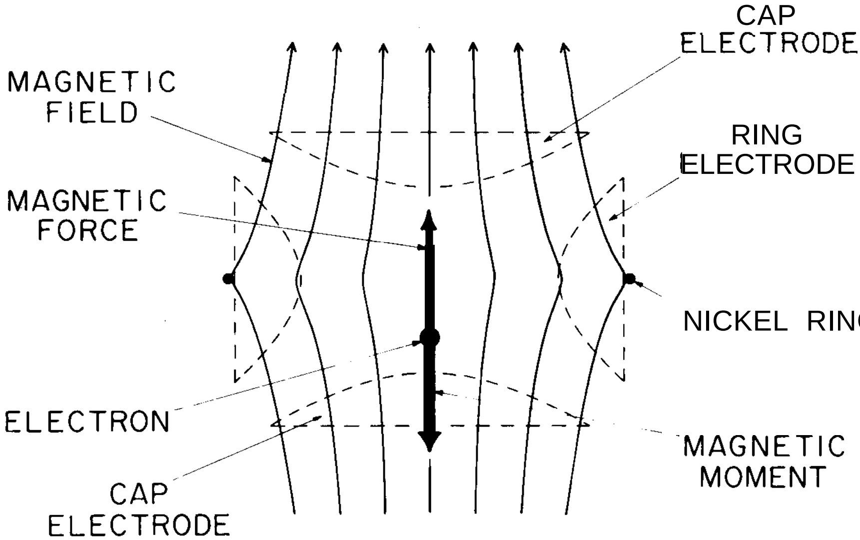

Figure 6. Weak magnetic bottle for continuous Stern-Gerlach effect. When in the lowest cyclotron and magnetron level the electron forms a 1 μm long wave packet, 30 nm in diameter, which may oscillate undistorted in the axial electric potential well. The inhomogeneous field of the auxiliary magnetic bottle produces a minute spin-dependent restoring force that causes the axial frequency ν_z for spin ↑ and ↓ to differ by a small but detectable value. Reproduced from (Dehmelt 1988a) with permission, copyright Springer Verlag.

deep, to the axial well of large electrostatic depth D = 5eV, with m, n respectively denoting spin and cyclotron quantum numbers. Thus jumps in m or n show up as jumps in ν_z,

$$\nu_z = \nu_{z0} + (m + n + 1/2)\delta,$$

with δ = 1.2Hz in our experiments, and ν_{z0} the axial frequency of a hypothetical electron without magnetic moment. Random jumps in m, n occur, when spin or cyclotron resonances are excited. Figure 6A shows an early example of a series of such jumps in m or spin flips. For the spin spontaneous transitions are totally negligible. Standard text books discuss

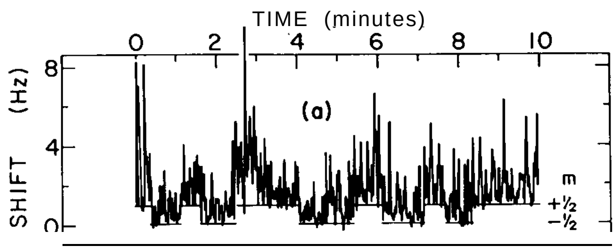

Figure 6A. Spin flips recorded by means of the continuous Stern-Gerlach effect. The random jumps in the base line indicate jumps in m at a rate of about I/minute when the spin resonance is excited. The upwards spikes or “cyclotron grass" are explained by expected rapid random thcrma1 excitation and spontaneous decay of cyclotron levels with an average value < n > ≈ 1.2. Adapted from (Van Dyck et al. 1977) with permission, copyright American Institute of Physics.

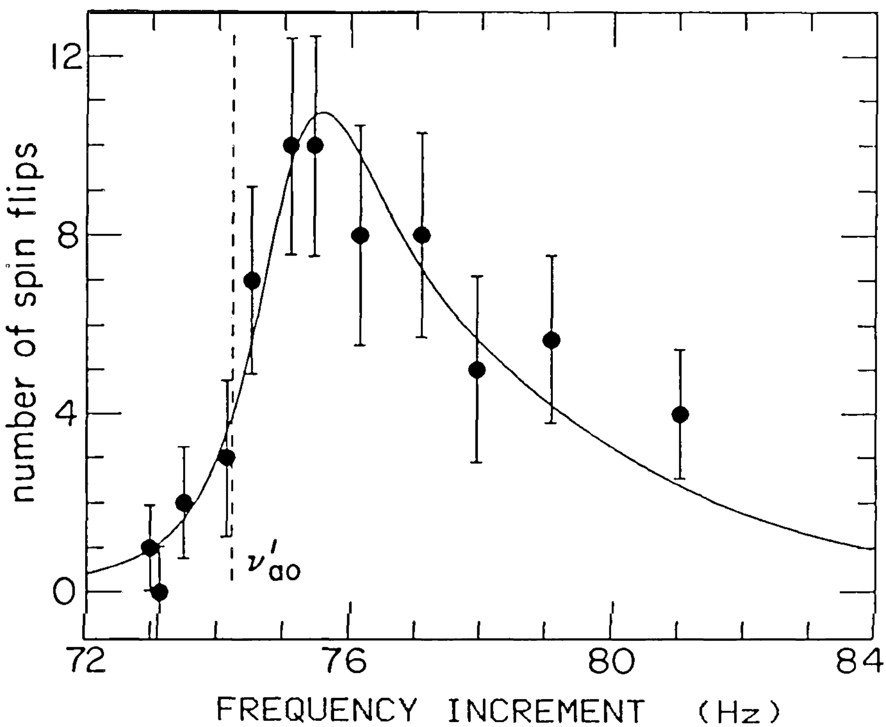

Figure 7. Plot of electron spin resonance in geonium near 141 GHz. A magnetic radiofrequency field causes random jumps in the spin quantum number. As the frequency of the exciting field is stepped through the resonance in small increments, the number of spin flips occurring in a fixed observation period of about ½ hour are counted and then plotted vs frequency. (Actually the 141 GHz field flipping the spin is produced by the cyclotron motion of the electron through an inhomogeneous magnetic rf field at $\nu_s - \nu_c$ = 164 MHz.) Reproduced from (Van Dyck et al. 1987) with permission, copyright American Institute of Physics.

transitions between two sharp levels induced by a broad electromagnetic spectrum $\rho(\nu)$: The transition rate from either level is the same and is proportional to the spectral power density $\rho(\nu_s)$ of the radiation field at the transition frequency ν_s. Ergo, the average dwell times in either level are the same, compare Fig. 6A. In the geonium experiments the frequency of the weak rf field is sharp, but the spin resonance is broadened and has a shape $G_s(\nu)$. One may convince oneself that moving the sharp frequency of the rf field upwards over the broad spin resonance should produce the same results as moving a broad rf field of spectral shape $\rho(\nu) \propto G_s(\nu)$ downwards over a sharp spin resonance: The rate of all spin flips or jumps in m in either direction counted in the experiment is proportional to $G_s(\nu)$. To obtain the plot of $G_s(\nu)$ in Fig. 7 the frequency of the rf field was increased in small steps, and at each step spin flips were counted for a fixed period of about ½ hour. From our ν_s, ν_c, data for electron and positron (Van Dyck et al. 1987) we have determined

$$\tfrac{1}{2}g^{exp} = \nu_s/\nu_c = 1.001\ 159\ 652\ 188(4),$$

the same for particle and anti-particle. The error in their difference is only half as large. Heroic quantum electro-dynamical calculations (Kinoshita 1988) have now yielded for the shift of the g factor of a point electron associated with turning on its interaction with the electromagnetic radiation field

$$\tfrac{1}{2}(g^{point}-2) = \tfrac{1}{2}\Delta g^{\ KINOSHITA} = 0.001\ 159\ 652\ 133(29).$$

In the calculations $\Delta g^{\ KINOSHITA}$ is expressed as a power series in α/π. Kinoshita has critically evaluated the experimental a input data on which he must rely. He warns that the error in his above result, which is dominated by the error in a, may be underestimated. Muonic, hadronic and other small contributions to g amount to less than about 4x10-12 and have been included in the shift. Kinoshita's result may be used to correct the experimental g value and find

$$g = g^{exp} - \Delta g^{KINOSHITA1} = 2 + 11(6)\mathrm{x}10^{-11}.$$

ELECTRON RADIUS R?

Extrapolation from known to unknown phenomena is a time-honored approach in all the sciences. Thus from known g, and R values of other near-Dirac particles and our *measured* g value of the electron I attempt to extrapolate a value for its radius. Stimulated by 1980 theoretical work of Brodsky & Drell, I (1989a) have plotted $|g\text{-}2| = R/\lambda_C$ in Figure 8 for the helium3 nucleus, triton, proton, and electron. Here λ_C is the Compton wavelength of the respective particle. The plausible relation given by Brodsky and Drell (1980) for the simplest composite theoretical model of the electron,

$$|g - 2| = R/\lambda_C, \text{ or}$$

$$|g - g_{DIRAC}| = R/\lambda_C$$

fits the admittedly sparse data surprisingly well. Even for such a very different spin ½ structure as the atomic ion $^4He^+$ composed of an a-particle and an electron the data point does not fall too far off the full line. Intersection in Figure 8 of this line with the line $|g\text{-}2| = 1.1\mathrm{x}10^{-10}$ for the Seattle g data yields for the electron the extrapolated point shown and with $\lambda_C = 0.39\mathrm{x}10^{-10}$ cm an electron radius

$$R \approx 10^{-20}\ \mathrm{cm}.$$

The row of X's reflects the data range defined by the uncertainty in the Seattle g data and the upper limit $R < 10^{-17}$ cm determined in high energy collision experiments. It appears that this combination of current data is not in harmony with electron structure models assuming special symmetries that predict the quadratic relation $|g\text{-}2| \approx (R/\lambda_C)^2$ shown by the dashed line. This favors the linear relation used in the above extrapolation of R for the electron. Thus, the electron may have size and structure!

If one feels that the excess g value 1 l(6) x 10^{-11} measured is not signifi-

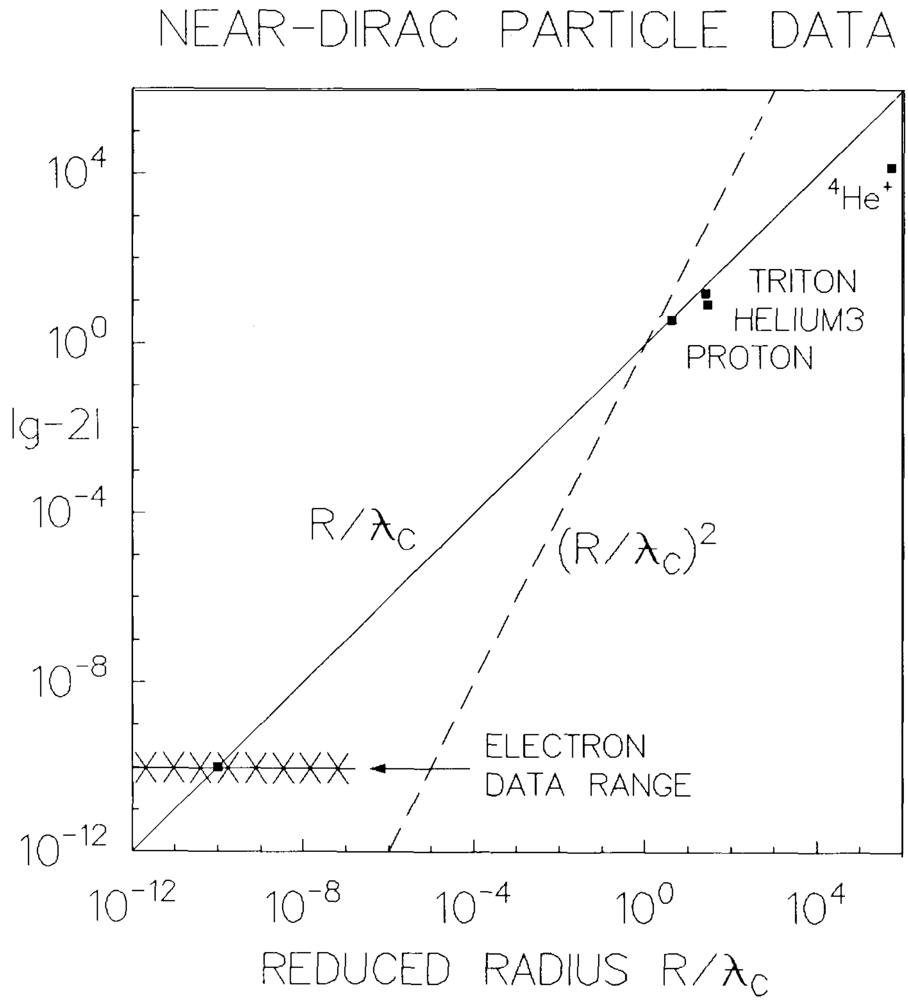

Figure 8. Plot of |g-2| values, with radiative shifts removed, vs reduced rms radius R/λ_C for ncar-Dirac- particles. The full line (g-21 = R/λ_C predicted by the simplest theoretical model provides a surprisingly good fit to the data points for proton, triton and helium3 nucleus. It may be used to obtain a new radius value for the *physical* electron from its intersection with the line |g-2| = 1.1×10^{-10} representing the Seattle electron g data. The data are much less well fitted by the relation $|g-2| = (R/\lambda_C)^2$, which is shown for comparison in the dashed line. The atomic ion $^{4}He^{+}$ is definitely *not* a near-Dirac particle, but even its data point does not fall too far off the full line. Adapted from (Dehmelt 1990) with permission, copyright American Institute of Physics.

cant because of its large relative error then, the value $R \approx 10^{-20}$ cm given here still constitutes an important new upper limit. Changing the point of view, the close agreement of g^{point} with g^{exp} provides the most stringent experimental test of the fundamental theory of Quantum Electrodynamics in which R = 0 is assumed. Furthermore the near-identity of the g values measured for electron and positron in Seattle constitutes the most severe test of the CPT theorem or mirror symmetry of a *charged* particle pair.

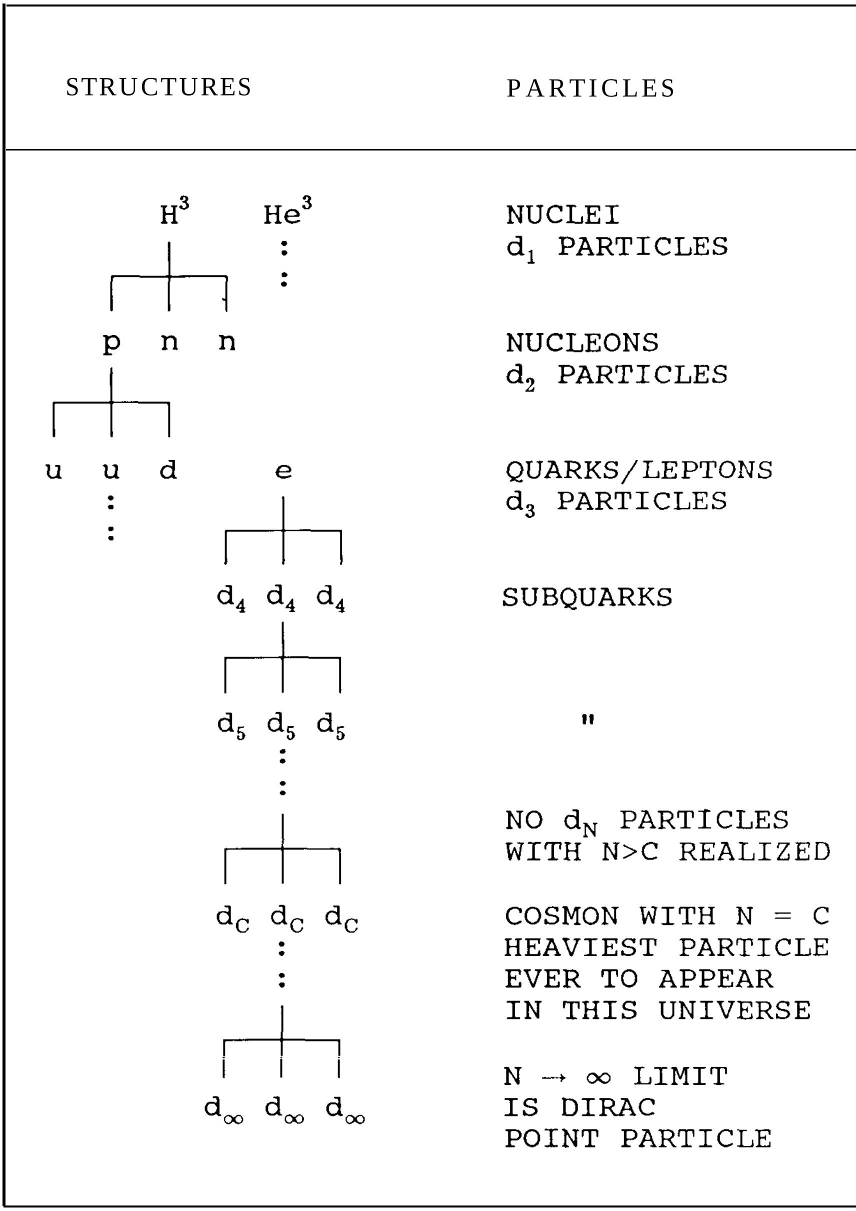

Figure 9. Triton model of near-Dirac particles. Reproduced from (Dehmelt 1989b) with permission, copyright the National Academy of Sciences of the USA.

LEMAÎTRE'S "L'ATOME PRIMITIF" REVISITED - A SPECULATION

Beginning 1974 Salam and others have proposed composite electron and quark models (Lyons 1983). On the strength of these proposals and with an eye on Figure 8, I view the electron as the third approximation of a Dirac particle, d_3 for short, and as composed of three fourth-approximation Dirac

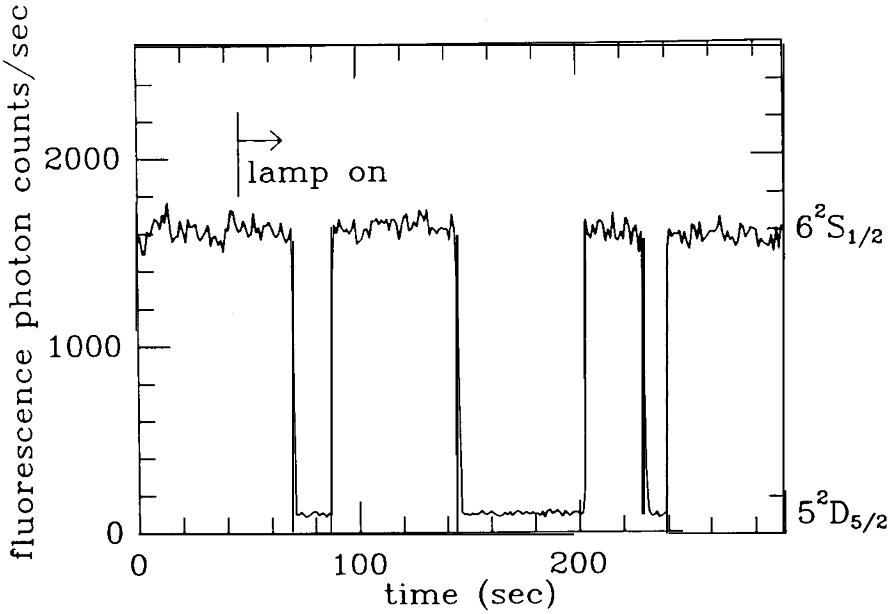

Figure 10. Spontaneous decay of Ba^+ ion in metastable $D_{5/2}$-levcl. Illuminating the ion with a laser turned close to its resonance line produces strong resonance fluorescence and an easily detectable photon count of I600 photons/xc When later an auxiliary, weak Ba^+ spectral lamp is turned on the ion is randomly transported into the metastable $D_{5/2}$ level of 30 sec lifetime and becomes invisible. After dwelling in this shelving level for 30 sec on the average, it drops down to the $S_{½}$ ground state spontaneously and becomes visible again. This cycle then repeats. Reproduced from (Nagourney et al. 1986) with permission, copyright American Institute of Physics.

or d_4 particles. The situation is taken to be quite similar to that previously encountered in the triton and proton subatomic particles, respectively assumed to be of type d_1 and d_z. In more detail, three d_4 subquarks of huge mass m_4 in a deep square well make up the electron in this working hypothesis. However, their mass $3m_4$ is almost completely compensated by strong binding to yield a total relativistic mass equal to the observed mass m_e of the electron. Figure 8 may even suggest a more speculative extrapolation: The e-constituents, in the infinite regression $N \rightarrow \infty$ - proposed in Figure 9, have ever more massive, ever smaller sub-sub-. . . . constituents d_N. However, these higher order subquarks are realized only up to the "cosmon" with N = C, the most massive particle ever to appear in this universe. At the beginning of the universe, a lone bound cosmon-anticosmon pair or life time-broadened cosmonium atom state of near-zero total relativistic mass/energy was created from Vilenkin’s (1984) metastable “nothing” state of zero relativistic energy in a spontaneous quantum jump of cosmic rarity. Similar, though much more frequent, quantum jumps that have recently been observed in a trapped Ba^+ ion are shown in Figure 10. In this case the system also jumps spontaneously from a state (ion in metastable $D_{5,2}$ level plus no photon) to a new state (ion in $S_{½}$ ground level plus photon) of the same total energy. The “cosmonium atom” introduced here is merely a modernized version* of Lemaître’s "l'atome primitif’ or world-atom whose explosive radioactive decay created the universe. At the beginning of the world the short-lived cosmonium atom decayed into an early gravitation-dominated standard big bang state that eventually developed into a state, in which again rest mass energy, kinetic and Newtonian gravitational potential energy add up to zero (see formula 8 of Jordan 1937). The electron is a much more complex particle than the cosmon. It is composed of 3^{C-3} cosmon-like d_c’s, but only two particles of this type formed the cosmonium world-atom from which sprang the universe. In closing, I should like to cite a line from *William Blake.*

“To see a world in a grain of sand - - - ”

and allude to a possible parallel

to see worlds in an electron -

* This is by no means the first modernization attempt. M. Goldhaber has kindly brought it to my attention that hc had introduced a different “cosmon” already in 1956 in his paper “Speculations on Cosmogony,” SCIENCE 124, 218.

REFERENCES

Brodsky, S. J., and Drell, S. D., "Anomalous Magnetic Moment and Limits on Fermion Substructure," Phys. Rev. D 22, 2236 (1980).

Dehmelt, H. (1983) "Stored Ion Spectroscopy", in ***Advances in Laser Spectroscopy,*** F. T. Arecchi, F. Strumia & H. Walther, Eds., Plenum, New York.

Dehmelt, H. (1988a) "Single Atomic Particle Forever Floating at Rest in Free Space: New Value for Electron Radius," Physica Scripta ***T22,*** 102.

Dehmelt, H. (1988b) "New Continuous Stern Gerlach Effect and a Hint of 'The' Elementary Particle," Z. Phys. D ***10, 127-*** 134.

Dehmelt, H. (1989a) "Geonium Spectra * Electron Radius * Cosmon" in High ***Energy Spin*** Physics, 8th International Symposium, K. Heller, Ed. (AIP Conference Proceedings No. 187, New York) p. 319.

Dehmelt, H. (1989b) "Triton,..electron,..cosmon..: An infinite regression?," Proc. Natl. Acad. Sci. USA 86, 8618-8619.

Dehmelt, H. (1990) "Less is more: Experiments with an Individual Atomic Particle at Rest in Free Space" Am. J. Phys., 58, 17.

Gabrielse, G., Dehmelt, H., and Kells, W. (1985) "Observation of a Relativistic, Bistable Hysteresis in the Cyclotron Motion of a Single electron" Phys. Rev. Letters 54, 537.

Jordan, P., (1937) "Die physikalischen Weltkonstanten" Naturwissenschaften 25, 513.

Kinoshita, T. (1988) "Fine-Structure Constant Derived from Quantum Electrodynamics," Metrologia 25, 233.

Lemaître, ***G.*** (1950) ***THE PRIMEVAL ATOM*** (Van Nostrand, New York) p. 77.

Lyons, L. (1983) "An Introduction to the Possible Substructure of Quarks and Leptons," Progress in Particle and Nuclear Physics 10, 227, see references cited herein.

Nagourney, W., Sandberg, J., and Dehmelt, H. (1986) "Shelved optical electron amplifier: Observation of quantum jumps." Phys. Rev. Letters 56, 2797.

Van Dyck, Jr., R. S., Ekstrom, P., and Dehmelt, H. (1977) "Precise Measurement of Axial, Magnetron, and Spin-Cyclotron Beat Frequencies on an Isolated l-meV Electron", Phys. Rev. Lett. 38, 310

Van Dyck, Jr., R. S., Schwinberg, P. B. & Dehmelt, H. G. (1978) "Electron Magnetic Moment from Geonium Spectra," in New Frontiers in High Energy Physics (Eds. B. Kursunoglu, A. Perlmutter, and L. Scott), Plenum New York.

Van Dyck, Jr., R. S., Schwinberg, P. B. & Dehmelt, H. G. (1986) "Electron Magnetic Moment from Geonium Spectra: Early Experiments and Background Concepts," Phys. Rev. D 34, 722.

Van Dyck, Jr., R. S., Schwinberg, P. B. & Dehmelt, H. G. (1987) "New High Precision Comparison of Electron/Positron g-Factors," Phys. Rev. Letters 59, 26.

Vilenkin, A. (1984) "Quantum Creation of Universe," Phys. Rev. D 30, 509 - 5 15.

Wineland, D., Ekstrom, P., and Dehmelt, H. (1973) "Monoelectron Oscillator," Phys. Rev. Lett. ***31, 1297.***

Wolfgang Paul

WOLFGANG PAUL

I was born on August 10, 1913 in Lorenzkirch, a small village in Saxony, as the fourth child of Theodor and Elisabeth Paul, née Ruppel. All in all we were six children. Both parents were descendants from Lutheran ministers in several generations. I grew up in München where my father has been a professor for pharmaceutic chemistry at the university. He had studied chemistry and medicine having been a research student in Leipzig with Wilhem Ostwald, the Nobel Laureate 1909. So I became familiar with the life of a scientist in a chemical laboratory quite early. Unfortunately, my father died when I was still a school boy at the age of fifteen years. But my interest in sciences was awaken, even my parents were very much in favour of a humanistic education. After finishing the gymnasium in München with 9 years of latin and 6 years of ancient greek, history and philosophy, I decided to become a physicist. The great theoretical physicist, Arnold Sommerfeld, an University colleague of my late father, advised me to begin with an apprenticeship in precision mechanics. Afterwards, in the fall 1932, I commenced my studies at the Technische Hochschule München. Listening to the very inspiring physics lectures by Jonathan Zenneck with lots of demonstrations - 6 full hours a week - I felt being on the right track.

After my first examination in 1934 I turned to the Technische Hochschule in Berlin. I was lucky in finding in Hans Kopfermann a teacher with a feeling for the essentials in physics but also a very liberal man, who had taken a fatherly interest in me. He, a former Ph.D. student of James Franck, had just returned from a three years stay at the Niels Bohr Institute in Copenhagen, working in the field of hyperfine spectroscopy and nuclear moments. All in all I worked 16 years with him.

As a theorist Richard Becker taught at the TH Berlin whom I met later at the University of Gottingen again. Both men had the strongest influence on my scientific thinking. But it was not only the scientific aspect. In the Germany of these days just as important was the human and the political attitude. And I am still a little bit proud having been accepted by these sensitive men in this respect. Here are the roots for my later engagement in the anti-nuclear weapon discussion and for having signed the declaration of the so-called “Göttinger Eighteen” in 1957 with its important consequences in German politics.

In 1937 after my diploma exam with Hans Geiger as examinator I followed Kopfermann to the University of Kiel where he had just been appointed Professor Ordinarius. For my doctor thesis I had chosen the determination of the nuclear moments of Beryllium from the hyperfine spectrum. I developed an atomic beam light source to minimize the Doppler effect. But just before the decisive measurements I was drawn to the air force a few days before the war started. Fortunately, a few month later I got a leave of absence to finish my thesis and to take my doctor exam at the TH Berlin. In 1940 I was exempted from military service. I joined again the group around Kopfermann which 2 years later moved to Göttingen. There in 1944 I became Privatdozent at the University.

In these years I worked in mass spectrometry and isotope separation together with W. Walcher. When we heard of the development of the betatron by D. Kerst in the United States and also of a similar development by Gund at the Siemens company, Kopfermann saw immediately that scattering experiments with high energy electrons would enable the study of the charge structure of nuclei. He convinced me to turn to this new very promising field of physics and I soon participated in the first test measurements at the 6 MeV betatron at the Siemens laboratory. Later after the war we succeeded in getting this accelerator to Göttingen.

But due to the restriction in physics research imposed by the military government I turned for a few years my interest to radiobiology and cancer therapy by electrons in collaboration with my colleague G. Schubert from the medical faculty.

Besides we performed some scattering experiments and studied first the electric disintegration of the deuteron, and not to forget for the first time we measured the Lamb shift in the He-spectrum with optical methods.

In 1952 I was appointed Professor at the University of Bonn and Director of the Physics Institute, with very good students waiting for a thesis advisor. I was very lucky that my best young collaborators followed me, O. Osberghaus, H. Ehrenberg, H. G. Bennewitz, G. Knop, and H. Steinwedel as a "house theoretician". Here we started new activities: molecular beam physics, mass spectrometry and high energy electron physics. It was a scanty period after the war. But in order to become in a few years competitive with the well advanced physics abroad we tried to develop new methods and instruments in all our research.

In this period these focusing methods in molecular beam physics with quadrupole and sextupole lenses having already started in Göttingen with H. Friedburg, were further developed and enabled new types of experiments. The quadrupole mass spectrometer and the ion trap were conceived and studied in many respects by research students. And with the generous support of the Deutsche Forschungsgemeinschaft we have built a 500 MeV electron synchrotron, the first in Europe working according to the new principle of strong focusing. It was followed in 1965 by a synchroton for 2500 MeV. My colleagues H. Ehrenberg, R. H. Althoff and G. Knop were sharing this success with me.

In recent years my interest turned to neutron physics with a new device, a magnetic storage ring for neutrons.

U. Trinks and K.J. Kügler and later my two sons Lorenz and Stephan, joined me in our experiments with stored neutrons at the ILL in Grenoble.

My experience in accelerator physics brought me in close contact to CERN. I served there from the very early days on as an advisor. Having spent the year 1959 in Geneve I became director of the nuclear physics division for the years 1964-67. I was for several years member and later chairman of the Scientific Policy Committee and for many years scientific delegate of Germany in the CERN Council. For a short period I was chairman of ECFA, the European Committee for Future Accelerators.

Together with my friends W. Jentschke and W. Walcher in 1957 we started the German National Laboratory DESY in Hamburg which I joined as chairman of the directorate 1970 - 73. For several years I was chairman of its scientific council. In the same positions I served in the first years of the Kernforschungsanlage Jülich.

In 1970 I spent some weeks as Morris Loeb lecturer at Harvard University. 1978 I was lecturing as distinguished scientist at the FERMI Institute of the University of Chicago and in a similar position at the University of Tokyo. Since 1981 I am Professor Emeritus at the Bonn University.

In the past decades of recovery of German Universities and Physics research I was engaged in many advisory bodies. I have served as a referee and later as member of senate to the Deutsche Forschungsgemeinschaft. I was member and chairman of several committees: for reforming the university structure and for research planning of the federal government.

Ten years ago I was elected President of the Alexander von Humboldt Foundation which since 130 years fosters the international collaboration among scientists all over the world in the universal spirit of its patron Humboldt.

I was married for 36 years to the late Liselotte Paul, née Hirsche. She shared with me the depressing period during and after the war and due to her optimistic view of life she gave me strength and independence for my profession. Four children were born to us, two daughters, Jutta and Regine, an historian of art and a pharmacist, and two sons, Lorenz and Stephan, both being physicists. Since 1979 I am married to Dr. Doris Walch-Paul, teaching medieval literature at the University of Bonn.

Memberships and Distinctions

Member:

Deutsche Akademie der Naturforscher "Leopoldina"
Akademie der Wissenschaften in Dusseldorf, Heidelberg und Göttingen
Orden Pour le Mérite für Wissenschaft und Künste, Vice chancelor for the Sciences
Honourary member of DESY, Hamburg
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Robert-Wichard-Pohl-Preis der Deutschen Physikalischen Gesellschaft
Goldmedal of the Academy of Sciences in Prague

ELECTROMAGNETIC TRAPS FOR CHARGED AND NEUTRAL PARTICLES

Nobel Lecture, December 8, 1989

bY

WOLFGANG PAUL

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Experimental physics is the art of observing the structure of matter and of detecting the dynamic processes within it. But in order to understand the extremely complicated behaviour of natural processes as an interplay of a few constituents governed by as few as possible fundamental forces and laws, one has to measure the properties of the relevant constituents and their interaction as precisely as possible. And as all processes in nature are interwoven one must separate and study them individually. It is the skill of the experimentalist to carry out clear experiments in order to get answers to his questions undisturbed by undesired effects and it is his ingenuity to improve the art of measuring to ever higher precision. There are many examples in physics showing that higher precision revealed new phenomena, inspired new ideas or confirmed or dethroned well established theories. On the other hand new experimental techniques conceived to answer special questions in one field of physics became very fruitful in other fields too, be it in chemistry, biology or engineering. In awarding the Nobel prize to my colleagues Norman Ramsey, Hans Dehmelt and me for new experimental methods the Swedish Academy indicates her appreciation for the aphorism the Göttingen physicist Georg Christoph Lichtenberg wrote two hundred years ago in his notebook “one has to do something new in order to see something new”. On the same page Lichtenberg said: “I think it is a sad situation in all our chemistry that we are unable to suspend the constituents of matter free”.

Today the subject of my lecture will be the suspension of such constituents of matter or in other words, about traps for free charged and neutral particles without material walls. Such traps permit the observation of isolated particles, even of a single one, over a long period of time and therefore according to Heisenberg’s uncertainty principle enable us to measure their properties with extremely high accuracy.

In particular, the possibility to observe individual trapped particles opens up a new dimension in atomic measurements. Until few years ago all measurements were performed on an ensemble of particles. Therefore, the measured value - for example, the transition probability between two eigenstates of an atom - is a value averaged over many particles. Tacitly one assumes that all atoms show exactly the same statistical behaviour if one attributes the result to the single atom. On a trapped single atom, however, one can observe its interaction with a radiation field and its own statistical behaviour alone.

The idea of building traps grew out of molecular beam physics, mass spectrometry and particle accelerator physics I was involved in during the first decade of my career as a physicist more than 30 years ago. In these years (1950 - 55) we had learned that plane electric and magnetic multipole fields are able to focus particles in two dimensions acting on the magnetic or electric dipole moment of the particles. Lenses for atomic and molecular beams [1,2,3] were conceived and realized improving considerably the molecular beam method for spectroscopy or for state selection. The lenses found application as well to the ammonia as to the hydrogen maser [4].

The question "What happens if one injects charged particles, ions or electrons, in such multipole fields" led to the development of the linear quadrupole mass spectrometer. It employs not only the focusing and defocusing forces of a high frequency electric quadrupole field acting on ions but also exploits the stability properties of their equations of motion in analogy to the principle of strong focusing for accelerators which had just been conceived.

If one extends the rules of two-dimensional focusing to three dimensions one posseses all ingredients for particle traps.

As already mentioned the physics or the particle dynamics in such focusing devices is very closely related to that of accelerators or storage rings for nuclear or particle physics. In fact, multipole fields were used in molecular beam physics first. But the two fields have complementary goals: the storage of particles, even of a single one, of extremely low energy down to the micro-electron volt region on the one side, and of as many as possible of extremely high energy on the other. Today we will deal with the low energy part. At first I will talk about the physics of dynamic stabilization of ions in two- and three-dimensional radio frequency quadrupole fields, the quadrupole mass spectrometer and the ion trap. In a second part I shall report on trapping of neutral particles with emphasis on an experiment with magnetically stored neutrons.

As in most cases in physics, especially in experimental physics, the achievements are not the achievements of a single person, even if he contributed in posing the problems and the basic ideas in solving them. All the experiments I am awarded for were done together with research students or young colleagues in mutual inspiration. In particular, I have to mention H. Friedburg and H. G. Bennewitz, C.H. Schlier and P. Toschek in the field of molecular beam physics, and in conceiving and realizing the linear quadrupole spectrometer and the r.f. ion trap H. Steinwedel, 0. Osberghaus and especially the late Erhard Fischer. Later H.P. Reinhard, U. v. Zahn and F. v. Busch played an important role in developing this field.

Focusing and Trapping of particles

What are the principles of focusing and trapping particles? Particles are elastically bound to an axis or a coordinate in space if a binding force acts on them which increases linearly with their distance r

$$F = -cr.$$

In other words if they move in a parabolic potential

$$\Phi \sim (\alpha x^2 + \beta y^2 + \gamma z^2)$$

The tools appropriate to generate such fields of force to bind charged particles or neutrals with a dipole moment are electric or magnetic multipole fields. In such configurations the field strength, or the potential respectively increases according to a power law and shows the desired symmetry. Generally if m is the number of "poles" or the order of symmetry the potential is given by

$$\Phi \sim r^{m/1} \cos(m/2 \cdot \varphi).$$

For a quadrupole $m = 4$ it gives $\Phi \sim r^2 \cos 2\varphi$, and for a sextupole $m = 6$ one gets $\Phi \sim r^3 \cos 3\varphi$ corresponding to a field strength increasing with r and r^2 respectively.

Trapping of charged particles in 2- and J-dimensional quadrupole fields

In the electric quadrupole field the potential is quadratic in the Cartesian coordinates.

$$\Phi = \frac{\Phi_0}{2r^2}\left(\alpha x^2 + \beta y^2 + \gamma z^2\right) \tag{1}$$

The Laplace condition $\Delta\Phi = 0$ imposes the condition $\alpha + \beta + \gamma = 0$ There are two simple ways to satisfy this condition.

a) $a = 1 = -\gamma$, $\beta=0$ results in the two-dimensional field

$$\Phi = \frac{\Phi_0}{2r_0^2}\left(x^2 - z^2\right) \tag{2}$$

b) $a = \beta = 1$, $\gamma = -2$ generates the three-dimensional configuration, in cylindrical coordinates

$$\Phi = \frac{\Phi_0(r^2 - 2z^2)}{r_0^2 + 2z_0^2} \text{ with } 2z_0^2 = r_0^2. \tag{3}$$

The two-dimensional quadrapole or the mass filter [5,6]

Configuration a) is generated by 4 hyperbolically shaped electrodes linearly extended in the y-direction as is shown in Fig. 1. The potential on the electrodes is $\pm\Phi_0/2$ if one applies the voltage Φ_0 between the electrode pairs. The field strength is given by

$$E_x = -\Phi_0/r_0^2 \cdot x \quad , \quad E_z = \Phi_0/r_0^2 \cdot z \quad , \quad E_y = 0$$

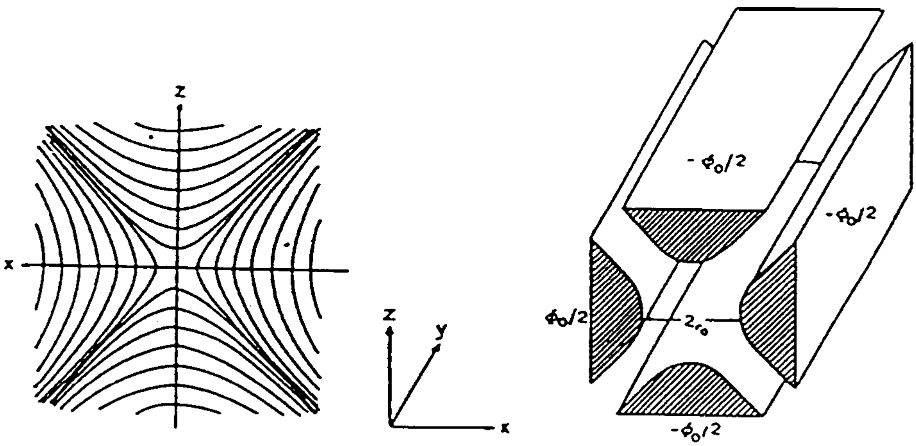


Figure I. a) Equipotential lines for a plane quadrupole fild, b) the electrodes Structure for the mass filter.

If one injects ions in the y-direction it is obvious that for a constant voltage Φ_0 the ions will perform harmonic oscillations in the the x-y-plane but due to the opposite sign in the field E_z their amplitude in the z-direction will increase exponentially. The particles are defocused and will be lost by hitting the electrodes.

This behaviour can be avoided if the applied voltage is periodic. Due to the periodic change of the sign of the electric force one gets focusing and defocusing in both the x- and z-directions alternating in time. If the applied voltage is given by a dc voltage U plus an r.f. voltage V with the driving frequency ω

$$\Phi_0 = U + V\cos\omega t$$

the equations of motion are

$$\begin{aligned} \ddot{x} + \frac{e}{mr_0^2}(U + V\cos\omega t)\,x = 0 \\ \ddot{z} - \frac{e}{mr_0^2}(U + V\cos\omega t)\,z = 0 \end{aligned} \tag{4}$$

At first sight one expects that the time-dependent term of the force cancels out in the time average. But this would be true only in a homogenous field. In a periodic inhomogenous field, like the quadrupole field there is a small average force left, which is always in the direction of the lower field, in our case toward the center. Therefore, certain conditions exist that enable the ions to traverse the quadrupole field without hitting the electrodes, i.e. their motion around the y-axis is stable with limited amplitudes in x- and z-directions. We learned these rules from the theory of the Mathieu equations, as this type of differential equation is called.

In dimensionless parameters these equations are written

$$\begin{aligned} \frac{d^2x}{d\tau^2} + (a_x + 2q_x\cos 2\tau)\,x = 0 \\ \frac{d^2z}{d\tau^2} + (a_z + 2q_z\cos 2\tau)\,z = 0 \end{aligned} \tag{5}$$

By comparison with equation (4) one gets

$$a_x = -a_z = \frac{4eU}{mr_0^2\omega^2}\ ,\ q_x = -q_z = \frac{2eV}{mr_0^2\omega^2}\ ,\ \tau = \frac{\omega t}{2}. \qquad 63)$$

The Mathieu equation has two types of solution.

1. stable motion: the particles oscillate in the x-z-plane with limited amplitudes. They pass the quadrupole field in y-direction without hitting the electrodes.

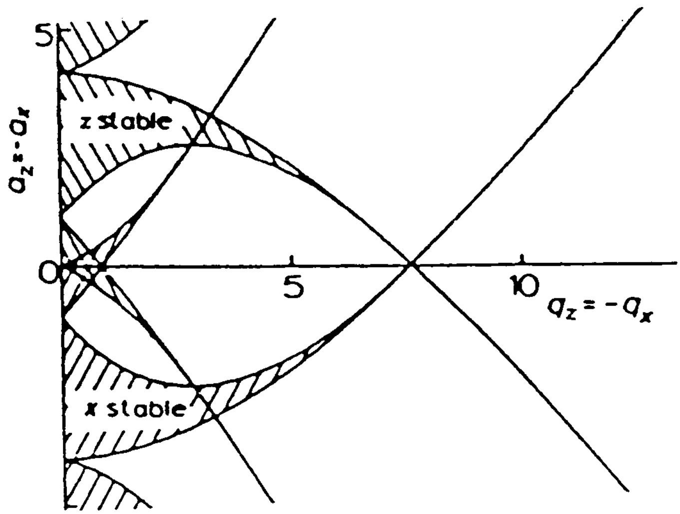


Figure 2. The overall stability diagram for the two-dimensional quadrupole field.

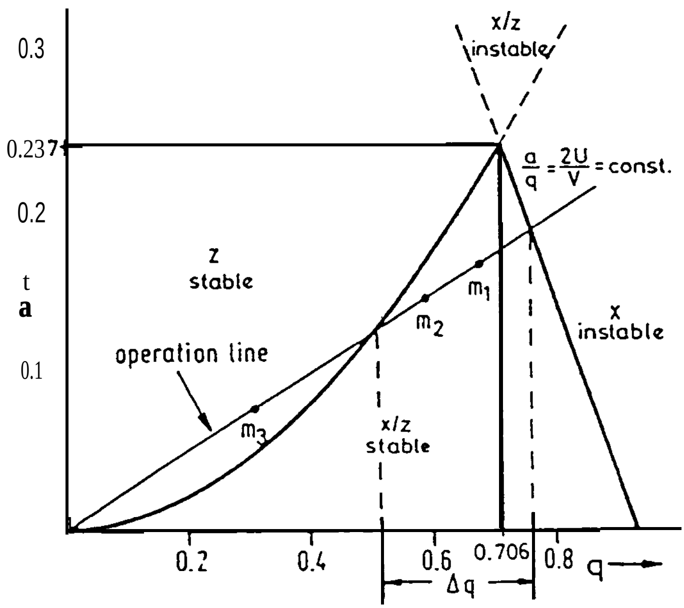


Figure 3. The lowest region for simultaneous stability in x-and z-direction. All ion masses lie on the operation line, m1 > m1.

2. unstable motion: the amplitudes grow exponentialy in x, z or in both directions. The particles will be lost.

Whether stability exists depends only on the parameters a and q and not on the initial parameters of the ion motion, e.g. their velocity. Therefore, in an a-q-map there are regions of stability and instability (Fig.2). Only the overlapping region for x and z stability is of interest for our problem. The most relevant region $0 < a$, $q < 1$ is plotted in Fig. 3. The motion is stable in x and z only within the triangle.

For fixed values $r_0\omega$, U and V all ions with the same m/e have the same operating point in the stability diagram. Since a/q is equal to 2U/V and does not depend on m, all masses lie along the operating line a/q = const. On the q axis (a = 0, no d.c. voltage) one has stability from $0 < q < q_{max} = 0.92$ with the consequence that all masses between $\infty > m > m_{min}$ have stable orbits. In this case the quadrupole field works as a high pass mass filter. The mass range Δm becomes narrower with increasing dc voltage U i.e. with a steeper operating line and approaches $\Delta m = 0$, if the line goes through the tip of the stability region. The bandwidth in this case is given only by the fluctuation of the field parameters. If one changes U and V simultaneously and proportionally in such a way that a/q remains sonstant, one brings the ions of the various masses successively in the stability region scanning through the mass spectrum in this way. Thus the quadrupole works as a mass spectrometer.

A schematic view of such a mass spectrometer is given in Fig. 4. In Figs. 5a,b. the first mass spectra obtained in 1954 are shown [6]. Clearly one sees the influence of the d.c. voltage U on the resolving power.

In quite a number of theses the performance and application of such

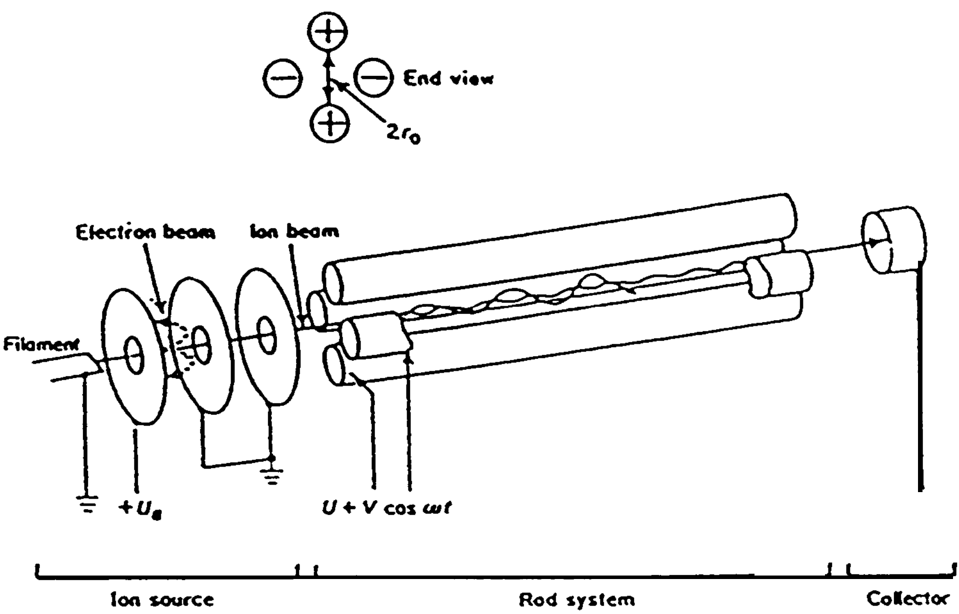


Figure 4. Schematic view of the quadrupole mass spectrometer or mass filter.

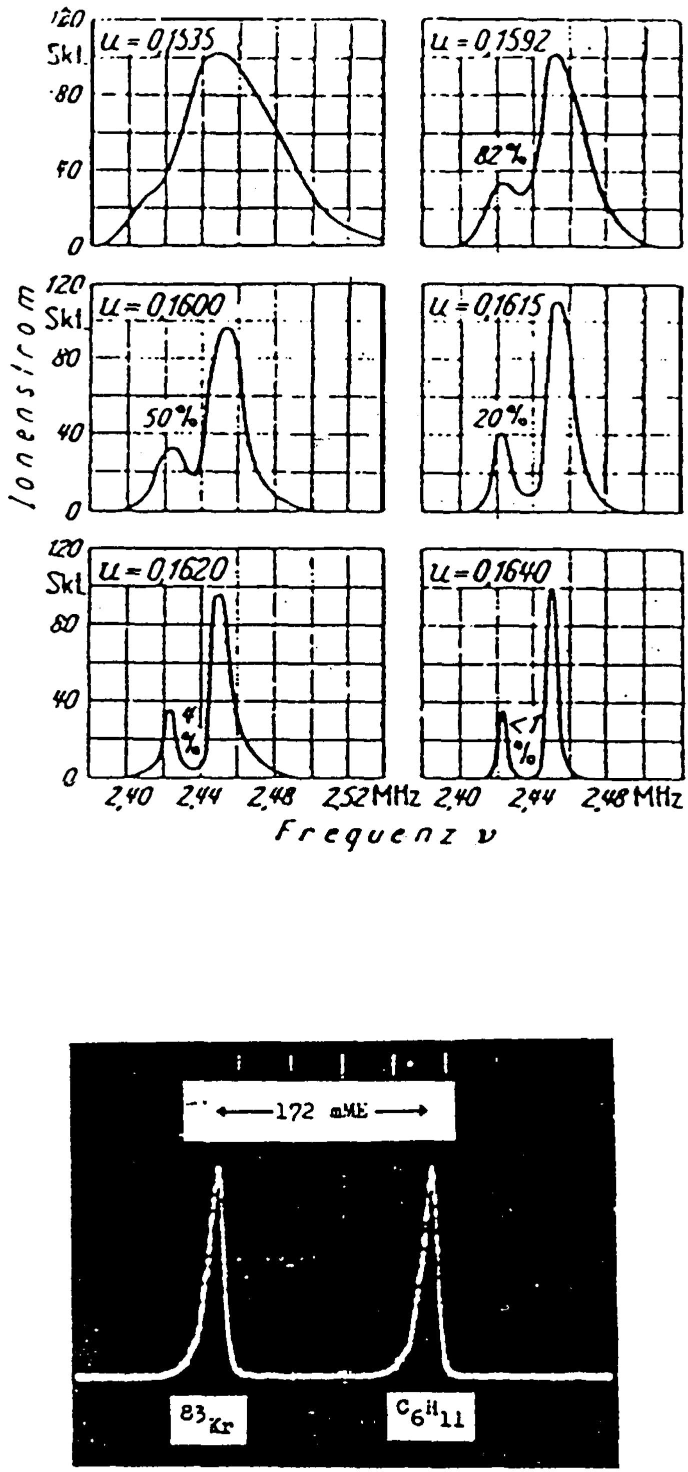


Figure 5. a) Very first mass spectrum of Rubidium. Mass scanning was achieved by periodic variation of the driving frequency v. Parameter: u = $\frac{U}{V}$, at u = 0.164 ^{85}Rb and ^{87}Rb are fully resolved. b) Mass doublet ^{83}Kr - C_6H_{11}. . Resolving power $m/\Delta m$ = 6500 [9].

instruments was investigated at Bonn University [7,8,9]. We studied the influence of geometrical and electrical imperfections giving rise to higher multipole terms in the field. A very long instrument (l = 6 m) for high precision mass measurements was built achieving an accuracy of $2 \cdot 10^{-7}$ in determining mass ratios at a resolving power $\frac{m}{\Delta m}$ = 16 000. Very small ones were used in rockets to measure atomic abundances in the high atmosphere. In another experiment we succeeded in separating isotopes in amounts of milligrams using a resonance method to shake single masses out of an intense ion beam guided in the quadrupole.

In recent decades the r.f. quadrupole whether as mass spectrometer or beam guide due to its versatility and technical simplicity has found broad applications in many fields of science and technology. It became a kind of standard instrument and its properties were. treated extensively in the literature [10].

The Ion Trap

Already at the very beginning of our thinking about dynamic stabilization of ions we were aware of the possibility using it for trapping ions in a three-dimensional field. We called such a device “Ionenkäfig”[11,12,13]. Nowadays the word “ion trap” is preferred.

The potential configuration in the ion trap has been given in eq. (3). This configuration is generated by an hyperbolically shaped ring and two hyperbolic rotationally symmetric caps as it is shown schematically in Fig. 6a. Fig. 6b gives the view of the first realized trap in 1954.

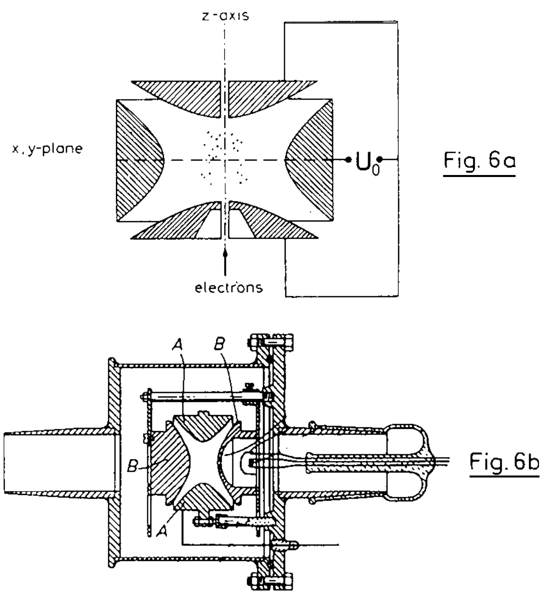


Figure 6. a) Schematic view of the ion trap. b) Cross section of the first trap (1955).

If one brings ions into the trap, which is easily achieved by ionizing inside a low pressure gas by electrons passing through the volume, they perform the same forced motions as in the two-dimensional case. The only difference is that the field in z-direction is stronger by a factor 2. Again a periodic field is needed for the stabilization of the orbits. If the voltage $\Phi_0 = U + V\cos\omega t$ is applied between the caps and the ring electrode the equations of motion are represented by the same Mathieu functions of eq.(5). The relevant parameters for the r motion correspond to those in the x-direction in the plane field case. Only the z parameters are changed by a factor 2.

Accordingly, the region of stability in the a-q-map for the trap has a different shape as is shown in Fig. 7. Again the mass range of the storable ions (i.e. ions in the stable region) can be chosen by the slope of the operation line $u/q = 2U/V$. Starting with operating parameters in the tip of the stable region one can trap ions of a single mass number. By lowering the d.c. voltage one brings the ions near the q-axis where their motions are much more stable.

For many applications it is necessary to know the frequency spectrum of the oscillating ions. From mathematics we learn that the motion of the ions can be described as a slow (secular) oscillation with the fundamental fre-

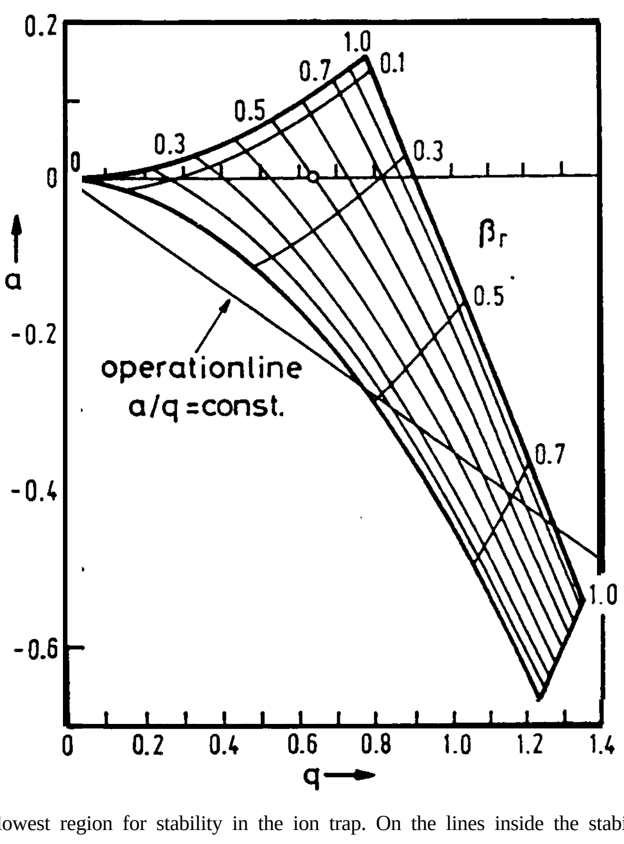


Figure 7. The lowest region for stability in the ion trap. On the lines inside the stability region β_z and β_r resp. are constant.

quencies $\omega_{r,z} = \beta_{r,z} \cdot \omega/2$ modulated with a micromotion, a much faster oscillation of the driving frequency ω if one neglects higher harmonics. The frequency determining factor β is a function only of the Mathieu parameters a and q and therefore mass dependent. Its value varies between 0 and 1; lines of equal β are drawn in Fig. 7.

Due to the stronger field the frequency ω_z of the secular motion becomes twice ω_r. The ratio ω/ω_z is a criterion for the stability. Ratios of 10: 1 are easily achieved and therefore the displacement by the micromotion averages out over a period of the secular motion.

The dynamic stabilization in the trap can easily be demonstrated in a mechanical analogue device. In the trap the equipotential lines form a saddle surface as is shown in Fig. 8. We have machined such a surface on a round disc. If one puts a small steel ball on it, then it will roll down: its position is unstable. But if one let the disk rotate with the right frequency

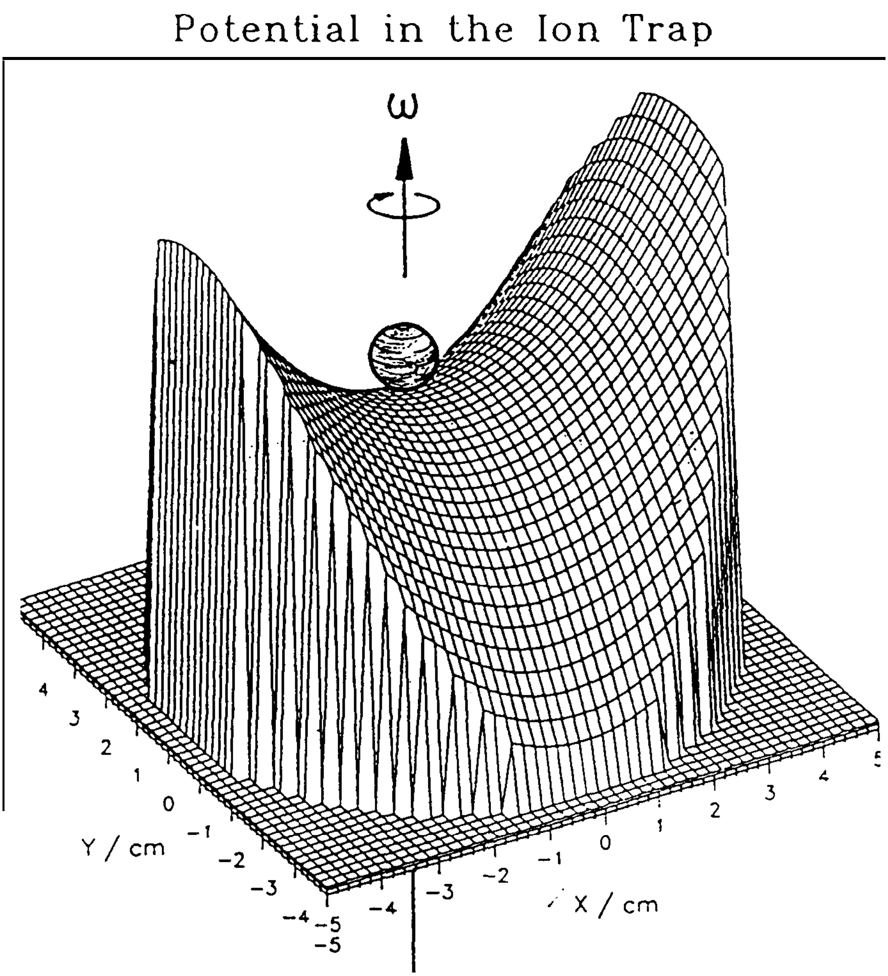


Figure 8. Mechanical analogue model for the ion trap with steelball as “particle”

appropriate to the potential parameters and the mass of the ball (in our case a few turns/s) the ball becomes stable, makes small oscillations and can be kept in position over a long time. Even if one adds a second or a third ball they stay near the center of the disc. The only condition is that the related Mathieu parameter q be in the permitted range. I brought the device with me. It is made out of Plexiglas which allows demonstration of the particle motions with the overhead projector.

This behaviour gives us a hint of the physics of the dynamic stabilization. The ions oscillating in the r- and z-directions to first approximation harmonically, behave as if they are moving in a pseudo potential well quadratic in the coordinates. From their frequencies ω_r and ω_z we can calculate the depth of this well for both directions. It is related to the amplitude V of the driving voltage and to the parameters a and q. Without any d.c. voltage the depth is given by $D_z = (q/8)\ V$, in the r-direction it is half of this. As in practice V amounts to a few hundred volts the potential depth is of the order of 10 Volts. The width of the well is given by the geometric dimensions. The resulting configuration of the pseudo potential [14] is therefore given by

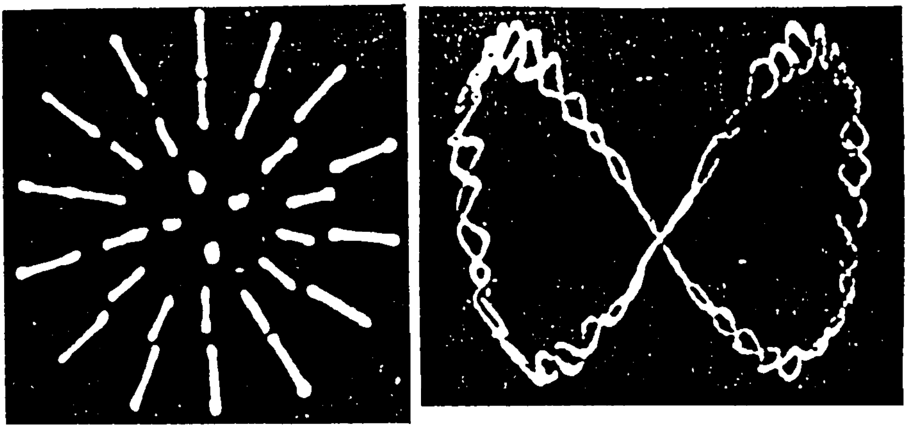
$$\Phi = D \frac{(r^2 + 4z^2)}{r_0^2 + 2z_0^2}.$$

Cooling process

As mentioned, the depth of the relevant pseudopotential in the trap is of the order of a few volts. Accordingly the permitted kinetic energy of the stored ions is of the same magnitude and the amplitude of the oscillations can reach the geometrical dimensions of the trap. But for many applications one needs particles of much lower energy well concentrated in the center of the trap. Especially for precise spectroscopic measurements it is desirable to have extremely low velocities to get rid of the Doppler effect and an eventual Stark effect, caused by the electric field. It becomes necessary to cool the ions. Relatively rough methods of cooling are the use of a cold buffer gas or the damping of the oscillations by an external electric circuit. The most effective method is the laser induced sideband fluorescence developed by Wineland and Dehmelt [15].

In 1959 Wuerker et al. [16] performed an experiment trapping small charged Aluminium particles ($\phi \sim mm$) in the quadrupole trap. The necessary driving frequency was around 50 Hz accordingly. They studied all the eigenfrequencies and took photographs of the particle orbits; see Figs. 9a, b. After they have damped the motion with a buffer gas they observed that the randomly moving particles arranged themselves in a regular pattern. They formed a crystal.

In recent years one has succeeded in observing optically single trapped ions by laser resonance fluorescence [17]. Walther et al., using a high resolution image intensifier observed the pseudo-crystallization of ions in the trap after cooling the ions with laser light. The ions are moving to such



b a

Figure 9. a) Photomicrograph of a Lissajous orbit in the r-z-plane of a single charged particle of Aluminium powder. The micro motion is visible. b) Pattern of "condensed" Al particles [16].

positions where the repulsive Coulomb force is compensated by the focusing forces in the trap and the energy of the ensemble has a minimum. Figs. 10a, b show such a pattern with 7 ions. Their distance is of the order of a few micrometers. These observations opened a new field of research [18].

The Ion Trap as Muss Spectrometer

As mentioned the ions perform oscillations in the trap with frequencies ω_r and ω_z which at fixed field parameters are determined by the mass of the ion. This enables a mass selective detection of the stored ions. If one connects the cap electrodes with an active r.f. circuit with the eigenfrequency Ω, in the case of resonance $\Omega = \omega_z$, the amplitude of the oscillations increases linearly with time. The ions hit the cap or leave the field through a bore hole and can easily be detected by an electron multiplier device. By modulating the ion frequency determining voltage V in a sawtooth mode one brings the ions of the various masses one after the other into resonance, scanning the mass spectrum. Fig. 11 shows the first spectrum of this kind achieved by Rettinghaus [19].

The same effect with a faster increase of the amplitude is achieved if one inserts a small band of instability into the stability diagram . It can be generated by superimposing on the driving voltage V cos t a small additional rf voltage, e.g. with frequency $\omega/2$, or by adding a higher multipole term to the potential configuration [5b,20].

In summary the ion trap works as ion source and mass spectrometer at the same time. It became the most sensitive mass analyzer available as only a few ions are necessary for detection. Its theory and performance is reviewed in detail by R.E. March [21].

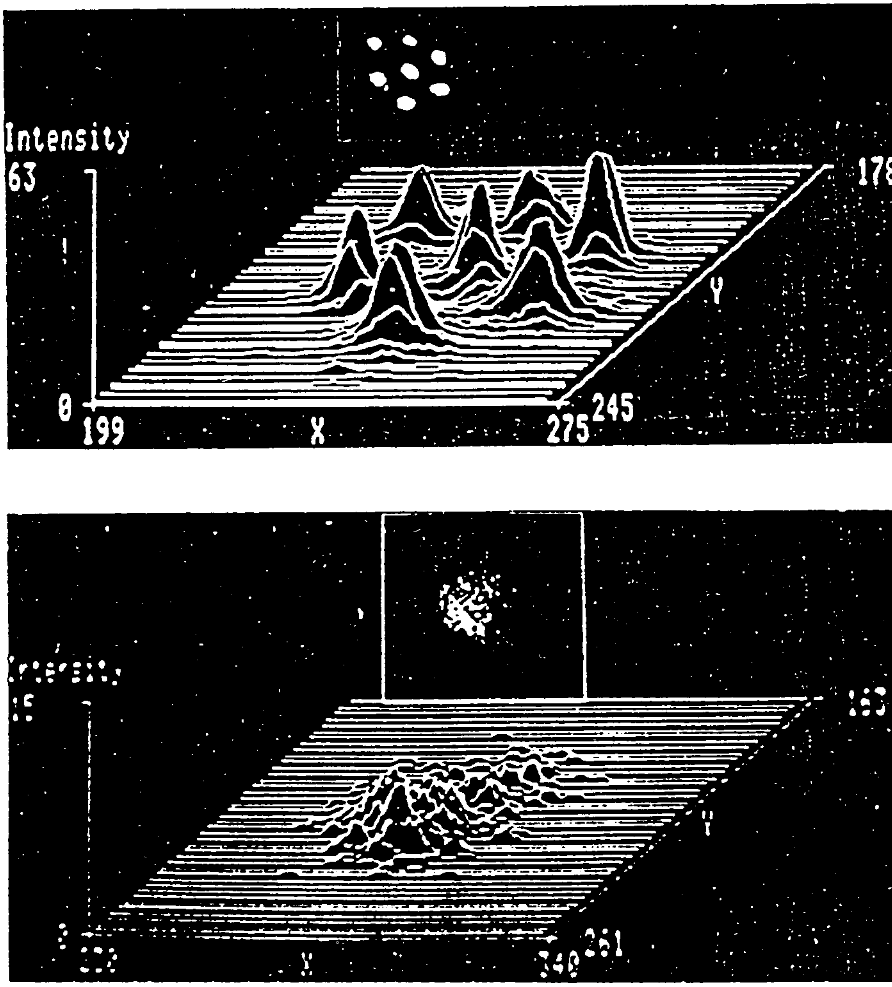


Figure 10. a) Pseudo crystal of 7 magnesium ions. Particle distance 23 µm. b) The same trapped particles at "higher temperature". The crystal has melted [18].

The Penning Trap

If one applies to the quadrupole trap only a d.c. voltage in such a polarity that the ions perform stable oscillations in the z-direction with the frequency $\omega_z^2 = \frac{2eU}{m r_0^2}$ the ions are unstable in the x-y-plane, since the field is directed outwards. Applying a magnetic field in the axial direction, the z-motion remains unchanged but the ions perform a cyclotron motion ω in the x-y-plane. It is generated by the Lorentz force F_L directed towards the center. This force is partially compensated by the radial electric force $F_r = \frac{eU}{r_0^2} r$. As long as the magnetic force is much larger than the electric one, stability exists in the r-y-plane as well. No r.f. field is needed. The resulting rotation frequency calculates to

$$\omega = \omega_c - \frac{\omega_z^2}{2\omega}.$$

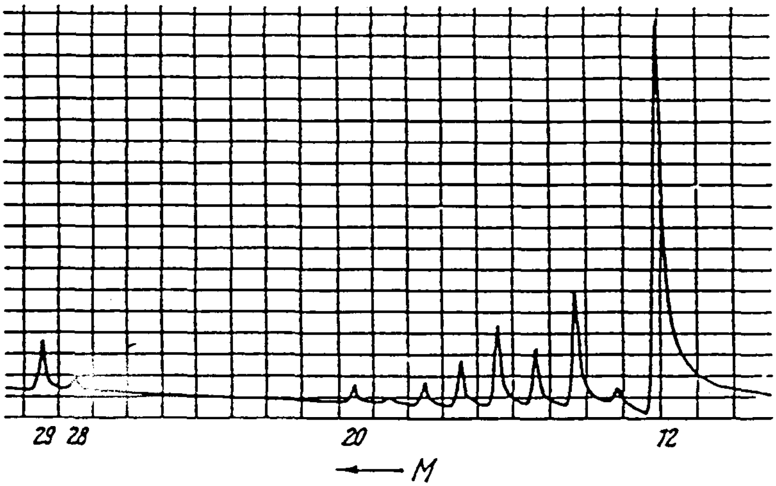


Figure *Il.* First mass spectrum achieved with the ion trap. Gas: air at 2 . 10^{-9} torr [19]

It is slightly smaller than the undisturbed cyclotron frequency eB/m. The difference is due to the magnetron frequency

$$\omega_M = \frac{\omega_z^2}{2\omega}$$

which is independent of the particle mass.

The Penning trap [22], as this device is called, is of advantage if magnetic properties of particles have to be measured, as for example Zeeman transitions in spectroscopic experiments, or cyclotron frequencies for a very precise comparison of masses as are performed e.g. by G. Werth. The most spectacular application the trap has found in the experiments of G. Gräff [23] and H. Dehmelt for measuring the anomalous magnetic moment of the electron. It was brought by Dehmelt [24] to an admirable precision by observing only a single electron stored for many months.

Traps for neutral particles

In the last examination I had to pass as a young man I was asked if it would be possible to confine neutrons in a bottle in order to prove if they are radioactive. This question, at that time only to be answered with “no”, pursued me for many years until I could have had replied: Yes, by means of a magnetic bottle. It took 30 years until by the development of superconducting magnets its realization became feasible.

Using the example of such a bottle I would like to demonstrate the principle of confining neutral particles. Again the basis is our early work on focusing neutral atoms and molecules having a dipole moment by means of multipole fields making use of their Zeeman or Stark effect to first and second order [1,2,3]. Both effects can be used for trapping. Until now only magnetic traps were realized for atoms and neutrons. Particularly, B. Martin, U. Trinks, and K. J. Kügler contributed to their development with great enthusiasm.

The principle of magnetic bottles

The potential energy U of a particle with a permanent magnetic moment μ in a magnetic field is given by $U = -\mu B$. If the field is inhomogenous it corresponds to a force $F = grad(\mu B)$. In the case of the neutron with its spin $h/2$ only two spin directions relative to the field are permitted. Therefore, its magnetic moment can be oriented only parallel or antiparallel to B. In the parallel position the particles are drawn into the field and in the opposite orientation they are repelled. This permits their confinement to a volume with magnetic walls.

The appropriate field configuration to bind the particles harmonically is in this case a magnetic sextupole field. As I have pointed out such a field B increases with r^2, $B = \frac{B_0}{r_0^2}\cdot r^2$ and the gradient $\frac{\delta B}{\delta r}$ with r respectively.

In such a field neutrons with orientation $\mu\uparrow\uparrow B$ satisfy the confining condition as their potential energy $U = +\mu B \sim r^2$ and the restoring force $\mu grad B = -cr$ is always oriented towards the center. They oscillate in the field with the frequency $\omega^2 = \frac{2\mu B_0}{m r_0^2}$. Particles with $\mu\uparrow\downarrow B$ are defocused and leave the field. This is valid only *as* long as the spin orientation is conserved. Of course, in the sextupole the direction of the magnetic field changes with the azimuth but as long as the particle motion is not too fast the spin follows the field direction adiabatically conserving the magnetic quantum state. This behaviour permits the use of a magnetic field constant in time in contrast to the charged particle in an ion trap.

An ideal linear sextupole in the x-z-plane is generated by six hyperbolically shaped magnetic poles of alternating polarity extended in y-direction, as shown in Figs. 12a, b. It might be approximated by six straight current leads

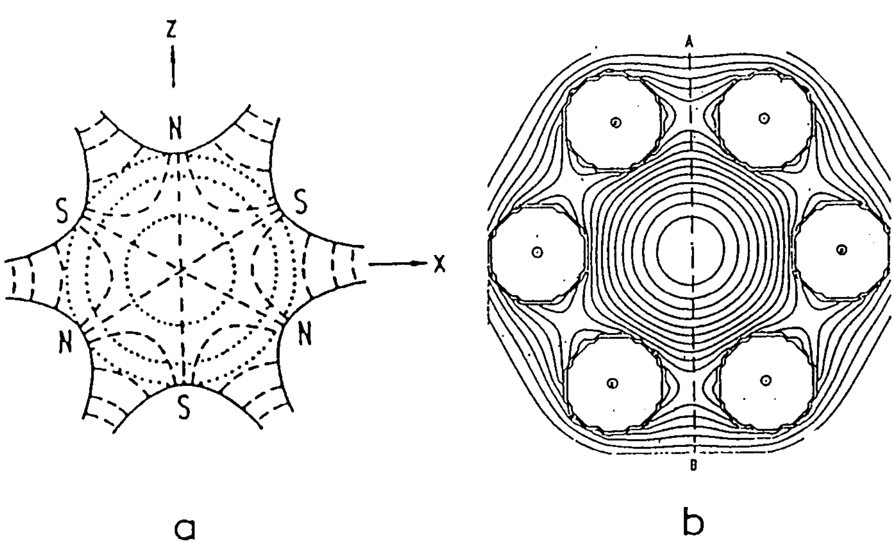


Figure 12. a) Ideal sextupole field. Dashed: magnetic field lines, dotted: lines of equal magnetic potential, B = const. b) Linear sextupole made of 6 straight current leads with alternating current direction.

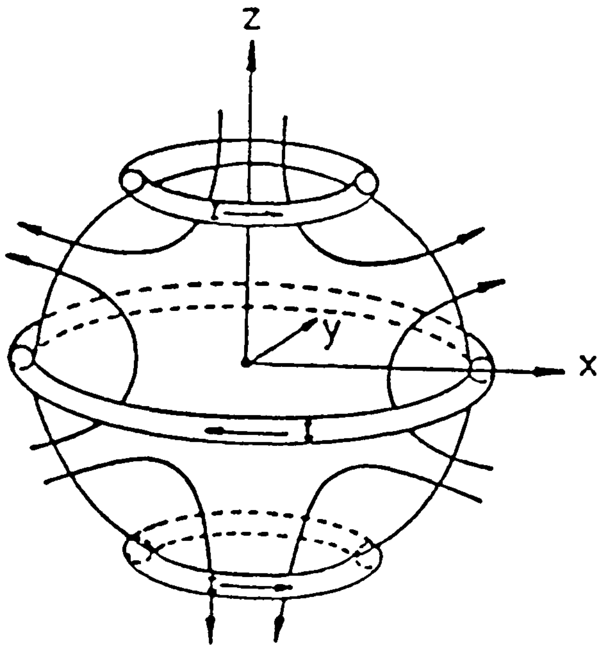


Figure 17. Sextupole sphere

with alternating current directions arranged in a hexagon. Such a configuration works as a lense for particles moving along the y-axis.

There are two possibilities to achieve a closed storage volume: a sextupole sphere and a sextupole torus. We have realized and studied both.

The spherically symmetric field is generated by three ring currents in an arrangement shown in Fig. 13. The field B increases in all directions with r^2 and has its maximum value B_0 at the radius r_0 of the sphere. Using superconducting current leads we achieved $B_0 = 3T$ in a sphere with a radius of 5 cm. But due to the low magnetic moment of the neutron $\mu = 6 \cdot 10^{-8}\, eV/T$ the potential depth μB_0 is only $1.8 \cdot 10^{-7}$ **eV** and hence the highest velocity of storable neutrons is only vmax = *6m/s.* Due to their stronger moment for Na atoms these values are $2.2 \cdot 10^{-4}\, eV$ and 37 m/s, respectively.

The main problem with such a closed configuration is the filling process, especially the cooling inside. However, in 1975 in a test experiment we succeeded in observing a storage time of 3 s for sodium atoms evaporated inside the bottle with its Helium cooled walls [25]. But the breakthrough in confining atoms was achieved by W. D. Phillip and H.J. Metcalf using the modern technique of Laser cooling [26].

The problem of storing neutrons becomes easier if one uses a linear sextupole field bent to a closed torus with a radius R as is shown in Fig. 14. The magnetic field in the torus volume is unchanged $B = \frac{B_0}{r_0^2} \cdot r^2$ and has no component in azimuthal direction. The neutrons move in a circular orbit with radius *Rs* if the centrifugal force is compensated by the magnetic force

$$F_c = \frac{mv_\varphi^2}{R_S} = \mu \left.\frac{\delta B}{\delta r}\right]_{R_S} .$$

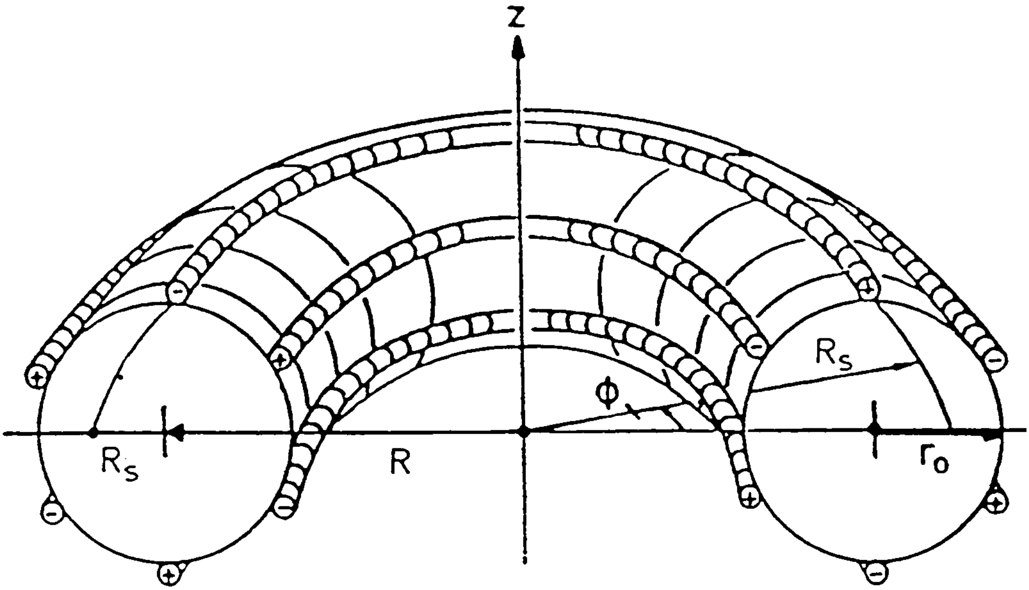


Figure *14.* Sextupole torus. R_s orbit of circulating neutrons.

In such a ring the permitted neutron energy is limited by

$$E_{max} = \mu \cdot B_0 \left(\frac{R}{r_0} + 1\right) .$$

It is increased by a factor $(\frac{R}{r_0} + 1)$ compared to the case of the sextupole sphere. As the neutrons have not only an azimuthal velocity but also components in r and z directions they are oscillating around the circular orbit.

But this toroidal configuration has not only the advantage of accepting higher neutron velocities, it also permits an easy injection of the neutrons in the ring from the inside. The neutrons are not only moving in the magnetic potential well but they also experience the centrifugal barrier. Accordingly, one can lower the magnetic wall on the inside by omitting the two inward current leads. The resulting superposition of the magnetic and the centrifugal potential still provides a potential well with its minimum at the beam orbit. But there is no barrier for the inflected neutrons.

It is obvious, that the toroidal trap in principle works analogous to the storage rings for high energy charged particles. In many respects the same problems of instabilities of the particle orbits by resonance phenomena exist, causing the loss of the particles. But also new problems arise like, e.g. undesired spin flips or the influence of the gravitational force. In accelerator physics one has learned to overcome such problems by shaping the magnetic field by employing the proper multipole components. This technique is also appropriate in case of the neutron storage ring. The use of the magnetic force μ . *gradB* instead of the Lorentz force being proportional to *B* just requires multipole terms of one order higher. Quadrupoles for

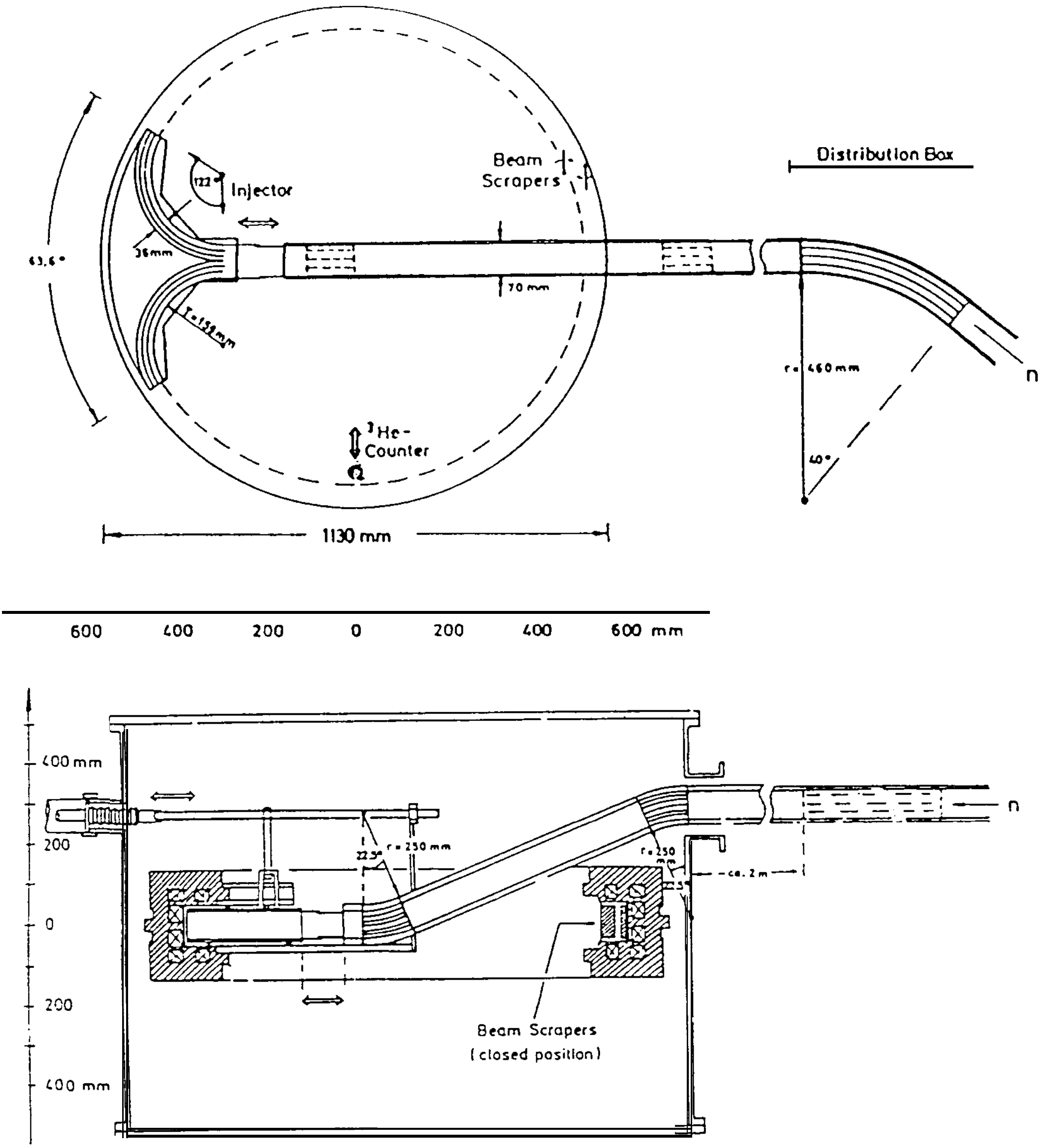


Figure 15. Schematic top and side view of the neutron storage ring experiment.

focusing have to be replaced by sextupoles and e.g. octupoles for stabilization of the orbits by decapoles.

In the seventies we have designed and constructed such a magnetic storage ring with a diameter of the orbits of 1 m. The achieved usable field of 3.5 T permits the confinement of neutrons in the velocity range of 5 - 20 m/s corresponding to a kinetic energy up to $2 \cdot 10^{-6}$ *eV*. The neutrons are injected tangentially into the ring by a neutron guide with totally reflecting walls. The inflector can be moved mechanically into the storage volume and shortly afterwards be withdrawn.

The experimental set up is shown in Fig. 15. A detailed description of the storage ring, its theory and performance is given in [27]. In 1978 in a first experiment we have tested the instrument at the Grenoble high flux reactor. We could observe neutrons stored up to 20 min after injection by moving a neutron counter through the confined beam after a preset time. As by the detection process the neutrons are lost, one has to refill the ring starting a new measurement. But due to the relatively low flux of neutrons in the acceptable velocity range, their number was too low to make relevant measurements with it.

In a recent experiment [28] at a new neutron beam with a flux improved by a factor 40 we could observe neutrons up to 90 min, i.e. roughly 6 times the decay time of the neutron due to radioactive decay. Fig. 16 shows the measured profile of the neutron beam circulating inside the magnetic gap. Measuring carefully the number of stored neutrons as a function of time we could determine the lifetime to $\tau = 877 \pm 10$ s (Fig. 17).

The analysis of our measurements lets us conclude that the intrinsic storage time of the ring for neutrons is at least about one day. It shows that we had understood the relevant problems in its design.

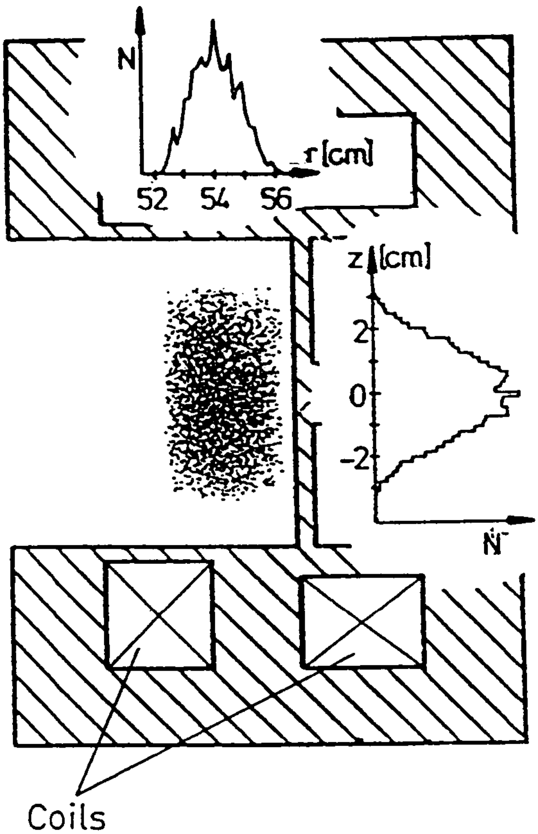


Figure 16. Beam profile of the stored neutrons inside the magnet gap 400 sec after injection.

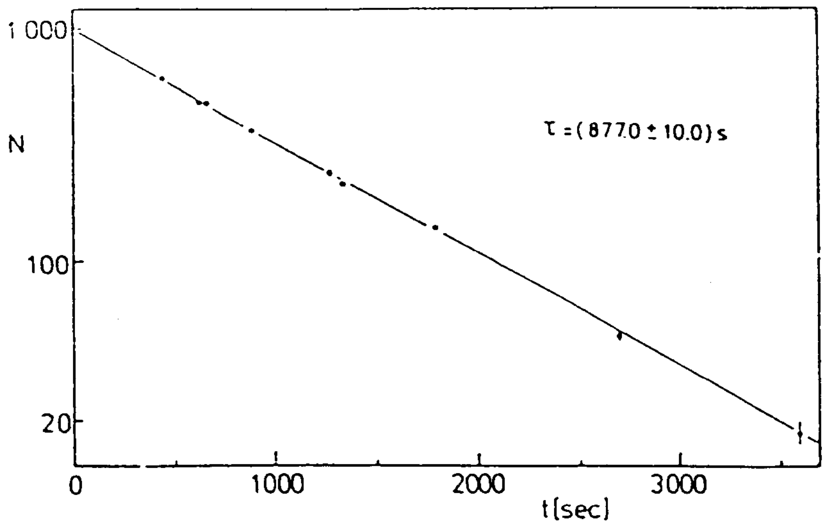


Figure 17. Logarithmic decrease of the number of stored neutrons with time.

The storage ring as a balance

This very reproducible performance permitted another interesting experiment. As I explained the neutrons are elastically bound to the symmetry plane of the magnetic field. Due to their low magnetic moment the restoring force is of the order of the gravitational force. Hence it follows that the weight of the neutron stretches the magnetic spring the particle is hanging on; the equilibrium center of the oscillating neutrons is shifted downwards. The shift z_0. is given by the balance mg = $\mu gradB$. One needs a gradient $\frac{\delta B}{\delta z}$ = 173 *Gauss/cm* for compensating the weight. As the gradient in the ring increases with z and is proportional to the magnetic current Zone calculates the shift z_0 to

$$z_0 = const. mg/I.$$

It amounts in our case to z_0 = 1.2 *mm* at the highest magnet current Z = 200 *A* and 4.8 *mm* at 50 A accordingly.

By moving a thin neutron counter through the storage volume we could measure the profile of the circulating neutron beam and its position in the magnet. Driving alternating the counter downwards and upwards in many measuring runs we determined z_0 as a function of the magnet current.

The result is shown in Fig. 18. The measured data taken with different experimental parameters are following the predicted line. A detailed analysis gives for the gravitational mass of the neutron the value

$$m_g = (1.63 \pm 0.06) \cdot 10^{-24}\, g.$$

It agrees within 4 % with the well known inertial mass.

Thus the magnetic storage ring represents a balance with a sensitivity of 10^{-25} g. It is only achieved because the much higher electric forces play no role at all.

I am convinced that the magnetic bottles developed in our laboratory as described will be useful and fruitful instruments for many other experiments in the future as the Ion Trap has already proved.

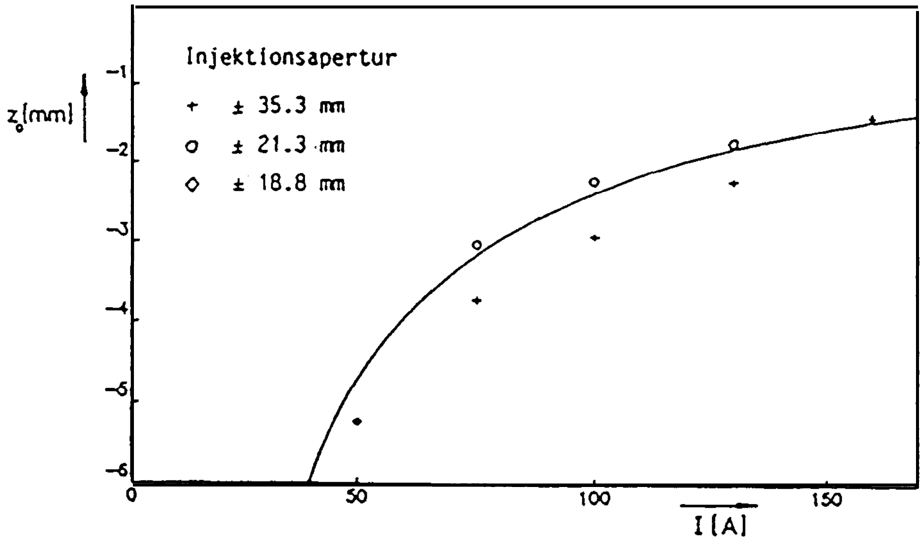


Figure 18. Downward shift of the equilibrium center of the neutron orbits due to the weight of the neutron as function of the magnetic current.

REFERENCES

[1] H. Friedburg and W. Paul, Naturwissenschaft 38, 159 (1951).
[2] H. G. Bennewitz and W. Paul, Z. f. Physik 139,489 (1954).
[3] H. G. Bennewitz and W. Paul, Z. f. Physik, 141, 6 (1955).
[4] C. H. Townes, Proc. Nat. Acad. of Science, 80, 7679 (1983).
[5] a) W. Paul and H. Steinwedel, Z. f. Naturforschung 8a, 448 (1953); b) German Patent Nr. 944 900; USA Patent 2939958.
[6] W. Paul and M. Raether, Z. f. Physik, 140, 262 (1955).
[7] W. Paul, H. P. Reinhardt, and U. v. Zahn, Z. f. Physik 152, 143 (1958).
[8] F. v. Busch and W. Paul, Z. f. Physik, 164, 581 (1961).
[9] U. v. Zahn, Z. f. Physik, 168, 129 (1962).
[10] P. *H.* Dawson: *Quadrupole Muss Spectrometry and its Application,* Elsevier, Amsterdam 1976.
[11] W. Paul, 0. Osberghaus, and E. Fischer, Forsch.Berichte des Wirtschaftsministeriums Nordrhein-Westfalen Nr. 4 15 (1958).
[12] K. Berkling, Thesis Bonn 1956.
[13] E. Fischer, Zeitschrift f. Physik 156, 1 (1959).
[14] H. Dehmelt, Adv. in Atom and Molec. Phys., Vol. 3 (1967).
[15] D. J. Wineland and H. Dehmelt, Bull. Am. Phys. Soc., 20, 637 (1975).
[16] R. F. Wuerker and R.V. Langmuir, Appl. Phys. 30, 342 (1959).
[17] W. Neuhauser, M. Hohenstett, P. Toschek and A. Dehmelt, Phys. Rev. A22, 1137 (1980).
[18] F. Dietrich, E. Chen, J. W. Quint and H. Walter, Phys. Rev. Lett. 59, 2931 (1987).
[19] G. Rettinghaus, Zeitschrift Angew. Physik, 22, 321 (1967).
[20] F. v. Busch and W. Paul, Z. f. Physik, 165, 580 (1961).
[21] R. E. March and R. J. Hughes, *"Quadrupole Storage Mass Spectrometry",* -John Wiley, New York 1989.
[22] F. M. Penning, Physica 3, 873 (1936).
[23] G. Gräff, E. Klempt and G. Werth, Zeitschrift f. Physik 222, 201 (1969).
[24] R. S. van Dyck, P. B. Schwinberg, H. G. Dehmelt, Phys. Lett. 38, 310 (1977).
[25] B. Martin, Thesis Bonn University 1975.
[26] A. L. Migdal, J. Prodan, W. D. Phillips, Th. H. Bergmann, and H.J. Metcalf, Phys. Rev. I.ett. 54, 2596 (1985).
[27] K. J. Kügler, W. Paul, and U. Trinks, Nucl. Instrument. Methods A 228, 240 (1985).
[28] W. Paul, F. Anton, L. Paul, S. Paul, and W. Mampe, Z. f. Physik C 45, 25 (1989).

Physics 1990

JEROME I FRIEDMAN, HENRY W KENDALL and RICHARD E TAYLOR

for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics

THE NOBEL PRIZE IN PHYSICS

Speech by Professor Cecilia Jarlskog of the Royal Swedish Academy of Sciences.
Translation from the Swedish text.

Your Majesties, Your Royal Highnesses, Ladies and Gentlemen,

One of the most important tasks of physics is to provide us with a clearer picture of the world we live in. We know that the observable universe is much larger than any of us could imagine and is even, perhaps, no more than just an island in an ocean of universes. But the creation also has another unfathomable frontier-that towards smaller and smaller constituents: molecules, atoms and elementary particles.

It is the business of science to probe elementary particles as well as the most remote galaxies, collecting facts and deciphering relationships at all levels of creation. The amount of information increases rapidly and without understanding can become overwhelming. Such confusion prevailed at the end of 1950s. At the deepest level of the microscopic world were the electron, the proton and the neutron, particles which for years had been considered to be the fundamental building blocks of matter. However, they were no longer alone but were accompanied by many newly discovered particles. The special roles of the proton and the neutron are evident-among other things they are responsible for more than 99 percent of our weight. But what roles did the other particles play? Where had nature's elegance and beauty gone? Was there a hidden order not yet discovered by man?

There could be order but only at the price of postulating an additional, deeper level in nature-perhaps the ultimate level-consisting of only a few building blocks. Such an idea had been advanced and the new building blocks were called "quarks"-a word borrowed by the 1969 Nobel Prizewinner in Physics, Murray Gell-Mann, from "Finnegans Wake," for most of us an incomprehensible masterpiece by the great Irish novelist James Joyce. But the quark hypothesis was not alone. There was, for example, a model called "nuclear democracy" where no particle had the right to call itself elementary. All particles were equally fundamental and consisted of each other.

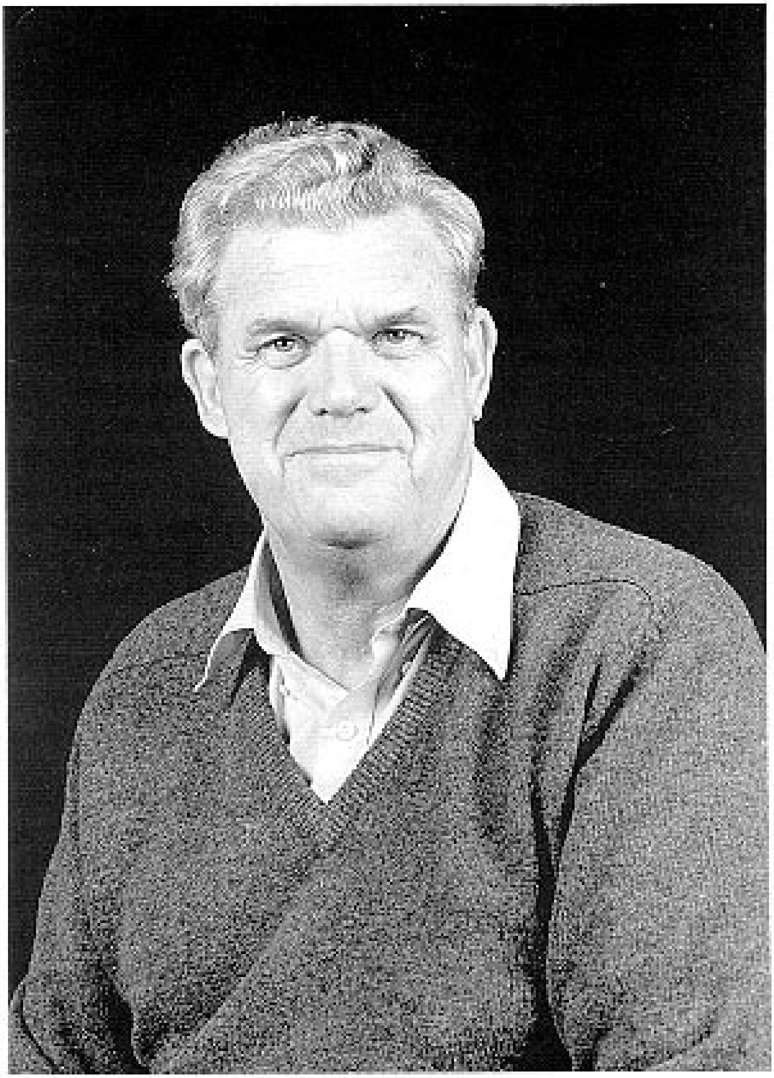
This year's Laureates lit a torch in this darkness. They and their co-workers examined the proton (and later on also the neutron) under a microscope-not an ordinary one, but a 2 mile-long electron accelerator built by Wolfgang K.H. Panofsky at Stanford, California. They did not anticipate anything fundamentally new: similar experiments, albeit at lower energies, had found that the proton behaved like a soft gelatinous sphere with many excited states, similar to those of atoms and nuclei. Nevertheless, the Laureates decided to go one step further and study the proton under extreme conditions. They looked for the electron undergoing a large deflection, and where the proton, rather than keeping its identity, seized a lot of the collision energy and broke up into a shower of new particles. This so-called "deep inelastic scattering" had generally been considered to be too rare to be worth investigating. But the experiment showed otherwise: deep inelastic scattering was far more frequent than expected, displaying a totally new facet of proton behavior. This result was at first skeptically received: perhaps the moving electron gave off undetected light. But this year's Prizewinners had been thorough and their findings were subsequently confirmed by other experiments.

The interpretation was given primarily by the theorists James D. Bjorken and the late Richard P. Feynman (Feynman stood in this Hall exactly 25 years ago to receive a Nobel Prize for another of his great contributions to physics). The electrons ricocheted off hard point-like objects inside the proton. These were soon shown to be identical with the quarks, thus simplifying the physicist's picture of the world; but the results could not be entirely explained by quarks alone. The Nobel Prize-winning experiment indicated that the proton also contained electrically neutral constituents. These were soon found to be "gluons," particles glueing the quarks together in protons and other particles.

A new rung on the ladder of creation had revealed itself and a new epoch in the history of physics had begun.

Dear Professors Friedman, Kendall and Taylor,

On behalf of the Royal Swedish Academy of Sciences I wish to convey to you our warmest congratulations for having taken us to the land of deep inelastic scattering where the colourful quarks and gluons first revealed themselves. You will now receive the Nobel Prize from the hands of His Majesty the King.



Richard E. Taylor

RICHARD E. TAYLOR

Medicine Hat is a small town in Southwestern Alberta founded just over 100 years ago in a valley where the Canadian Pacific Railway crossed the South Saskatchewan River. I was born there on November 2, 1929 and raised in comfortable if somewhat Spartan circumstances. My father was the son of a Northern Irish carpenter and his Scottish wife who homesteaded on the Canadian prairies; my mother was an American, the daughter of Norwegian immigrants to the northern United States who moved to a farm in Alberta shortly after the first World War. During my early years our family of three was part of a large family clan headed by my Scottish grandmother. I attended schools named after English Generals and Royalty - Kitchener, Connaught, Alexandra.

Although I read quite a bit and found mathematics easy, I was not an outstanding student. In high school I did reasonably well in mathematics and science thanks to some talented and dedicated teachers.

I was nearly ten years old when World War II began. That conflict had a great effect on our town, and on me. In rapid succession the town found itself host to an R.A.F. flight training school, a prisoner of war camp and a military research establishment. The wartime glamor of the military, the sudden infusion of groups of sophisticated and highly-educated people, and new cultural opportunities (the first live symphonic music I ever heard was played by German prisoners of war) all transformed our town and widened the horizons of the young people there. I developed an interest in explosives and blew three fingers off my left hand just before hostilities ended in Europe. The atomic bomb that ended the war later that summer made me intensely aware of physicists and physics.

Higher education was highly prized in the society of a small prairie town and I was expected to continue on to university. After some difficulties over low grades in some high school subjects, I was admitted to the University of Alberta in Edmonton. I registered in a special program emphasizing mathematics and physics and gradually became interested in experimental physics, continuing my studies towards a Masters degree at the same institution. My thesis research was a rather primitive effort to measure double P-decay in an aging Wilson cloud chamber. Between sessions at the University, I spent two summers as a research assistant at the Defense Research Board installation near Medicine Hat working with Dr. E.J. Wiggins, who encouraged me to continue my studies either in eastern Canada or in the United States.

Those were interesting years, and during this time I met, courted and married Rita Bonneau - a partnership which has enriched my life in every way. Together we decided to try California, and I was accepted into the graduate program at Stanford, while she found work teaching in a military school in order to support us both. The first two years at Stanford were exciting beyond description-the Physics Department at Stanford included Felix Bloch, Leonard Schiff, Willis Lamb, Robert Hofstadter, and W.K.H. (Pief) Panofsky who had just arrived from Berkeley. I found that I had to work hard to keep up with my fellow students, but learning physics was great fun in those surroundings. At the end of the second year I joined the High Energy Physics Laboratory where the new linear accelerator was just beginning to do experiments. My thesis work was accomplished there under Prof. Robert F. Mozley, on a rather difficult experiment producing polarized y-rays from the accelerator beam and then using those y-rays to study π–meson production.

In 1958 I was invited to join a group of physicists at the Ecole Normale Superieure in Paris who were planning experiments at an accelerator (similar to the linac at Stanford) which was under construction in Orsay. I stayed in France for about three years working on the experimental facilities for the accelerator, and then participated in some electron scattering experiments. My wife began a new career there as a librarian at the Orsay laboratory, a career which was interrupted for a while when our son, Ted, was born in 1960. We returned to the United States in 1961 but a continuing connection to French physics and physicists has been a significant element in my life since that time - including a Doctorate (Honoris Causa) very kindly conferred upon me in 1980 by the Universite de Paris-Sud.

Upon our return to the United States, I joined the staff of the Lawrence Berkeley Laboratory at the University of California. After less than a year in Berkeley, I moved back to Stanford where work on the construction of Stanford Linear Accelerator Center (SLAC) was just beginning. At SLAC, I started working on the design of the experimental areas for the new accelerator. By 1963 I had joined the group considering the requirements for electron scattering apparatus in the larger of two experimental areas. I worked closely with Pief Panofsky, and with collaborators from the California Institute of Technology and the Massachusetts Institute of Technology. I spent the next decade helping to build equipment and taking part in various electron scattering experiments, a number of which are the subject of the 1990 Nobel lectures. This was a period of intense activity, but also one of intense enjoyment for me. I was surrounded by people I liked and admired, and deeply involved in experiments which generated interest in laboratories and universities all over the world. I count myself extremely fortunate to have been at SLAC at that time.

I became a member of the SLAC faculty in 1968. In 1971, I was awarded a Guggenheim fellowship and spent an interesting sabbatical year at CERN, where I was impressed by the great progress that European science had made in the decade since I had worked in France.

Well before my trip to CERN, colleagues in the group at SLAC had become interested in testing some of the invariance properties of the electromagnetic interaction, a field which would absorb our efforts for most of the 1970s. When Charles Prescott joined the group in 1970, he began a serious study of ways to test parity conservation in the interaction between an electron and a nucleon. The electroweak theories of Weinberg and Salam predicted levels of nonconservation that looked extremely hard to measure. We attempted an experiment with the existing Yale polarized source, but the measurements did not reach the desired level of sensitivity. I was not very encouraging to my colleagues who wished to pursue the experiment to higher levels of accuracy. After the theoretical work of Veltman and ‘t Hooft and the discovery of neutral currents at CERN (during the year I was there) and at NAL (now Fermilab), the interest in experiments on parity conservation greatly intensified. In 1975 a new method for producing polarized electrons was discovered by a group in Colorado which included E. L. Garwin of SLAC. In 1978, after building a source for the linac based on the new method, we were able to demonstrate a violation of parity in close agreement with the electroweak predictions.

After the parity experiments, our group presented two proposals for large experimental facilities at PEP, the e^+e^- collider then being built at SLAC. Both those proposals were rejected. The group was finally successful in proposing a relatively small PEP detector, but I did not take part in that experiment.

In 198 1, I received an Alexander von Humboldt award which allowed me to spend most of the 1981-82 academic year at DESY in Hamburg. In 1982 I returned to SLAC as Associate Director for Research, a post I held until 1986 when I resigned to return to research. Since that time I have spent quite a bit of time in Europe and I am presently playing a very small role in the H, detector preparations at HERA.

DEEP INELASTIC SCATTERING: THE EARLY YEARS

Nobel Lecture, December 8, 1990

RICHARD E. TAYLOR

Stanford Linear Accelerator Center, Stanford, California, USA

FOREWORD

Soon after the 1990 Nobel Prize in Physics was announced Henry Kendall, Jerry Friedman and I agreed that we would each describe a part of the deep inelastic experiments in our Nobel lectures. The division we agreed upon was roughly chronological. I would cover the early times, describing some of the work that led to the establishment of the Stanford Linear Accelerator Center where the experiments were performed, followed by a brief account of the construction of the experimental apparatus used in the experiments and the commissioning of the spectrometer facility in early elastic scattering experiments at the Center.

In a second paper, Professor Kendall was to describe the inelastic experiments and the important observation of scale invariance which was found in the early electron-proton data.

In a final paper, Professor Friedman was to describe some of the later experiments at SLAC along with experiments performed by others using muon and neutrino beams, and how these experiments, along with advances in theory, led to widespread acceptance of the quark model as the best description of the structure of the nucleon.

This paper is, therefore, part of a set and should be read in conjunction with the lectures of H. W. Kendall[1] and J. I. Friedman.[2]

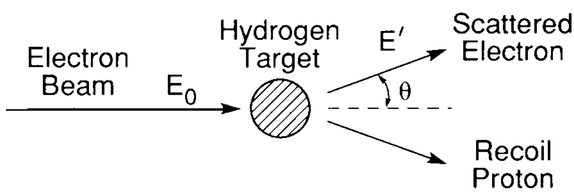
There were many individuals who made essential contributions to this work. Our acknowledgements to a number of them are given in Reference 3.

*

Forty years of electron scattering experiments have had a significant impact on the understanding of the basic components of matter. Progress in experimental high energy physics is often directly coupled to improvements in accelerator technology and experimental apparatus. The electron scattering experiments, including the deep inelastic experiments cited this year by the Royal Swedish Academy of Sciences, provide examples of this sort of progress. Experiments made possible by increasing electron energy and intensity, along with increasingly sophisticated detectors have continued to shed light on the structure of nuclei and nucleons over the years. Much additional information has come from experiments using secondary beams of muons and neutrinos from proton accelerators.

Scattering experiments can trace their roots back to the u-particle experiments[4] in Rutherford's laboratory which led to the hypothesis of the nuclear atom.[5] The u-sources used at that time emitted electrons as well as u-particles, but the electron momentum was too small to penetrate beyond the electron cloud of the target atoms, and electron scattering was just an annoying background in those experiments.

Following the landmark experiments of Franck and Hertz[6] on the interaction of electrons with the atoms of various gases, electron scattering was used extensively to investigate the electronic configurations of atoms. Later, after higher energy electrons became available from accelerators, interest in their use as probes of the nucleus increased. Rose[7] gave the first modern treatment of the subject in 1948, followed by Schiff,[8] who was exploring possible experiments for the new electron linear accelerator at Stanford. Schiff stressed the importance of e-p measurements which could probe the structure of the proton itself using the known electromagnetic interaction. Soon after, Rosenbluth[9] calculated the probability that an electron of energy E_0. will scatter through an angle θ in an elastic collision with a proton-corresponding to the following idealized experimental set up:



The energy E' of the scattered electron is less than the incident energy E_0. because energy is transferred to the recoil proton (of mass M):

$$E' = \frac{E_0}{1 + \frac{2E_0}{M}\sin^2\theta/2}$$

The square of the four momentum transfer, Q^2, is a measure of the ability to probe structure in the proton. The uncertainty principle limits the spatial definition of the scattering process to $\backsim \hbar/Q$ so Q^2, (and therefore E_0 must be large in order to resolve small structures.

$$Q^2 = 4E_0E'\sin^2\theta/2$$

When only the scattered electron is detected the elastic differential cross section, $d\sigma/d\Omega$, obtained by Rosenbluth is a simple expression, quite similar to the original Rutherford scattering formula:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E_0^2\sin^4\theta/2}\cdot\cos^2\theta/2\cdot\frac{E'}{E_0}\left[\frac{G_E^2+\tau G_M^2}{1+\tau} + 2\tau G_M^2\tan^2\theta/2\right],$$

where

$$7 = Q^2/4M^2$$

G_E and G_M are form factors describing the distributions of charge and magnetic moment respectively. They are functions of only the momentum transfer, Q^2.

$$G_E = G_E(Q^2) \qquad G_M = G_M(Q^2)$$

$$G_E(0) = 1 \qquad G_M(0) = \mu_p.$$

where μ_p is the magnetic moment of the proton (in units of A). If the charge and magnetic moment distributions are small compared with $\hbar/Q$, then G_E and G_M will not vary as Q^2 changes, but if the size of those distributions is comparable with A/Q then the G's will decrease with increasing Q^2.

Hanson, Lyman and Scott[(10)] were the first to observe elastic electron scattering from a nucleus using a 15.7 MeV external beam from the 22 MeV betatron at Illinois. They were studying the scattering of electrons by electrons and observed two peaks in the energy spectrum of the scattered electrons (Fig I).

In 1953, the commissioning of the first half of the new Mark III linac in the High Energy Physics Laboratory (HEPL) at Stanford provided an external electron beam of unprecedented intensity at energies up to 225 MeV. Complementing this advance in accelerator technology, Hofstadter and his collaborators constructed a quasi-permanent scattering facility (Fig. 2) based on a 180” magnetic spectrometer (radius of bending = 18 inches). The spectrometer could be rotated about the target to measure different scattering angles, and the excitation of the magnet could be varied to

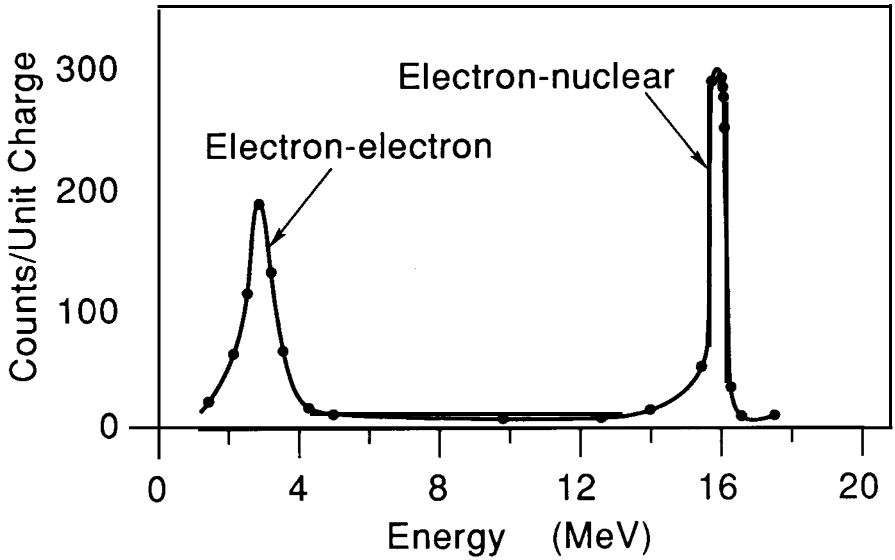


Fig. 1. First observation of elastic electron scattering from a nucleus, using 15.7 MeV electrons from the Illinois betatron, scattered at 10”.

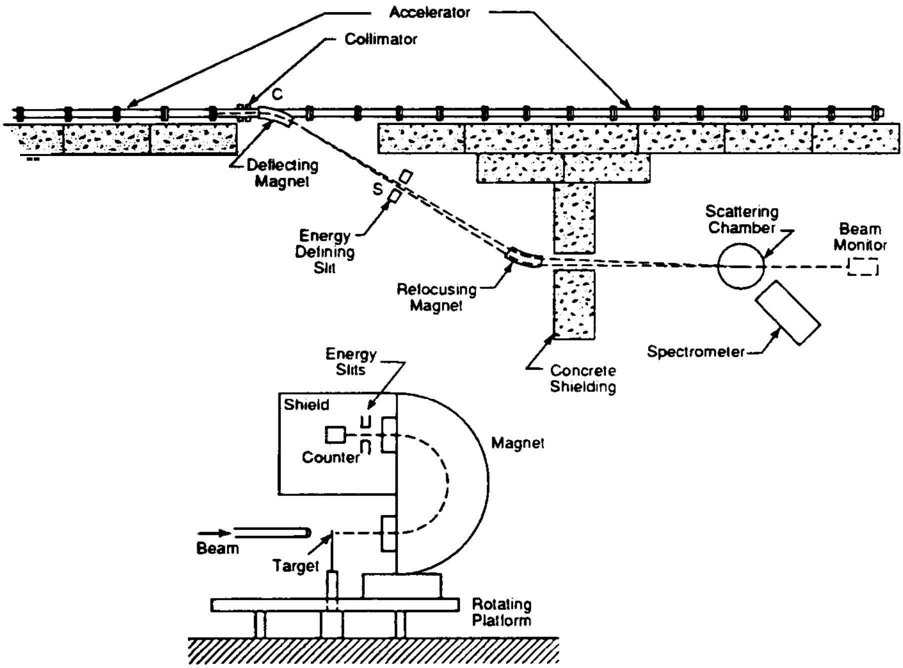


Fig. 2. Schematic of the electron scattering facility located at the halfway point of the Mark III linear accelerator at the High Energy Physics Laboratory at Stanford. The central orbit in the spectrometer has a radius of 18 inches.

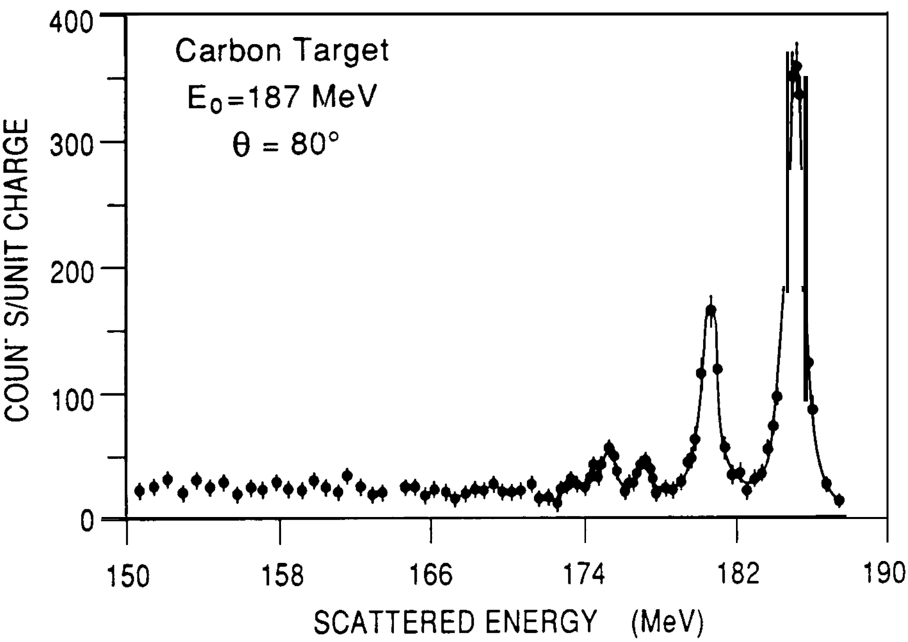


Fig. 3. Energy spectrum of 187 MeV electrons scattered through 80° by a carbon target, using the apparatus in Figure 2.

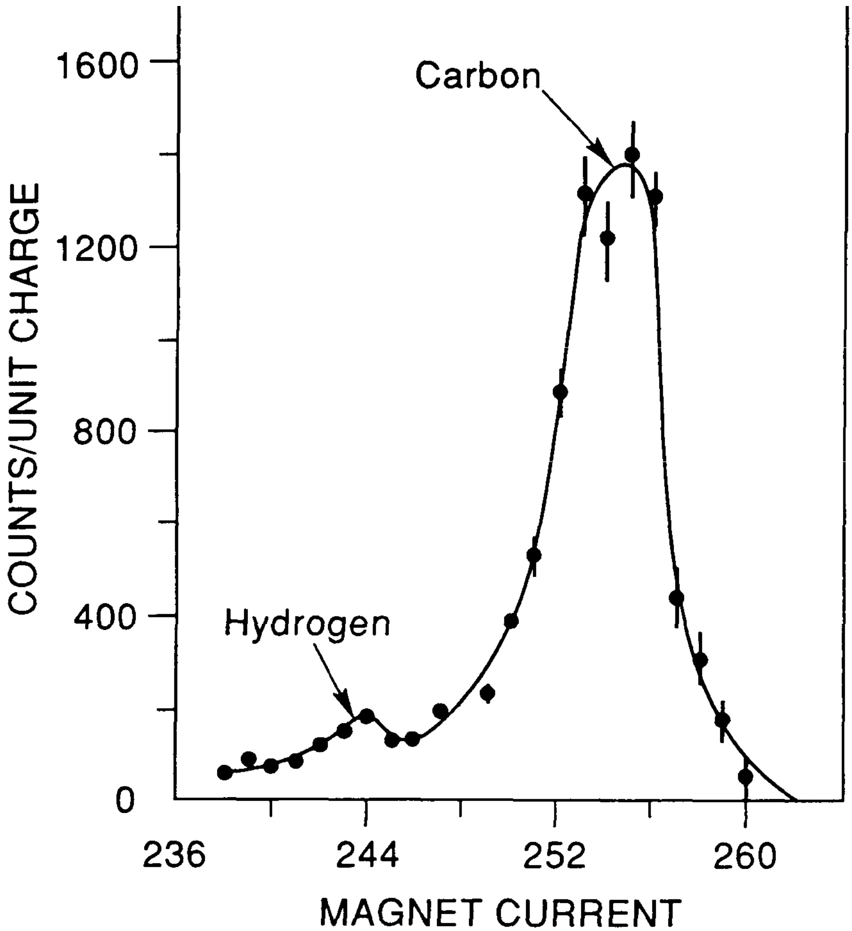


Fig. 4. Spectrum of scattered electrons from a CH_2 target showing evidence of electron-proton scattering, circa 1954.

change the energy of the electrons detected. This apparatus was used for a series of experiments with only minor modifications.

Nuclear scattering was easy to observe with this apparatus. At small angles, the "elastic peak" was the most prominent feature of the energy spectrum of the scattered electrons, although scattering with transitions to excited nuclear states was also evident[11] (Fig. 3). From the behavior of the elastic scattering cross sections at the various beam energies and various scattering angles, Hofstadter and his collaborators were able to measure the size and some simple shape parameters for many nuclides.

In 1953, this facility furnished the first evidence of elastic scattering from the proton, using a polyethylene target[12] as shown in Fig. 4. A hydrogen gas target was then constructed in order to reduce the backgrounds under the elastic peak, and in 1955, Hofstadter and McAllister[13] presented data showing that the form factors in the Rosenbluth cross section were less than

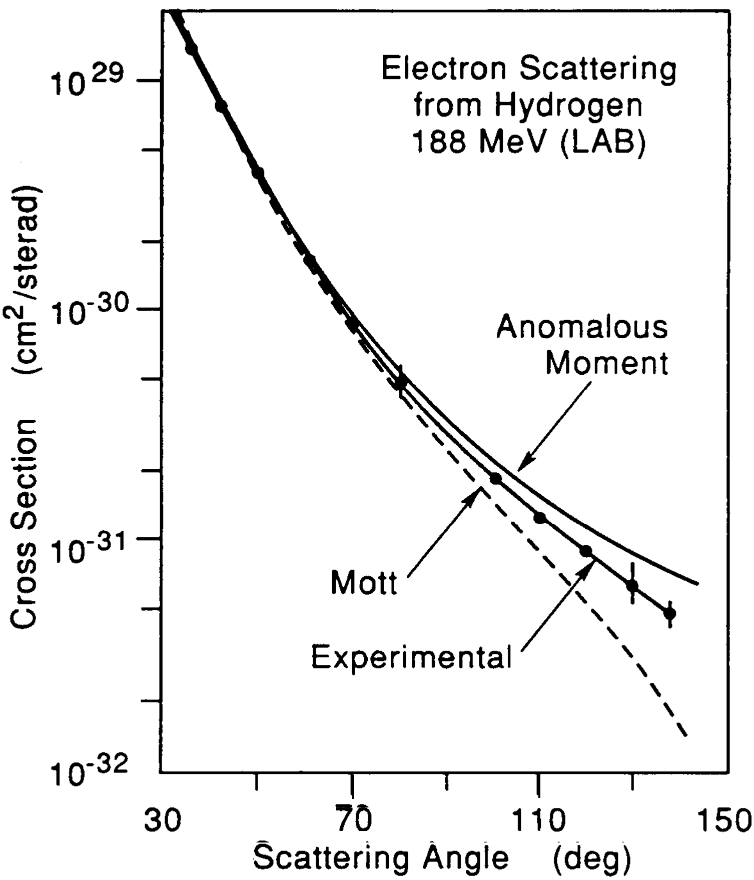


Fig. 5. **Elastic electron scattering cross sections from hydrogen compared with the Mott** scattering formula (electrons scattered from a particle with unit charge and no magnetic moment) and with the Rosenbluth cross section for a point proton with an anomalous magnetic moment. The data falls between the curves, showing that magnetic scattering is occurring but also indicating that the scattering is less than would be expected from a point proton.

unity (Fig. 5) - and were decreasing with increasing momentum transfer. They gave an estimate of (0.7 ± 0.2) X 10^{-13} cm for the size of the proton.

In 1955, new end station facilities at HEPL were commissioned, doubling the energy available for scattering experiments. Beams from the full length of the linac were available in the new area, reaching energies of 550 MeV (Fig. 6). A new spectrometer facility was installed by Hofstadter's group with a magnet of twice the bending radius (36 inches) of the spectrometer in use at the halfway station. A liquid hydrogen target was constructed and installed. This equipment was a considerable improvement (Fig. 7) and a large effort was focused on scattering from hydrogen.([14]) A graph of the measured form factors is shown in Fig. 8, which shows data for various values of Q^2 compared with a model proton with a "size" of 0.8 x 10^{-13} cm.

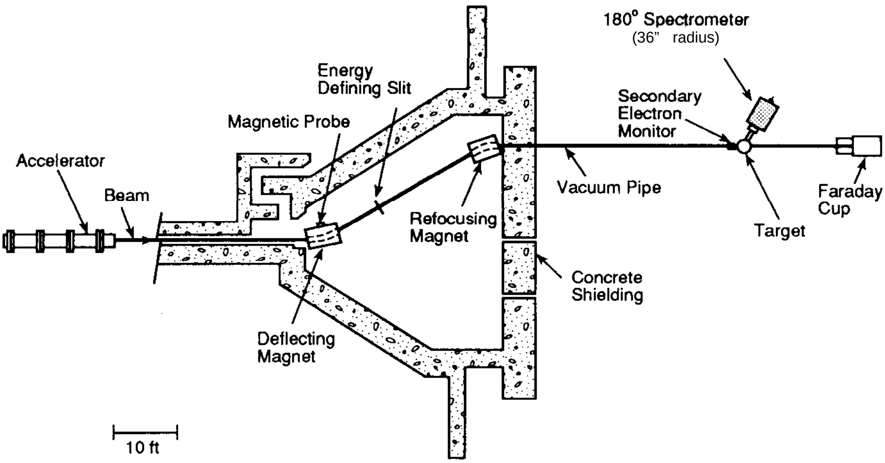


Fig. 6. Layout of the beam line and the 36 inch spectrometer in the End Station of the High Energy Physics Laboratory. This facility was used for electron scattering experiments for more than a decade by R. Hofstadter and his collaborators. (A 72 inch spectrometer was added in 1960 to analyze scattered electrons to an energy of 1000 MeV.)

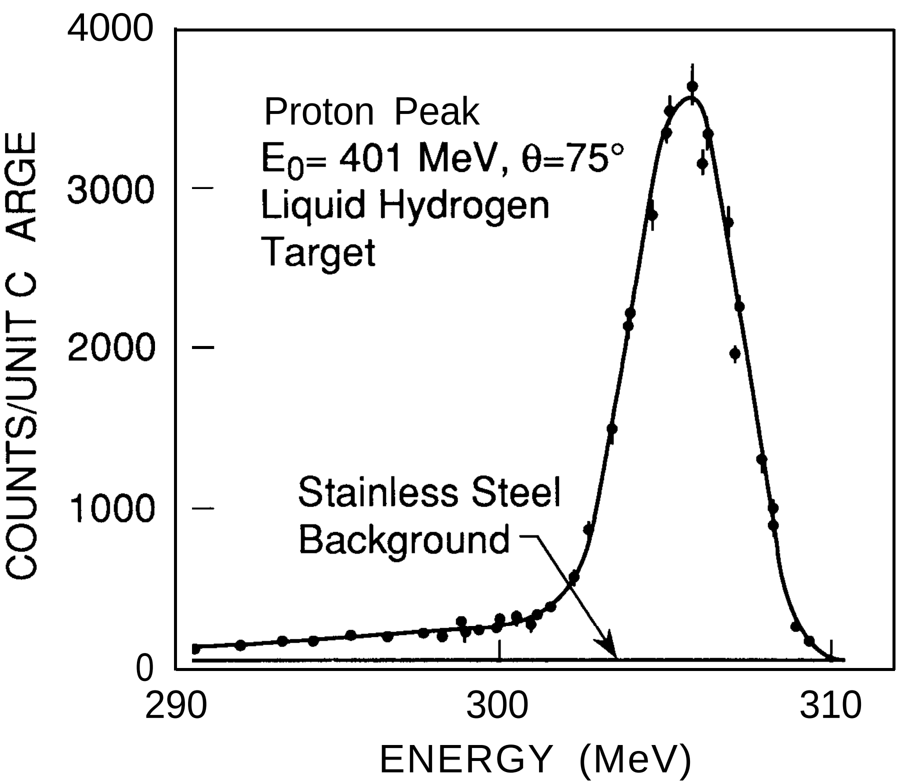


Fig. 7. Electron-proton scattering energy spectrum taken using the facility in Figure 6 and a liquid hydrogen target. The stainless steel container for the liquid hydrogen contributes very little background. The radiative tail of the elastic peak is clearly evident on the low energy side of the peak.

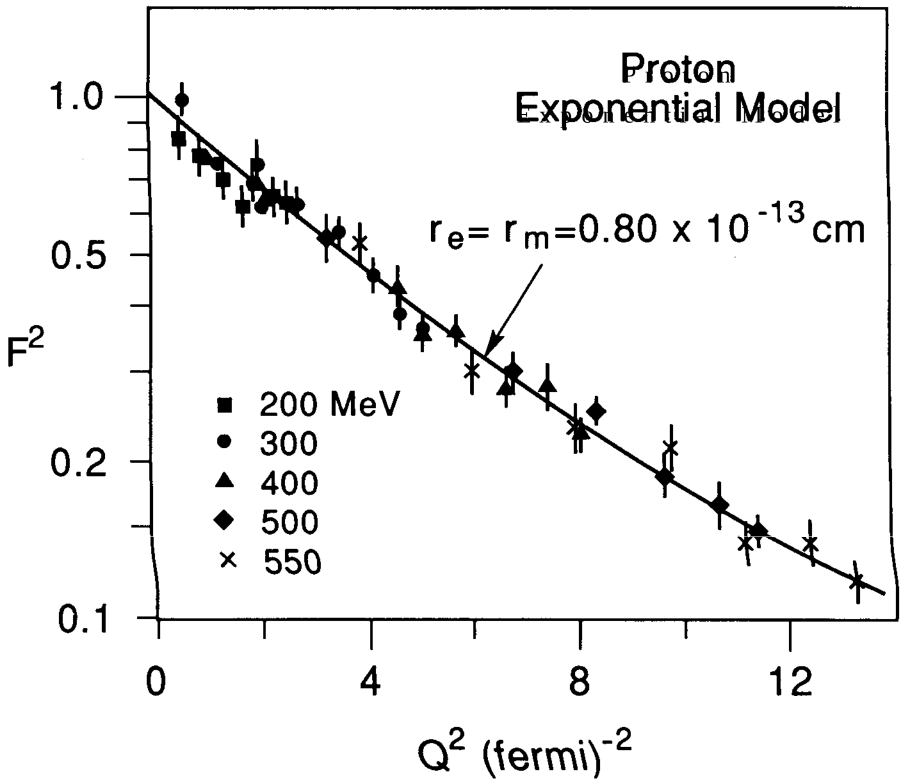


Fig. 8. **The proton form factor for various energies and momentum transfers as measured in early experiments using the 36 inch spectrometer facility at HEPL. The value of F^2 was** calculated from the original Rosenbluth formula which defined form factors $F_1(Q^2)$ and $F_2(Q^2)$. F_1 corresponds to the form factor for a Dirac (spin $\frac{1}{2}$) proton, and F_2 to the form factor for the anomalous magnetic moment. In the analysis of the data it was assumed that $F_1 = F_2$.

At higher values of Q^2 it became evident that $F_1 \neq F_2$, but rather that $G_E = G_M/\mu_p$ for the proton, and the use of the G's then became universal. ($G_M = F_1 + KF_2$ and $G_E \simeq F_1$ for small values of Q^2.) The curve shown in the figure was based on a model assuming exponentially falling distributions of charge and magnetic moment, each with a root mean square radius of 0.8 x 10^{-13}cm (1 Fermi = 10^{-13}cm, 1 (Fermi)-2 = 0.0388 GeV^2)

These experiments mark the beginning of the search for sub-structure in the proton. They showed persuasively that the proton was not a point, but an extended structure. This fundamental discovery was rapidly accepted by the physics community. It was generally assumed that there was a connection between spatial extent and structure, although I don't think anyone was seriously questioning the "elementary" character of the proton at that time. The available electron energies were not yet high enough for the exploration of inelastic scattering from the proton, and only elastic experiments provided clues about proton structure for the next several years.

The new facility was also used to measure scattering from deuterium, in order to extract information about the neutron. The form factor for elastic scattering from the loosely bound deuterium nucleus falls off extremely

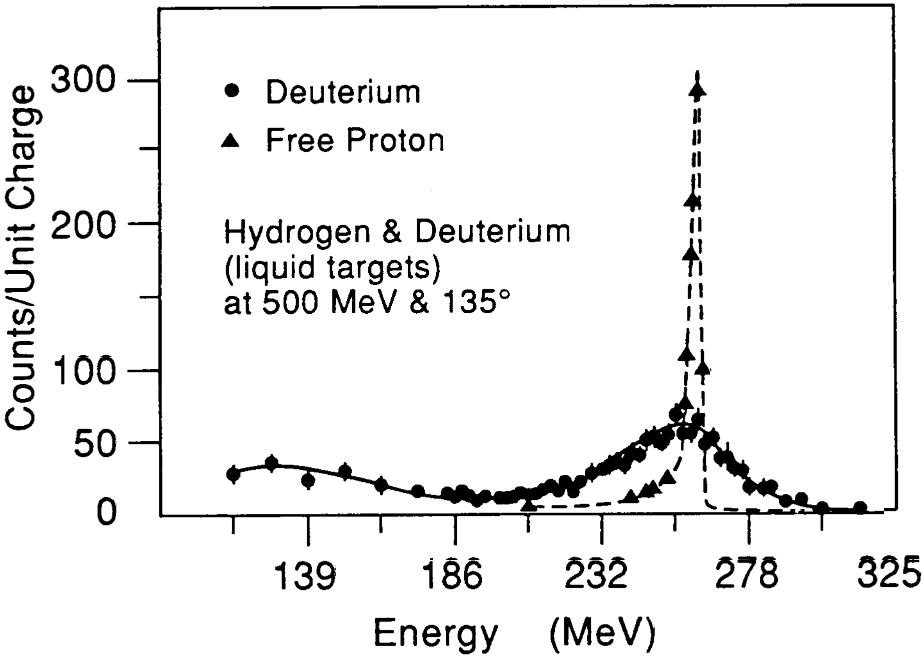


Fig. 9. **A comparison of the scattering of electrons from the proton and the quasi-elastic** scattering from the individual nucleons in deuterium. The elastic scattering from the deuterium nucleus would occur at an energy above the highest energy shown on the graph and would be negligible in comparison with the cross-sections illustrated here. The quasi-elastic scattering from either the proton or the neutron in deuterium is spread out over a wider range of energies than the scattering from the free proton because of the momentum spread of the nucleons in the deuterium nucleus.

rapidly with increasing momentum transfer, so the neutron was studied via quasi-elastic scattering- scattering from either the proton or the neutron, which together form the deuterium nucleus. The quasi-elastic scattering reaches a maximum near the location of the peak for electron-proton scattering, since the scattering takes place off a single nucleon and the recoil energy is largely determined by the mass of that nucleon (Fig. 9). One also observes the effects of the motion of the nucleons in deuterons, and one result is a measurement of the nucleon's momentum distribution in the deuterium nucleus.

The great success of the scattering program at HEPL had three consequences: Scattering experiments became more popular at existing electron synchrotrons, new synchrotrons were planned for higher energies, and discussions began at Stanford about a much larger linear accelerator- two miles long and powered by one thousand klystrons!

After more than a year of discussions and calculations, the physicists and engineers of the High Energy Physics Laboratory prepared the first proposal for a two-mile linear accelerator to be built at Stanford.[15] E.L. Ginzton, W.K.H. Panofsky and R.B. Neal directed the design effort, and Panofsky and Neal went on to direct the construction of what came to be called the Stanford Linear Accelerator Center (SLAC)-surely one of the great engineering achievements of the early 1960s.([16]) The new machine was a bold extrapolation of existing techniques. The design was conservative in the sense that working prototypes of all the machine components were in hand, but a formidable challenge because of the increase in scale. The investigation of the structure of the proton and neutron was a major objective of the new machine. The 20 GeV energy of the accelerator made both elastic and inelastic scattering experiments possible in a new range of values of Q^2, and presented our collaboration with a golden opportunity to pursue the studies of nucleon structure.

When it was proposed, the two-mile linac was the largest and most expensive project ever in high energy physics. Up until that time the field had been dominated by proton accelerators, and electron machines had been relatively small and few in number. Electrons were catching up and, in parallel with the Stanford linac, two large electron synchrotrons were proposed and built: the Cambridge Electron Accelerator (CEA) and the Deutches Electronen Synchrotron (DESY) in Hamburg, with peak energies of 5 and 6 GeV respectively. The establishment of SLAC in 1960 would eventually bring electron physics into direct competition with the largest proton accelerators of the time, the Brookhaven AGS and the CERN PS, both of which were already under construction in the late 1950s. The new electron accelerators would make available many opportunities for physicists.

The new linear accelerator consisted of two miles of accelerating waveguide, mounted in a tunnel buried 25 feet underground. In the initial phase, the waveguide was powered by two hundred and forty 20-30 MW

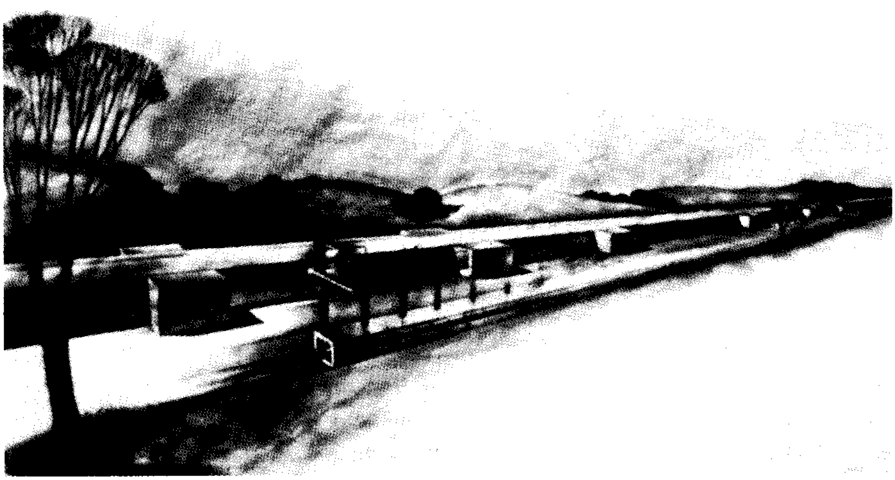


Fig. 10. Cut-away illustration of the two mile Stanford Linear Accelerator, showing the accelerator wave-guide buried 25 feet below the surface and the klystron gallery at ground level. Each klystron feeds 40 feet of accelerator wave-guide through penetrations connecting the accelerator housing with the klystron gallery.

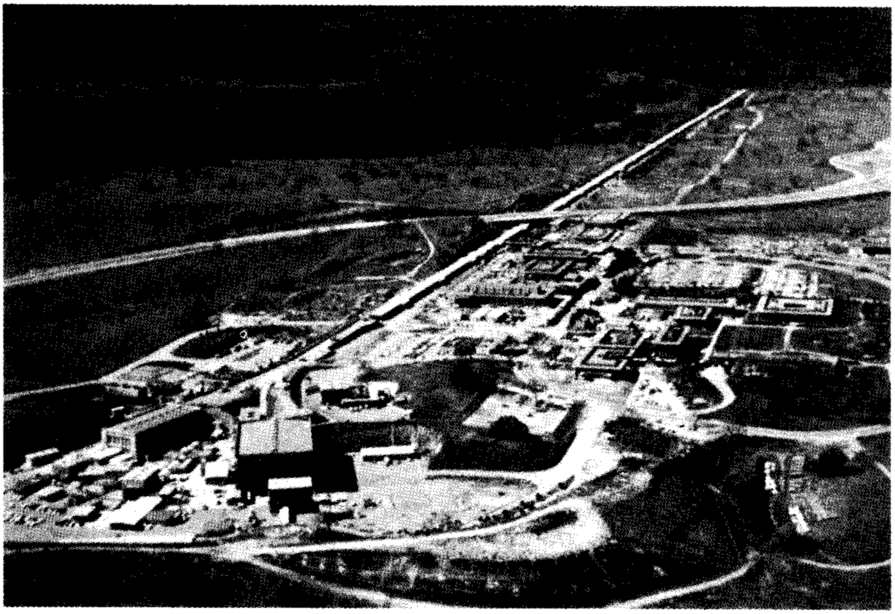


Fig. 12. Aerial view of the SLAC site. On the left are the experimental areas fed by beam lines from the accelerator. On the right is the campus area where offices, laboratories, and shops are located. The scattering experiments were performed in the large shielded building just to the left of center near the bottom of the picture. The structure crossing the accelerator is a superhighway which was under construction at the time this picture was taken.

klystrons housed in a building at ground level. The accelerator was sited in the hills behind Stanford on University land, and was probably the last of the university-based high energy physics accelerators in the U.S. (Figures 10 and 11).

The design parameters of the new machine- 20 GeV in energy and average currents in the neighborhood of 100 μA- presented many new problems for experiments. Two experimental areas (called End Stations in Figure 12) were developed initially-one heavily shielded area, where secondary beams of hadrons and muons could be brought out to various detectors, and a second area for electron and photon beam experiments. The "beam switchyard" connected each area to the accelerator with a magnetic beam transport system which defined the momentum spread of each beam to better than 0.2%, was achromatic and isochronous (in order to preserve the RF time structure of the beam). The transport systems were fed by a system of pulsed magnets, so that a given accelerator pulse could be directed into either of the two experimental areas. Unavoidable beam losses in the system would lead to high levels of radioactivity, and to challenging thermal design problems at the expected levels of beam currents. The design of this "switchyard" area was fairly well fixed by the end of 1963, along with the specifications for the heavily shielded end station buildings (see Ref. 16).

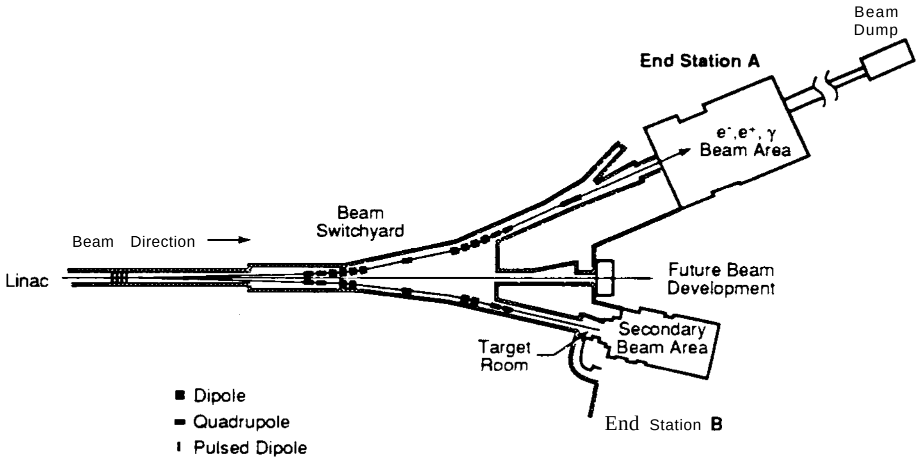


Fig. 12. Layout of the SLAC experimental areas and the beam switchyard.

The experimental area which was to be devoted to electron scattering and photoproduction experiments using the primary beam had to satisfy the experimental needs of several groups of experimenters. The challenge was to build apparatus which would allow rapid and efficient data collection in the new energy region which was being made available. The operating costs of the new accelerator (not to mention the depreciation on the capital costs of over 100 million dollars) would be many thousands of dollars per day, so it was important to balance costs in such a way that the experiments would give good value-a spectrometer with small solid angle would be cheaper, but might take much longer to make a given measurement. The major costs in this area would be for large magnetic spectrometers and shielding, and so some of the smaller components could be developed to a much more sophisticated level than had been possible at the smaller laboratories, while still adding only a small percentage to the overall costs.

Although half a decade had passed since the original proposal for SLAC, the basic physics aims remained much the same. The most effective technique still appeared to be the detection of a single particle from a given interaction. (The duty factor [i.e., the percentage of on-time] was low for the linac - the klystrons were pulsed for approximately two microseconds, at a rate of 360 times per second. This resulted in high instantaneous rates during the short pulses, and made coincidence experiments difficult.) The overall experimental design required instruments which would determine the energy and angle of a particle coming from a target placed in the beam of electrons. Magnetic spectrometers were still the most effective way to accomplish this, but they would be large and cumbersome devices at these energies.

The resolution in energy, ΔE, had to be much better than $m_\pi/E_{\max} \sim$ 0.7% in order to separate reactions that differed in the number of pions emitted. Since the energy of particles from a given reaction is a very steep function of angle, it was also necessary to measure the angle of scattering to high accuracy (~ 0.15 mrad). Practical spectrometers have angular acceptances much greater than the required resolution in angle, so the optics and the detectors had to be arranged in such a way that the true angle of scattering was determined along with the energy.

There were many discussions about the most effective design for the facilities. Records are sparse, but there are indications of frank and earnest discussions. There was a suggestion that a single 2 GeV spectrometer could cover most of the interesting electron scattering experiments, while others were suggesting that a complex system with a high energy forward spectrometer combined with a huge solenoidal detector in the backward direction was the right way to go.

In the Spring of 1964, I found myself gradually being elected to a position of responsibility for the design and engineering of the facilities in End Station A (as the larger of the two experimental areas was called). This was not an enviable position, since there was little agreement about what should be done, and most of the people involved clearly outranked me.

The sub-group interested in electron scattering experiments was pretty well convinced that a spectrometer of 8 - 10 GeV maximum energy with a solid angle $\gtrsim$ 1 milli-steradian would be capable of an extensive program of scattering measurements. By bending in the vertical plane, measurements of scattering angle and momentum could be separated at the location of the detectors. Preliminary designs for such a device had been proposed and had already influenced the layout of the end station, which by this time was in an advanced state of design. The spectrometer incorporated a vertical bend of ~ 30°, with focusing provided by separate quadrupoles preceding and following the bend (Fig. 13, elevation). The magnetic design of the spectrometer involved a lot of computation, but proceeded smoothly. After taking practical and financial constraints into account, the top momentum was fixed at 8 GeV and the solid angle at 1.0 milli-steradians.

In order to cover a range of scattering angles it was our intention to build the spectrometer so that it could be rotated around the target from an external control room (Fig. 13, plan). We needed frames which would hold hundreds of tons of magnets and counters in precise alignment while they were moved about the end station.

It was about this time that we began to assemble a team of engineers and draftsmen to translate the requirements into designs for working hardware. The group began the detailed design of the 8 GeV spectrometer components, while the debate continued about the rest of the complex.

By the middle of 1964 the utility of a forward-angle spectrometer which would analyze particles with a maximum momentum of 20 GeV was no longer questioned. Successful photoproduction experiments were being carried out at energies up to 5 GeV at the CEA electron synchrotron, and extending the energy of these measurements would obviously be a productive program for SLAC. Also, if the electric form factor of the proton, G_E,

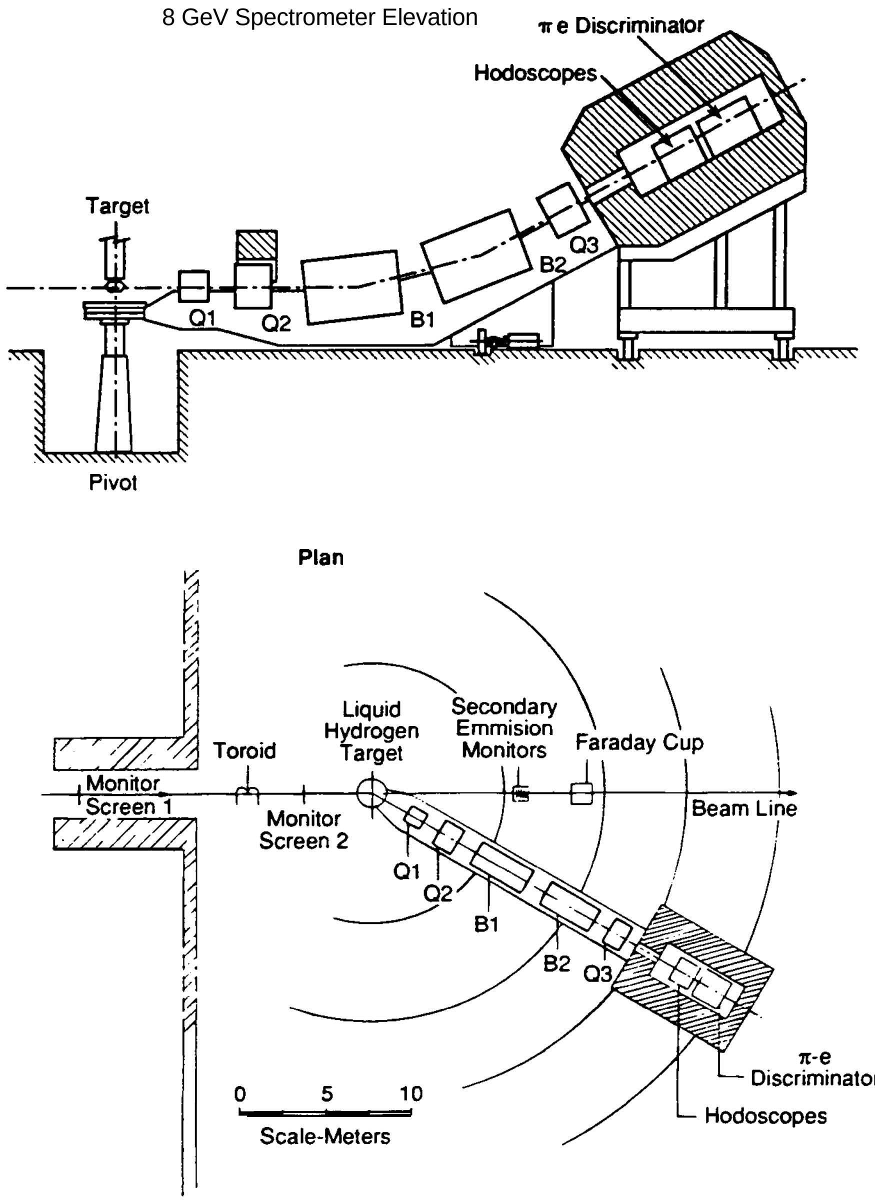


Fig. 13. Schematic drawings of the 8 GeV spectrometer. Five magnets (two bending magnets, (B), and three quadrupoles, (Q)) direct scattered particles into the detectors which are mounted in a heavily shielded enclosure. The whole assembly rides on the rails and can be pivoted about the target to change the angle of scattering of the detected electrons.

was to be measured, small-angle scattering experiments would be required.

Scaling up the 8 GeV spectrometer to 20 GeV (and keeping the resolution at 0.1%) would have required very large vertical displacements. Some attempts were made to design a big pit in the end station to accommodate

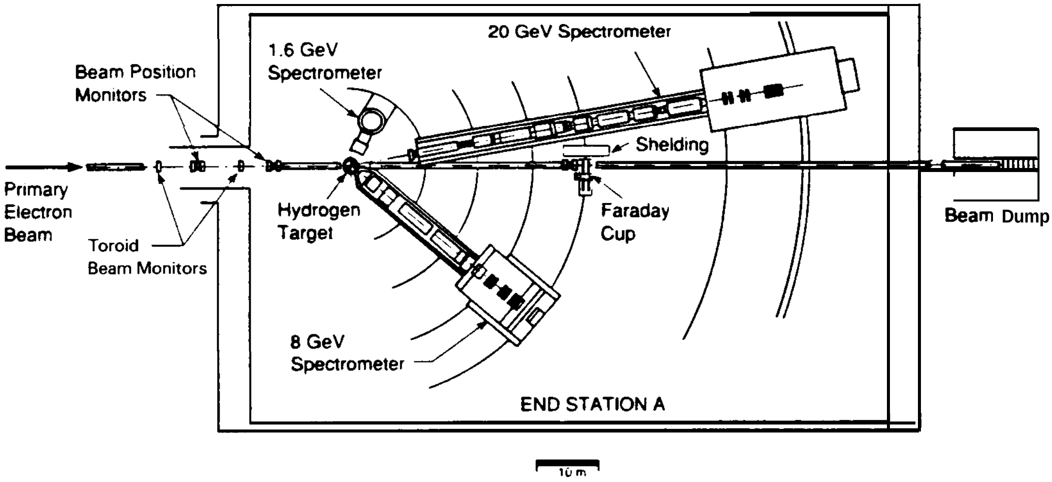


Fig. 14. Layout of spectrometers in End Station A. All three spectrometers can be rotated about the pivot. The 20 GcV spectrometer can be operated from about $1\frac{1}{2}°$ to $25°$, the 8 GeV from about $12°$ to over $90°$. The 1.6 GcV spcctrometer coverage is from ~ $50° - 150°$.

such a system which would bend downward, but it looked very awkward from a mechanical viewpoint. An ingenious solution was proposed by Panofsky and Coward, in which horizontal bending could be used while preserving orthogonal momentum and angle measurements at the focus. This proposal seemed complicated to me, and I resisted adopting the design. Finally, I was rescued by K. Brown's calculation of aberrations in this device, which he found to be unacceptably large. Shortly thereafter, Brown and Richter proposed a relatively simple spectrometer with a central crossover which allowed vertical bending, but kept the vertical height within bounds. A simple system of sextupoles was required to correct aberrations in the system. Once proposed, this design was accepted by all, and final layout of the spectrometers in the end station was soon accomplished (Fig. 14).

The two large groups at SLAC were not very interested in measurements in the backward direction at the time, but D. Ritson of the Stanford Physics Department saw an opportunity to continue his HEPL program of photoproduction measurements at higher energies, and proposed the construction of a 1.5 GeV, 90° spectrometer at large angles, a proposal which was accepted by the laboratory after a short delay, and the spectrometer was added to the facility.

With the magnetic design of the two large spectrometers fixed, design and construction of the facility began in earnest. The building of the facility was a joint effort of the SLAC-MIT-CIT group, the SLAC photoproduction group under B. Richter and the Stanford group interested in the 1.6 GeV spectrometer led by D. Ritson. The facility consisted of several parts.

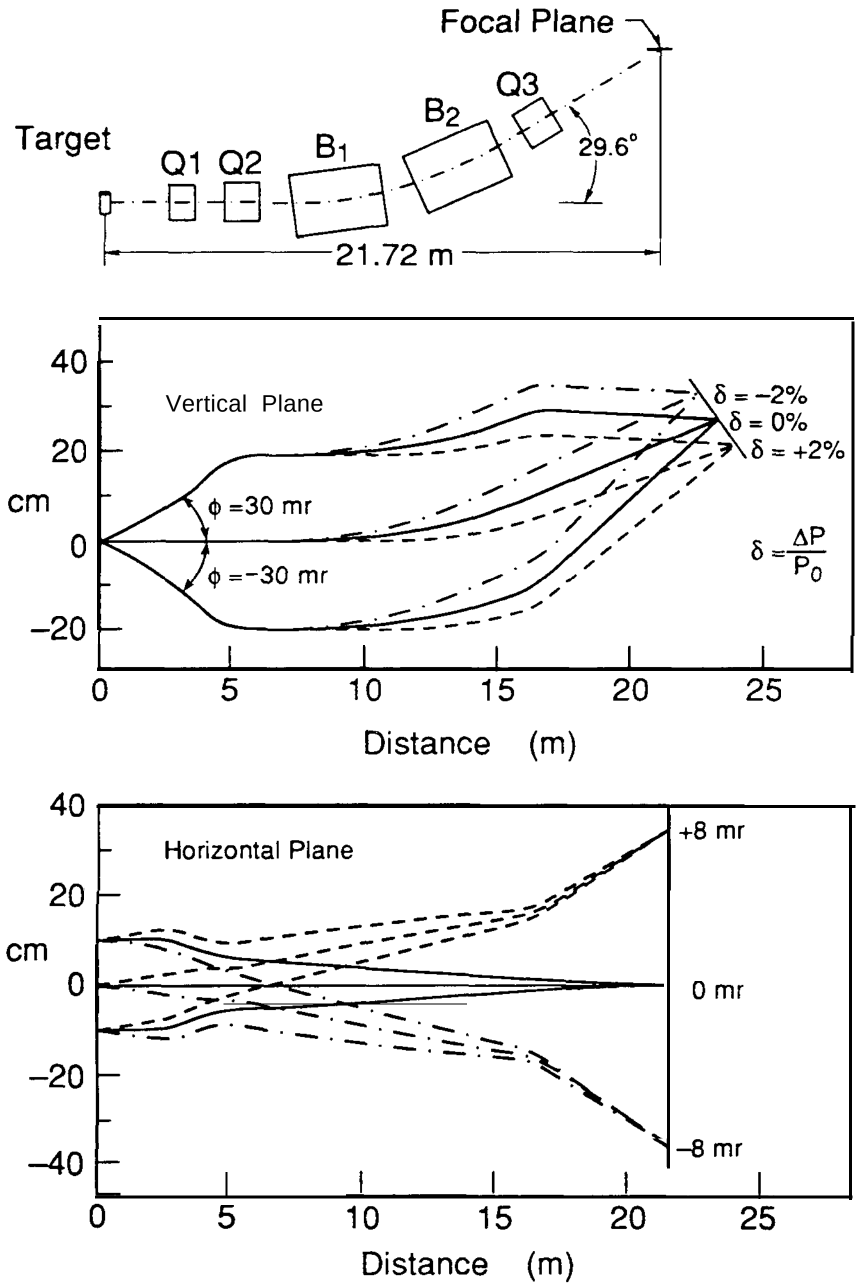


Fig. *15*. The magnet layout and optics of the 8 GeV spectrometer. The arrangement of magnet is shown at the top of the figure. In the vertical plane the focusing is "point to point" anc momenta arc dispersed along the focal plane. In the horizontal, the focusing is parallel to point and angles arc dispersed along the θ focal plane. (mr = milli-radian)

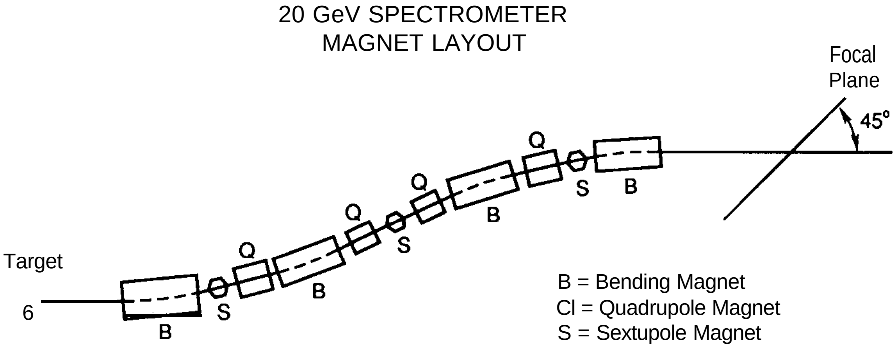


Fig. 16. Magnetic system for the 20 GeV spectrometer. With a momentum focus at the central sextupole, the final two bending magnets add to the momentum dispersion, even though the direction of bending is opposite to that in the first two bending magnets. The three sextupoles are used to adjust the angle of the focal plane to a convenient value.

The 8 GeV spectrometer used five magnetic elements-three quadrupoles and two bending magnets (Fig. 15). It had point-to-point focusing in the vertical plane (the plane in which momentum is dispersed). A detector hodoscope in the p-focal plane defined the differential momentum, Ap. In the horizontal plane (scattering plane), the spectrometer gave parallel-to-point focusing, allowing the use of a long target. A second hodoscope in the θ-focal plane determined the scattering angle. The *p*- and θ-focal planes were located close to each other, but were not coincident.

The 20 GeV spectrometer used eleven magnetic elements - four bending magnets, four quadrupoles, and three sextupoles - to produce very similar conditions at the *p*- and θ-focal planes (Fig. 16). An added feature was the extra p-focus in the middle of the magnetic system. A slit at this point could be used to control the A p/p band-pass of the instrument. A system of counters similar to those in the 8 GeV spectrometer was mounted in the shielding hut.

The 1.6 GeV spectrometer had only a single magnetic element (Fig. 17). Focusing was achieved by rotation of the pole tips out of the normal to the central orbit. Some sextupole fields were built into the pole faces to control aberrations.

The liquid hydrogen targets for the facility were of the condensation type. In these devices a separate target cell was in thermal contact with a reservoir of liquid hydrogen at atmospheric pressure. Gaseous hydrogen (or deuterium) introduced into the target cell at greater than atmospheric pressure would condense to the liquid phase.

The first target built for the facility was very simple in concept and used convection in the target cell to transfer the heat generated by the passage of the beam to the reservoir. It turned out that this mechanism was not effective at high beam power levels, and that, as a result, intense beams caused fluctuations in the liquid density. Targets were then built that used

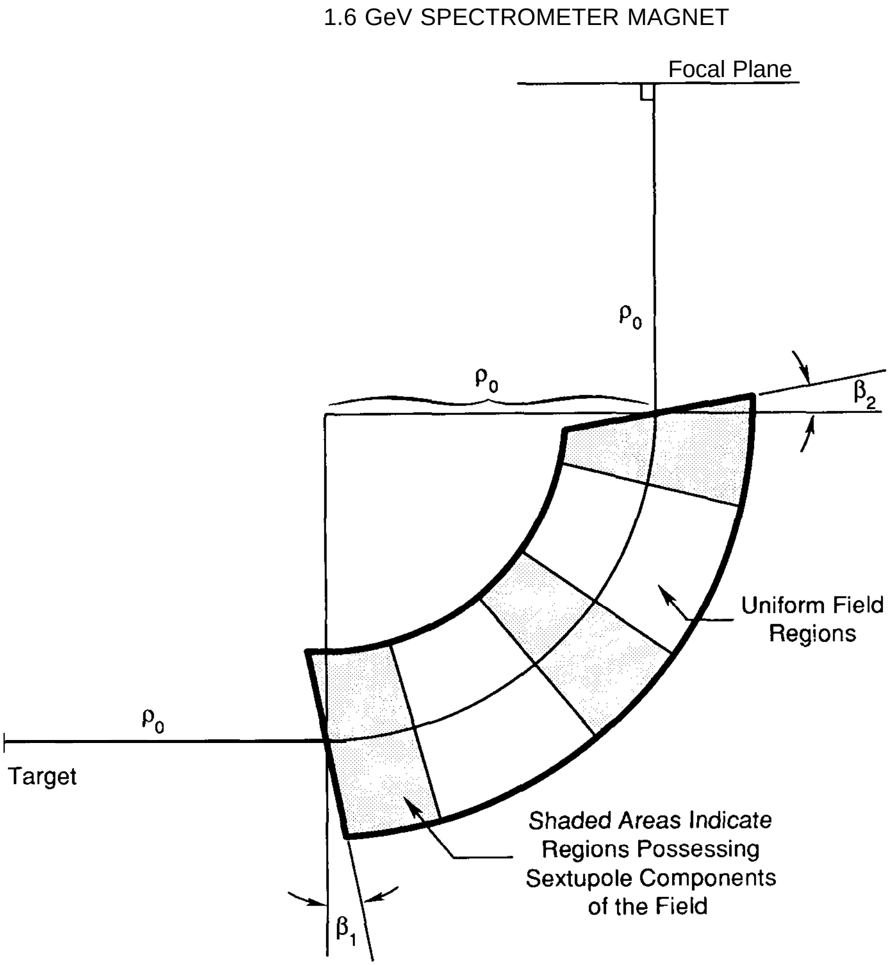


Fig. 17. Schematic of the 1.6 GeV spectrometer. Focusing is achieved by rotated pole tips (angles β_1, and β_2). and sextupoles are built into the pole faces to adjust the focal plane to be at right angles to the central ray.

forced circulation by a fan to keep the liquid in the target cell in closer thermal contact with the reservoir. Schematics of both targets are shown in Fig. 18. (Even the circulating targets had some problems at very high beam currents.)

The accuracy to which cross sections can be measured is directly related to the accuracy with which the incident beam intensity can be measured. The primary standard for the early experiments was a Faraday cup (Fig. 19a) in which 20 GeV electrons were stopped, and the resulting charge measured with an accurate current integrator. The Faraday cup could not be used with the full beam power of the linac because of thermal limitations, but it was used to calibrate other monitors at low repetition rates.

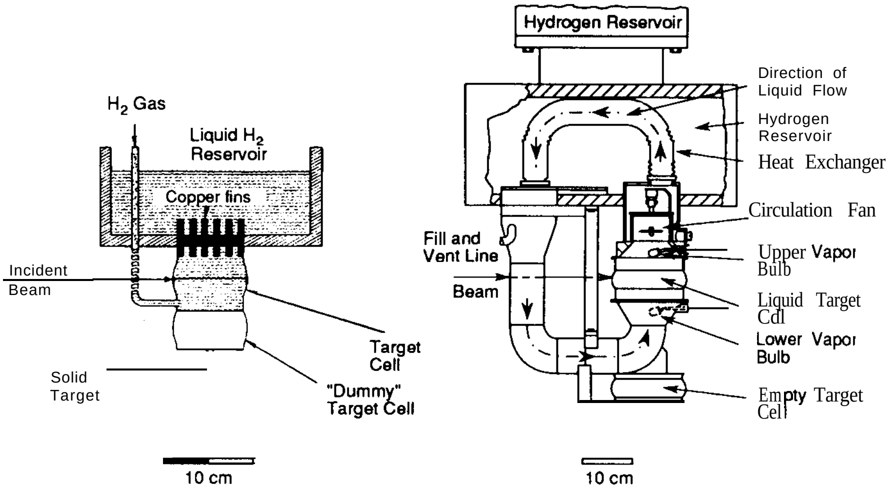


Fig. 18. a) Schematic of the first condensation hydrogen target built for the End Station A facility. The target could be displaced vertically to put either the dummy target or the solid targets on the beamline.

b) Schematic of a condensation target with forced circulation of the condensed hydrogen. As in (a) the target could be displaced vertically so that other targets could be placed in the beam line.

A new toroid monitor was specifically developed for the End Station A experiments. The principle of operation is illustrated in Fig. 19b. The beam acted as the primary winding of a toroidal transformer. Passage of a beam pulse through the toroid set up an oscillation, and the amplitude of that oscillation was sampled after a certain fixed interval. The sampling and subsequent readout of the signal determined the final accuracy of the monitor. The readout was carefully engineered by the SLAC electronics group, and as experience with this device increased, it became the absolute standard for beam current measurements, though often cross checked against the Faraday cup.

In addition to the beam monitors, there were various collimators and screens along the beam line, and a high-power beam dump buried in a hill a hundred meters or so behind the end station. An impressive cable plant connected the spectrometer detectors to the electronics in the “counting house” high above the end station floor.

I wish I had the skills to recreate for you the three years of intense activity that went into translating the paper plans of 1964 into the instruments which began to do physics in early 1967. The problems in procuring the precision magnets, the construction of the giant frames to hold the magnets and to support the massive shields for the detectors, the laying of the rails to extraordinary tolerances -all these and many other problems were attacked with drive and dedication by the mechanical engineering group. Even the professional crews hired to install large parts of the apparatus became

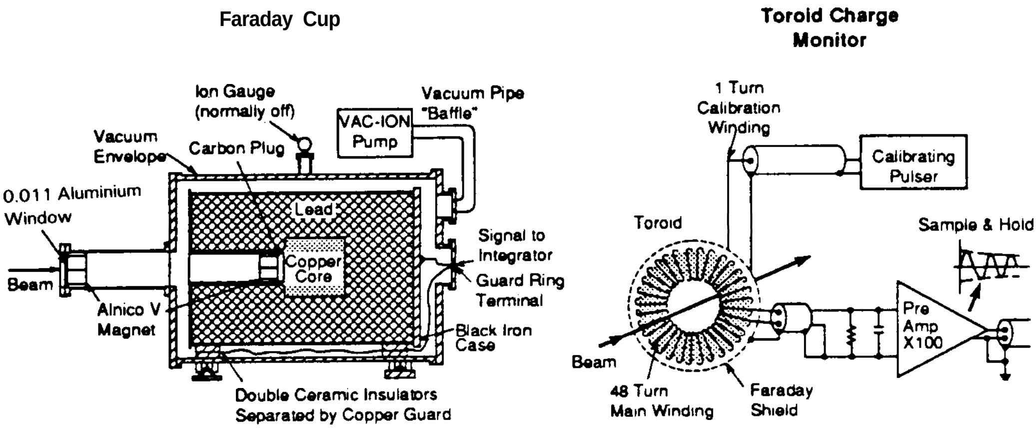


Fig. 19. a) Drawing of the Faraday cup. The beam was stopped in the carbon-copper core of the cup, and the lead absorbed y-rays created in the shower. The Alnico magnets deflected low energy electrons coming from the window so that they did not reach the cup, and those from the core did not escape from it.

b) Schematic of the toroidal transformer monitor. The beam acted as the primary winding of the ferrite core. A beam pulse caused a "ringing" of a damped LC circuit, the amplitude of which was read out after three quarters of a cycle.

infected with the enthusiasm of the engineers. I lived in mortal fear that a union steward would drop in unannounced and find a millwright (steel worker) building a wooden scaffold, while a carpenter was operating the crane. Figure 20 is a view of the experimental area with the completed 8 and 20 GeV spectrometers in place.

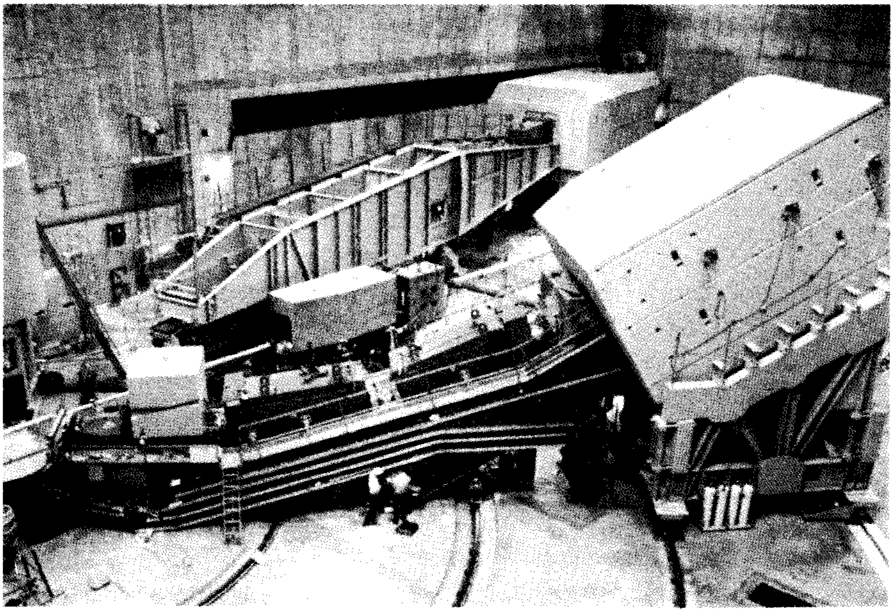


Fig. 20. Photograph of the 8 and 20 GeV spectrometers in End Station A.

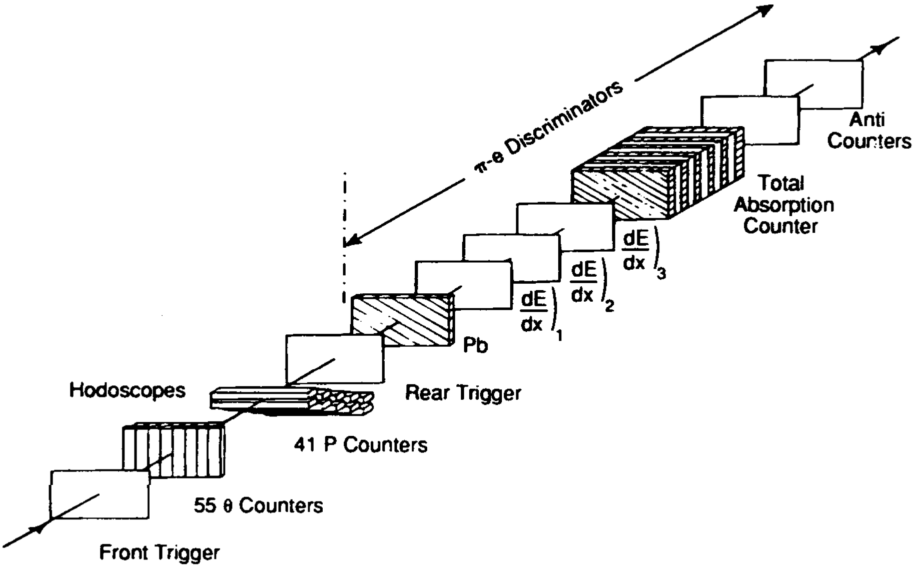


Fig. 21. Schematic drawing of the counter system inside the 8 GeV shielding hut.

The 8 GeV detectors were designed and built at MIT (Fig. 21). Two large scintillation counters acted as trigger counters, signalling the passage of charged particles through the counter system. Two multi-element scintillation counter hodoscopes (mounted between the trigger counters) defined the position of the track in the horizontal (θ) and vertical *(p)* directions. The hodoscopes each consisted of two layers of overlapping counters, so that each double hit defined the position to half a counter width. The location of the hits together with the angle and energy setting of the spectrometer defined the angle of scattering to ± 0.15 milli-radians and the momentum of the scattered particle to ± 0.05 %. Following the system of hodoscopes was a set of counters used to distinguish electrons from pions. The principal element was a total absorption lead-lucite shower counter. The pulse height threshold was set to be more than 99% efficient for electrons. In the elastic scattering experiments this counter alone was enough to ensure a pure electron signal, but for inelastic scattering, pion backgrounds increased and the use of the dE/dx counters was sometimes necessary. These counters measured the energy loss in a scintillator for particles which had passed through one radiation length of lead. Electrons will often shower in the radiator, giving large pulse height in the counters. In most cases pions will not shower, giving an almost independent indication of their identity. By the time of the first inelastic scattering experiments using the 8 GeV spectrometer, a gas cerenkov counter had been added in front of the trigger counter as a further tool for particle discrimination. The dE/dx system was used only for the lowest secondary energies where the pion-electron ratios were large. The 20 GeV spectrometer's counter system (Fig.

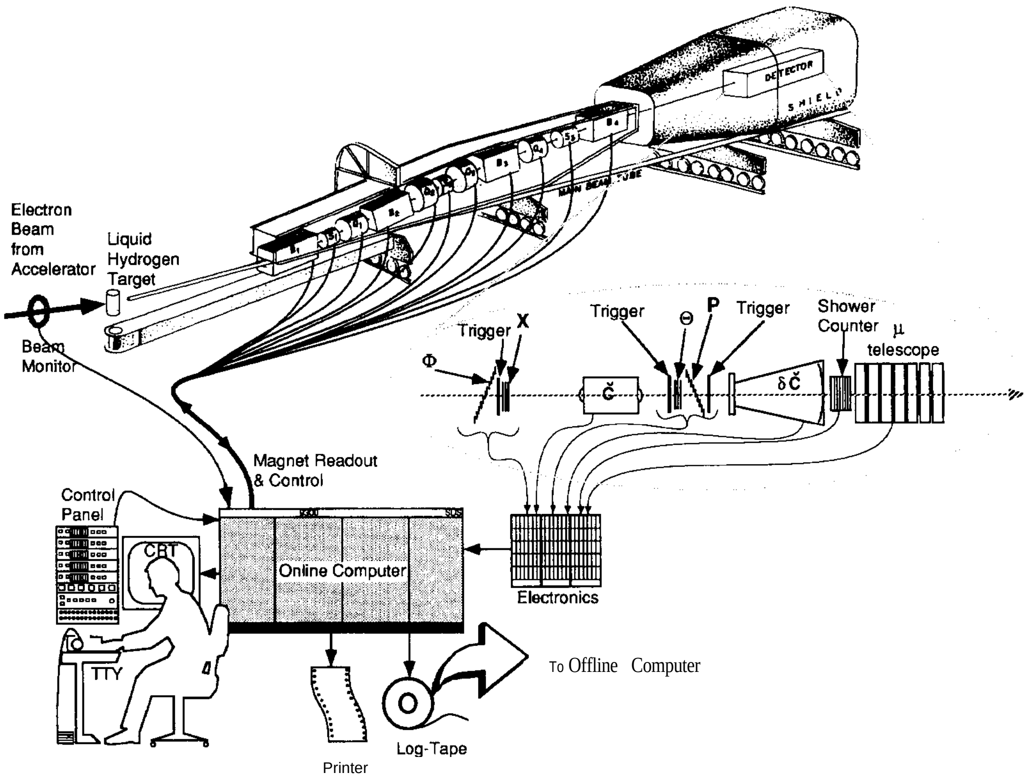


Fig. 22. Schematic of the 20 GeV spectrometer indicating the various computer control and read-out functions. Also shown is a schematic of the 20 GeV counter system. Particle identification in the spectrometer was somewhat more complex than for the 8 GeV instrument, partly because of the higher energies involved, but also because it was sometimes desirable to identify π mesons in a large electron background in the 20 GeV spectrometer.

22) was similar to that in the 8 GeV spectrometer, with the addition of a differential gas Cerenkov counter, and extra sets of hodoscopes which determined the angle of scatter outside the horizontal plane (φ hodoscope) and the position of the scattering center along the beam line (x hodoscope). The MIT group also took responsibility for much of the counting electronics, photo tube power supplies, etc., and were of great assistance to the electrical engineers in the SLAC group who installed the electronics and interfaced the on-line computer.

One innovation by the collaboration was the extensive use of on-line computation in the experiment. While not the first experiment to be equipped with an on-line computer, the degree of computer control was ambitious for the time. We purchased a fairly powerful mainframe, dedicated to only one experiment at a time. A lot of work was done on both software and hardware, so that the effort to set up and operate a given experiment was greatly reduced. The on-line analysis of a fraction of the

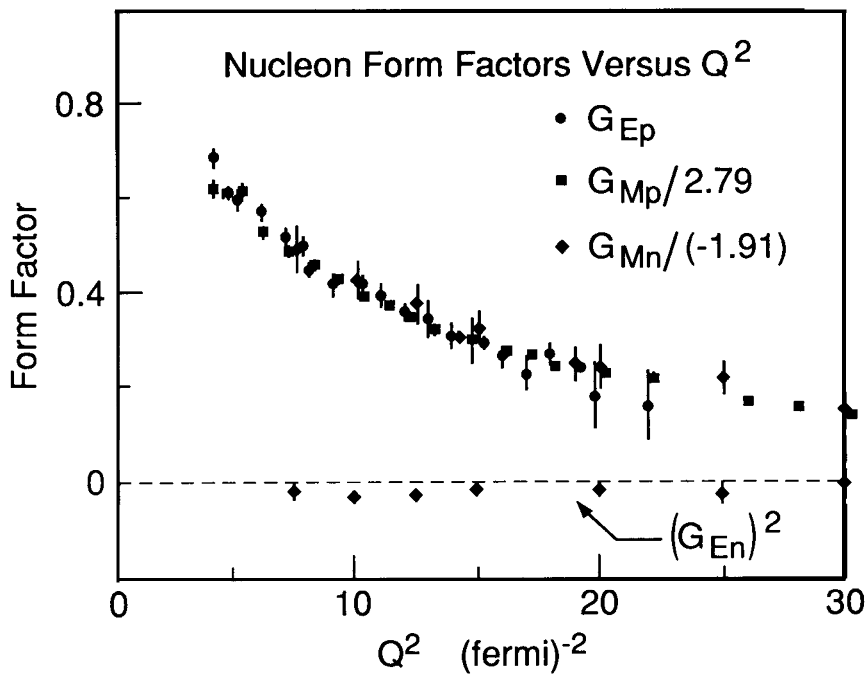


Fig. 23. Summary of results on nuclear form factors presented by the Stanford group at the 1965 "International Symposium on Electron and Photon Interactions at High Energies". (A momentum transfer of 1 GeV^2 is equivalent to 26 $Fermis^{-2}$.)

increasing data was a powerful way to check on the progress of the experiments (Fig. 22).

In the summer of 1966 there was a call for proposals to use the beam at SLAC. The accelerator was nearing completion, and some early tests of the accelerator with beam were being done with considerable success. Although the initial programs in End Station A were built into the design of the facility, it was now necessary to parcel out beam time and arrange the sequence of experiments for the first year of operation. The Cal Tech-MIT-SLAC collaboration prepared a proposal that consisted of three parts:

a. Elastic electron-proton scattering measurements (8 GeV spectrometer)

b. Inelastic electron-protron scattering measurements (20 GeV spectrometer)

c. Comparison of positron and electron scattering cross sections (8 GeV spectrometer)

It is clear from the proposal that the elastic experiment was the focus of interest at this juncture. "We expect that most members of the groups in the collaboration will be involved in the e-p elastic scattering experiment, and that the other experiments will be done by subgroups."

During the construction of SLAC and the experimental facilities a lot of progress had been made on the measurements of nucleon form factors at other laboratories. The program at HEPL had continued to produce a great

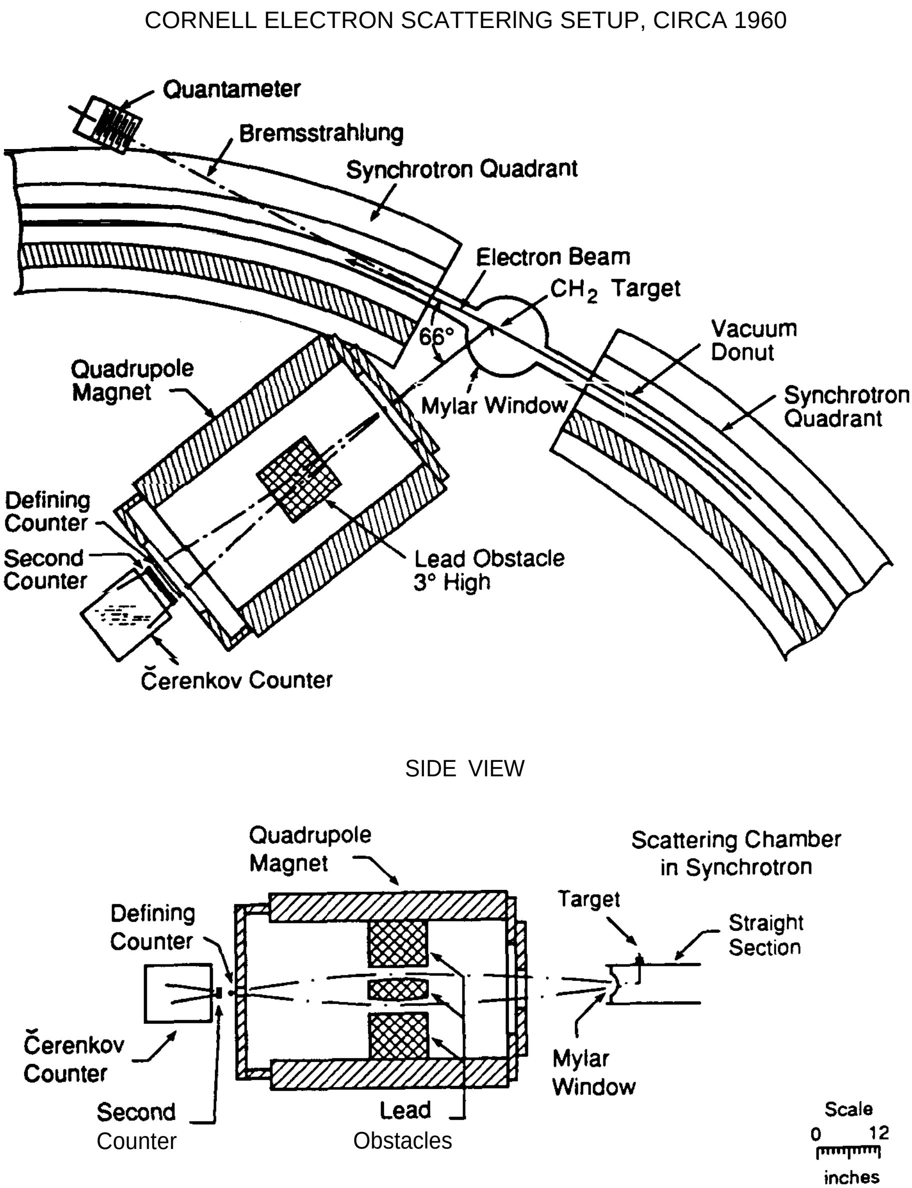


Fig. 24. Schematic of the equipment for electron scattering experiments at Cornell around 1960. These experiments used a quadrupole spectrometer to analyze electrons scattered from an internal target in the electron synchrotron. The target is mounted away from the normal orbit in the accelerator, and the beam is slowly moved onto the target after acceleration.

deal of new data using the facilities in the end station of the Mark III accelerator. A new spectrometer with a bending radius of 72 inches had been added to accommodate the increased energy available from the accelerator. Extensive results on both the proton and the deuteron were generated and reported[17] (Fig. 23).

At over 1 GeV, the Cornell electron synchrotron was the highest energy electron machine in the world for a few years in the early 1960s. Experimenters there made a series of measurements on CH_2 targets, using a quadrupole spectrometer of novel design[18] (Fig. 24) and a new type of γ ray monitor.[19] The results from Cornell started a trend toward the use of the electric and magnetic form factors([20]) (G_E and G_M), rather than one form factor for a spin 1/2 (Dirac) proton and a second for the anomalous magnetic moment of the proton.

The linear accelerator at Orsay had begun operations in 1959 and by the following year there was an active program of both nucleon and nuclear scattering. The emphasis shifted to colliding beam experiments in later years, but many scattering experiments were done in the intermediate energy stations of that accelerator with beams of up to 750 MeV.

Electrons had become a big success in high energy physics and a new high energy electron synchrotron was approved and built at Harvard. The Cambridge Electron Accelerator was built jointly by Harvard and MIT and came into operation in 1962 with a peak energy of 5 GeV. A program of electron scattering experiments using internal targets was soon in operation. The new accelerator opened up a new range of Q^2 for scattering experiments and several different experimental setups were used to measure the proton and neutron form factors. The higher Q^2 proton measurements fell very close to values expected from a straightforward extrapolation of the data at lower energies. The results[21] were summed up (somewhat later) by Richard Wilson in the words “The peach has no pit.” These results were the first evidence that the old core model of the proton was unlikely to be correct (Fig. 25).

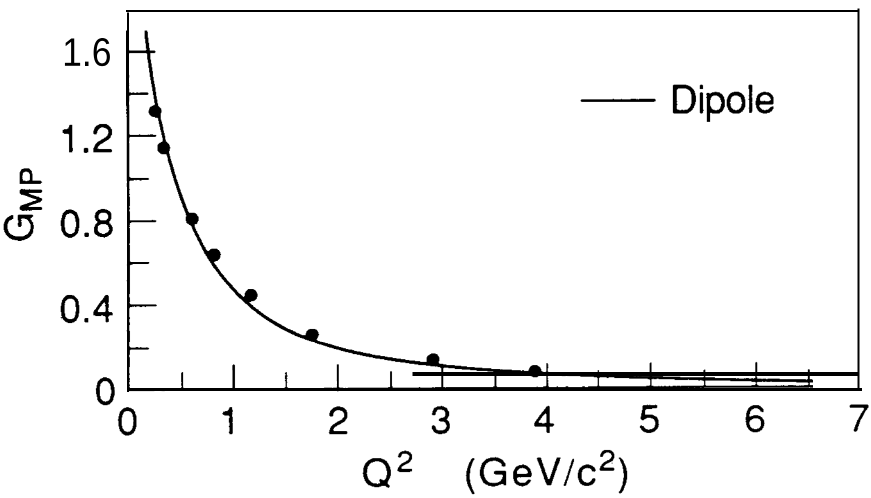


Fig. 25. G_M, for the proton from data taken at CEA. The curve labelled “dipole” is a tit which originated in the late 1950’s when the maximum measured Q^2 was limited to less than 1 GeV^2. It has the form $G_M = \mu_p/(1 + Q^2/.71\,GeV^2)^2$ and is in qualitative agreement with the CEA data at higher Q^2, though the fit is not very good in the statistical sense.

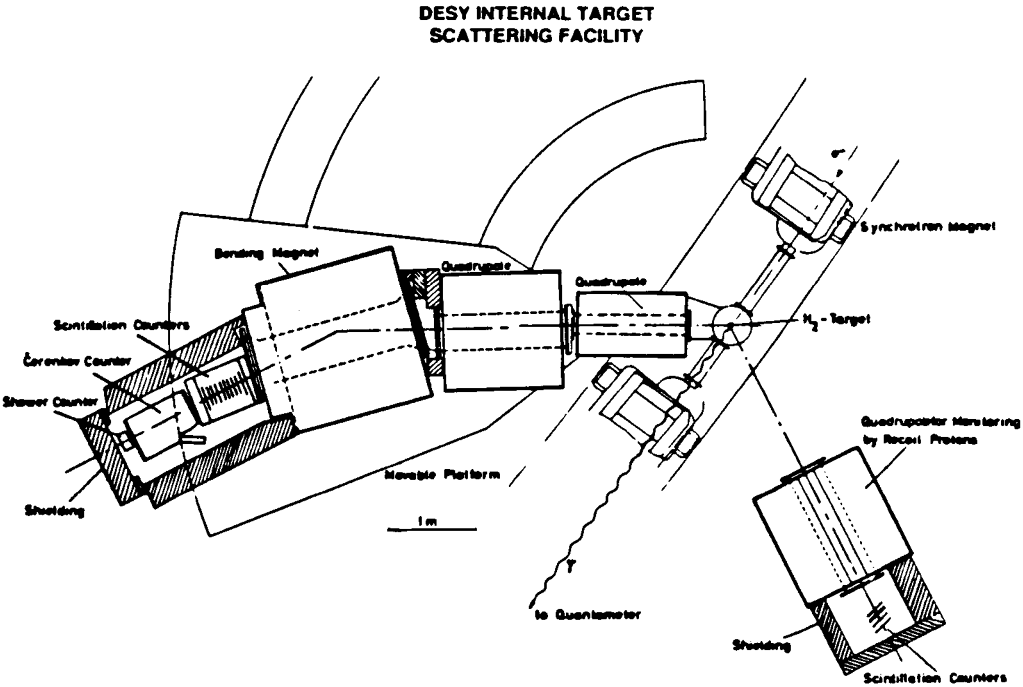


Fig. 26. Layout of the spectrometer setup for internal target electron scattering experiments at DESY. Later on, the same set-up was used to detect electron-proton coincidences in elastic scattering (in order to reduce backgrounds).

A slightly larger synchrotron was built in Hamburg, Germany at about the same time. DESY came into operation in 1964 with a peak energy of 6 GeV. An extensive series of nucleon scattering measurements, using both internal targets(22) (Fig. 26) and external beams(23) (Fig. 27), was undertaken.

With both CEA and DESY operating, the amount of elastic scattering data at high Q^2 (which essentially measures G_M) increased rapidly in both quantity and accuracy. The data continued to follow the so-called dipole model to a good approximation. By the Hamburg conference in 1965 there were no dissenters from the view that

$$G_{Ep} = \frac{G_{Mp}}{\mu_p} = \frac{G_{Mn}}{\mu_n},$$

$$G_{En} \cong 0 \text{ at large } Q^2,$$

and

$$G_{Ep}(Q^2) \cong \left(\frac{1}{1 + \frac{Q^2}{0.71\ \text{GeV}^2}} \right)^2 \text{ up to } Q^2 \sim 10\ \text{GeV}^2$$

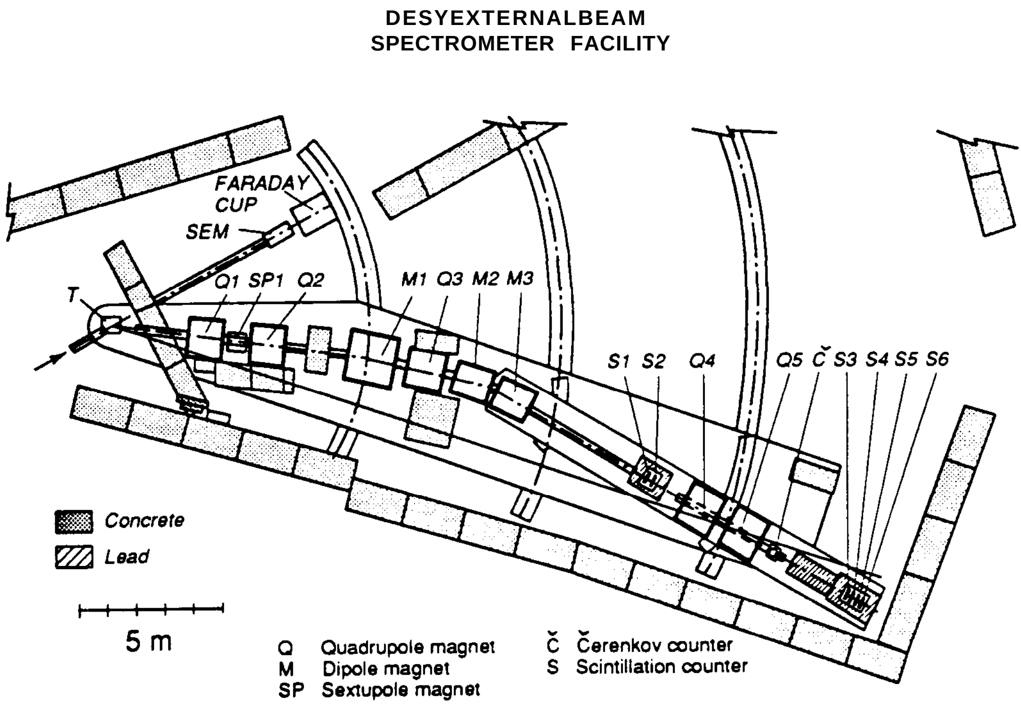


Fig. 27. Setup for external beam scattering experiments at DESY. The spectrometer was articulated between the magnets M_2 and M_3. By varying the bending in M_2 and M_3, lines of constant "missing mass" could be adjusted to a given slope at S_1 for different scattered energies.

SLAC was expected to test this formulation in the new range of Q^2 (Fig. 28) made available with 20 GeV electrons. Questions of interest concerned the evidence for a nucleon core and the validity of the dipole description of the form factor in the extended range of Q^2 available at the new accelerator. The cherished picture of a "real proton" surrounded by a meson cloud was already in pretty serious trouble, but more tests for a small core were outlined in the SLAC proposal. Other questions were related to particular models of behavior for the form factors which are not of great interest today.

Our SLAC proposal demanded certain specifications for the beams to be used in the experiment, which were within the design specifications of SLAC, but which were nonetheless very difficult to meet, given the fact that the accelerator was just being commissioned. Operating the accelerator for the initial scattering experiments was a challenging experience for the crew of accelerator operators, and many of them have indelible memories of those times.

The proposed experiment on elastic scattering aimed at measurements of the cross section at momentum transfers of 16 GeV^2 and beyond, even in the very first round of experimentation. There was an extensive discussion in the proposal about running at angles and energies in a manner which

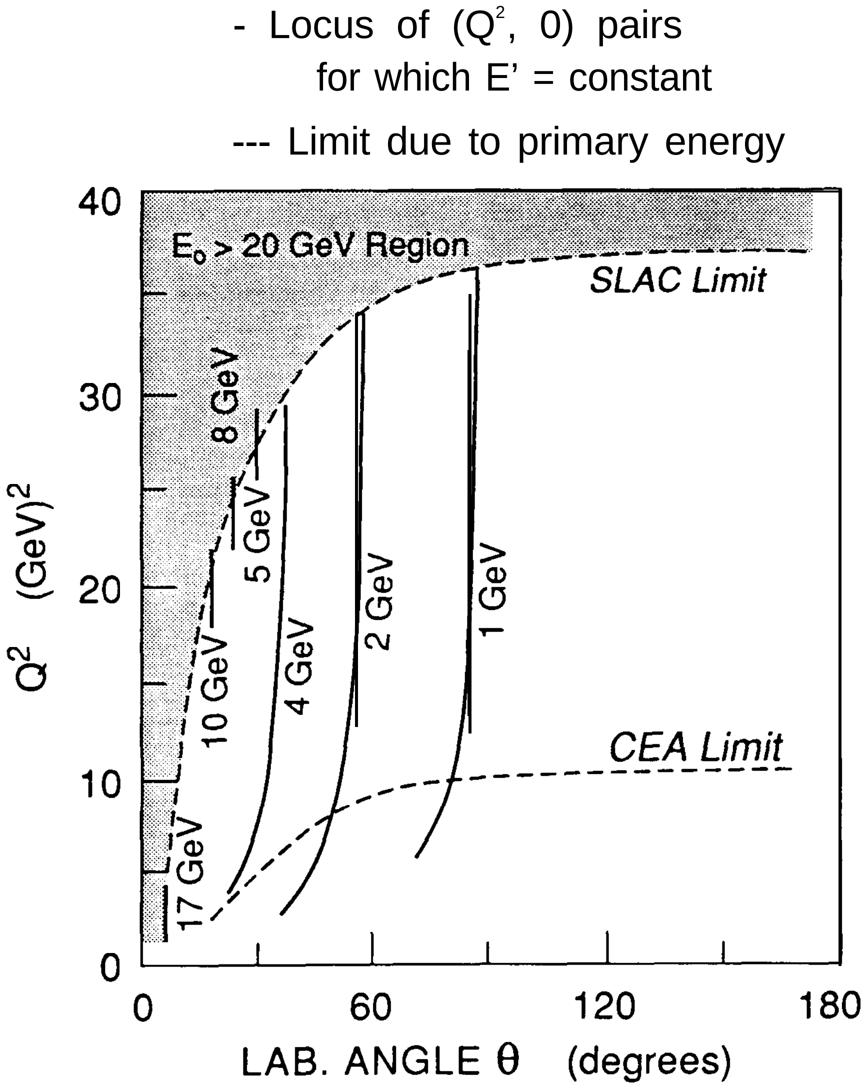


Fig. 28. Plot of elastic kinematics showing the extra kinematic region made available at SLAC for spectrometers of different maximum energies (above 4 GeV, only the maximum Q^2 is indicated to avoid confusion on the graph).

would result in an efficient separation of G_E. and G_M. Possible backgrounds were considered, and it was expected that they would be negligible. Radiative corrections to elastic scattering were expected to reach up to 30% for our apparatus and incoming energies of 20 GeV. These corrections arose from two related but physically distinct processes:

1. Electrons passing through the target and the target windows might emit radiation as a result of interactions with individual atoms (real bremsstrahlung) and thereby suffer an energy loss.

2. Scattered electrons might emit radiation in the scattering process itself ("wide-angle bremsstrahlung"). The effects of wide-angle bremsstrahlung were first discussed by Schwingerer[24] in 1949 and have been the subject of increasingly sophisticated calculations over the years.

In some cases the energy of the emitted radiation (in either reaction) was sufficient to affect the kinematics of the scattering to such an extent that the measuring apparatus would no longer "recognize" the interaction. For example, if sufficient (radiative) energy were lost in an elastic scatter, the energy of the scattered electron might fall below the range that the apparatus defined as the "elastic peak."

The emission of radiation gives rise to the characteristic "radiative tail" in the energy spectrum of elastically scattered electrons as shown schematically in Figure 29. The cross section measured by detecting the electrons in a certain energy range will be smaller than expected because some particles will be lost. It is customary to correct experimental cross sections for these losses-removing the dependence of the final cross section on the energy resolution of the apparatus.

A simple (first order) correction formula illustrates how such a correction might be applied.

$$\left.\frac{d\sigma}{d\Omega}\right|_{exp.} = (1 - \delta_s)\, e^{-\delta_r}\frac{d\sigma}{d\Omega}$$

where the wide-angle bremsstrahlung correction δ_s is

$$\delta_s = \frac{2a}{\pi}\left\{\left(1 - ln\,\frac{Q^2}{m_e^2}\right) ln\,\frac{\Delta E}{E}\right\}$$

m_e = mass of electron.
ΔE = energy resolution or acceptance
E = incident energy (assumes $E_s \sim E$)

and the real bremsstrahlung correction δ_r is

$$\delta_r = -\;\frac{t}{ln 2}\, ln\,\frac{\Delta E}{E}$$

t = thickness of target in radiation lengths

As long as the corrections can be calculated to sufficient accuracy, they are innocuous in elastic scattering, and determination of elastic form factors is straightforward.

Our proposal included a possible run plan for measuring G_E and G_M to values of Q^2 exceeding 15 GeV^2. (At the higher Q^2 one finds an upper bound on G_E, rather than a measure of its value.) The program was expected to take about 350 hours of beam time, and a first run of 200 hours was suggested, after which the requests would be updated using measured quantities, rather than estimates. This experiment was to be the first carried out with the new facility.

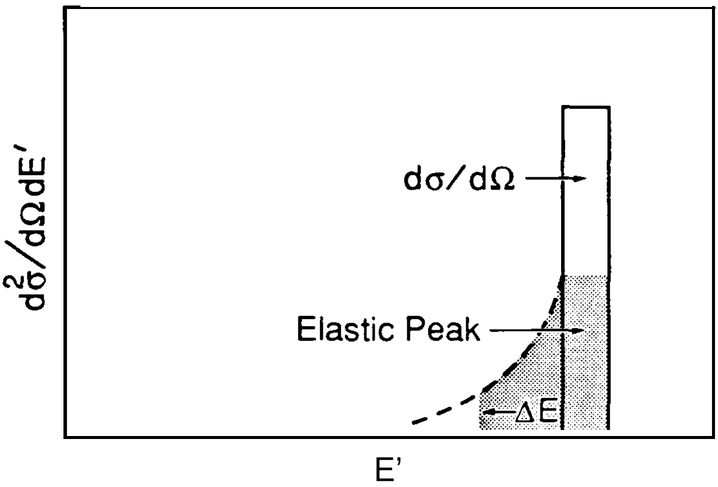


Fig. 29. Radiative effects in elastic scattering. In the absence of radiative effects, all elastic scatters would be found in the box labelled $d\sigma/d\Omega$ (the width of which depends on resolution in the incoming beam and the detection apparatus). Radiative processes result in energy losses for some scattered electrons, and so some electrons will be found in a "tail" on the low energy side of the peak. A measurement of the electrons in the shaded region results in a cross section which is somewhat smaller than $d\sigma/d\Omega$. This smaller $(d\sigma/d\Omega)_{meas}$ can be corrected for radiative losses to determine $d\sigma/d\Omega$.

The second part of the proposal concerned the measurement of inelastic scattering from the proton. Inelastic scattering from the nucleon had a much shorter history than elastic scattering so there was much less guidance for the design of that part of our proposal.

Inelastic scattering from *nuclei* was a common feature of the early scattering data at HEPL. The excitation of nuclear levels and the quasi-elastic scattering from the constituent protons and neutrons of a nucleus were observed in the earliest experiments. The excitation of nuclear levels in carbon could be seen in the data of Fig. 4, for example. Quasi-elastic scattering became more evident as momentum transfer was increased. Fig. 30 shows scattering from the same target as in Fig. 4, and at approximately the same incident energy, but at a scattering angle of 135°. A comparison of the two figures illustrates the growth in the fraction of quasi-elastic scattering as the angle (and therefore the momentum transfer) is increased. When the electrons scatter through 135°, the elastic peak is very small and the pattern of level excitation has changed because the different multipole transitions have different angular dependences. The most prominent feature of the spectrum is the broad quasi-elastic peak in Fig. 30 due to scattering from individual protons and neutrons. The width of the peak reflects the Fermi momentum of the nucleons in the nucleus.

The earliest experiments on the inelastic scattering of electrons from the proton itself were carried out by Panofsky and co-workers at HEPL in the second half of the 1950's.[25,26,27] The early experiments were comparisons

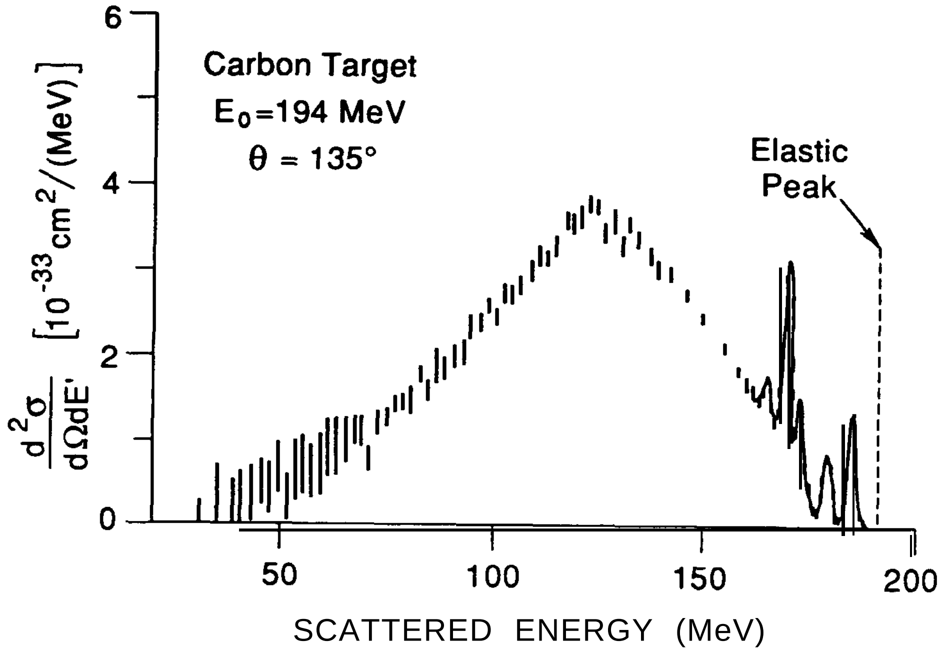


Fig. 30. Spectrum of electrons scattered inelastically from carbon. The excitation of nuclear levels is evident. The large, broad peak between 100 and 150 MeV is due to quasi-elastic scattering from the individual neutrons and protons that make up the carbon nucleus.

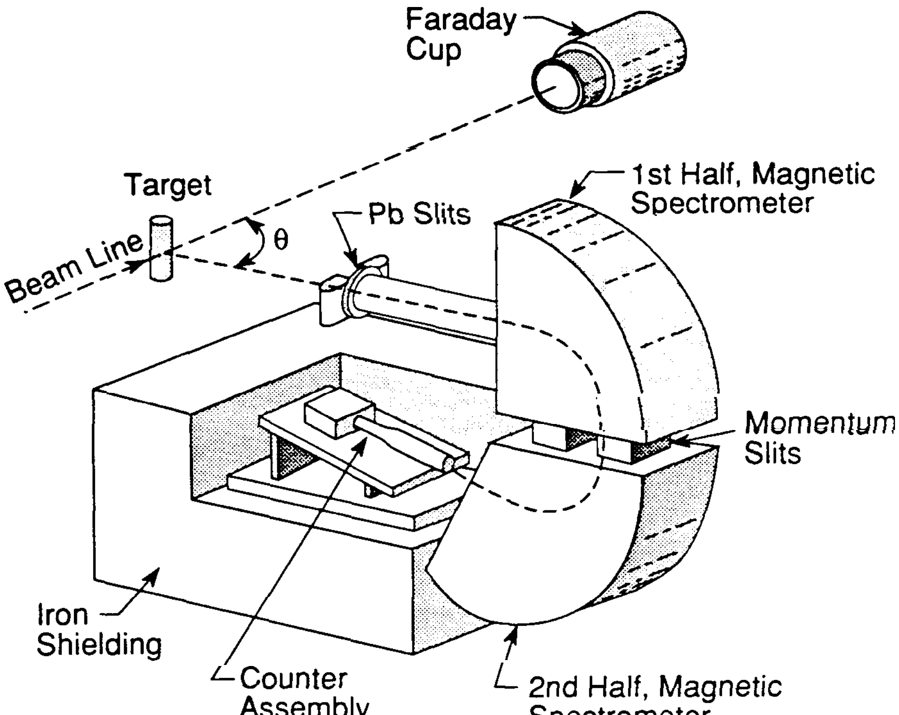


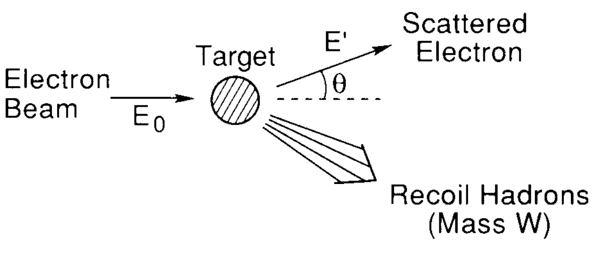
Fig. 31. The zero dispersion magnetic spectrometer used in inelastic experiments at HEPL. Splitting the magnet allowed the insertion of momentum defining slits in the middle of the bend.

of photo- and electroproduction of positive pions in lithium and (later) hydrogen targets. Those experiments checked the calculation of the electromagnetic fields that accompany a relativistic electron, but added little to the knowledge of meson dynamics beyond that which was known from photoproduction (because the dominant contribution to the electroproduction came from virtual photons with very small values of Q). The authors pointed out that observing the scattered *electrons* at a large angle (rather than the pions) might lead to more interesting results, and the next experiment was of that kind.

A new magnetic spectrometer was commissioned at HEPL at about this time[28], and was used for these experiments (Fig. 31). Panofsky and Allton[29] made measurements of the inelastic scattering of electrons from hydrogen in the region near the threshold for pion production. The energy of the available electrons was not high enough to reach much beyond the threshold for pion production, but the experiment established that the "tail" of the elastic peak was due to the two (calculable) radiative processes mentioned above. One process was elastic scattering preceded (or followed) by emission of bremsstrahlung in the material of the target; the other was "wide-angle bremsstrahlung" - the emission of a photon in the scattering interaction. The experiment was a quantitative test of calculations of the radiative tail of the elastic peak in the region near pion threshold.

The peak energy of the electrons from the Mark III accelerator was improving steadily during those years, and in 1959 Ohlsen[30] used the 36-inch spectrometer in the Hofstadter group's scattering facility (Fig. 6) to do an experiment similar to the Panofsky-Allton measurement. With increased energy, it was possible to make measurements covering the region of the first $\pi - p$ resonance, and a clear peak was observed at the resonance energy. The experimenters were also able to measure a rough Q^2 dependence of the peak cross section.

In 1962, Hand reported on a similar experiment (using the same spectrometer used by Allton) and the results were discussed in modern notation. In particular, there appears an inelastic equivalent of the Rosenbluth formula containing two form factors which are functions of Q^2 and ν, the energy loss suffered by the scattered electron. The measured quantities are E_0, E', and θ:



The kinematics of the scattering are described by

$$E' = \frac{E_0 - \frac{(W^2 - M^2)}{2M}}{1 + \frac{2E_0}{M}\sin^2\theta/2}$$

W is the mass of the final state of the struck hadron (when $W^2 = M^2$, the elastic kinematics are recovered). The square of the momentum transfer, Q^2

$$Q^2 = 4E_0E' \sin^2\theta/2$$

the energy loss

$$\nu = E_0 - E'$$

and W^2 are relativistically invariant quantities in the scattering process.

There are two equivalent formulations describing the cross sections which are in current use, one due to Drell and Walecka(31) which is very similar in form to the Rosenbluth expression

$$\frac{d\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E_0^2 \sin^2\theta/2} \cos^2\theta/2\,[W_2 + 2W_1 \tan^2\theta/2]$$

The structure functions W_1 and W_2 are functions of both the momentum transfer and energy loss, $W_{1,2}(Q^2,\nu)$. This is the most general form of the cross section in the (parity conserving) one photon approximation.

Hand'“” popularized a different but equivalent form for the cross section in which one of the form factors reduces to the photoproduction cross section at $Q^2 = 0$

$$\frac{d\sigma}{d\Omega dE'} = \frac{\alpha^2}{4\pi^2} \cdot \frac{(W^2 - M^2)\,E'}{MQ^2E_0\,(1-\varepsilon)} \left(\sigma_T + \varepsilon\sigma_L\right)$$

where

$$\varepsilon = \frac{1}{[1 + 2\tan^2\theta/2\,(1 + \nu^2/Q^2)]}$$

Again σ_T and σ_L (corresponding to the photo-cross sections for transversely polarized and longitudinally polarized virtual photons respectively) are functions of the momentum transfer and energy loss of the scattered electron, $Q_{L,T}(Q^2, \nu)$, with the limiting values at $Q^2 = 0$ of

$$\sigma_T(0) = \sigma\gamma_p$$
$$\sigma_L(0) = 0$$

These early experiments and the associated theoretical studies developed much of the framework for thinking about inelastic experiments at SLAC. The energy available limited the early experiments on the proton to studies of the π-p resonance near 1238 MeV.

An important influence came from the Laboratoire de l'Accelerateur

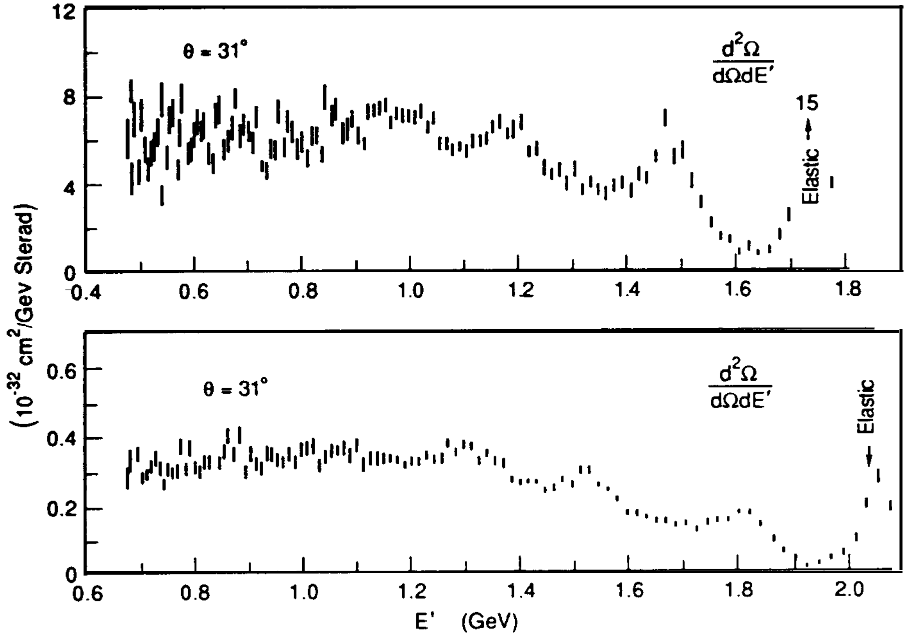


Fig. 32. Inelastic spectra from CEA at 3lo for initial energies of 2.4 GeV and 3.0 GeV. Three bumps are clearly evident corresponding to resonance excitations of the proton.

Lineaire in Orsay, where experiments on inelastic electron scattering from nuclei led to the study of radiative processes, and to the determination of radiatively corrected cross sections from inelastic scattering data.

The focus of our thinking about inelastic experiments during the construction period centered on the excitation of resonances and the Q^2 dependences of the "transition form factors" (the nucleon makes a transition from the ground state to the resonant state). We hoped to learn more about each of the observable resonances, and also expected to see new resonances that had not been electroproduced before and even some that had never been observed before in any reaction. Just before the proposal was submitted, data from the CEA was published showing clear evidence of three resonant states excited by inelastic electron scattering. The group at CEA used a quadrupole spectrometer to obtain spectra like those in Figure 32. The background of radiative events is substantial. Very interesting spectra from DESY,([34]) showing large non-resonant contributions to the inelastic cross section, would come later, at about the time that the first (inelastic) experiments were starting up at SLAC.

Our proposal was approved in 1966, along with proposals from other groups. The running time for the various parts of our proposal was interleaved with other runs to study photoproduction with the spectrometer facility (and with experiments on a streamer chamber which occupied a building behind End Station A and which used the same beam line).

By January of 1967, the 8 GeV spectrometer was nearly complete and we were beginning preparations for the initial elastic scattering experiment.

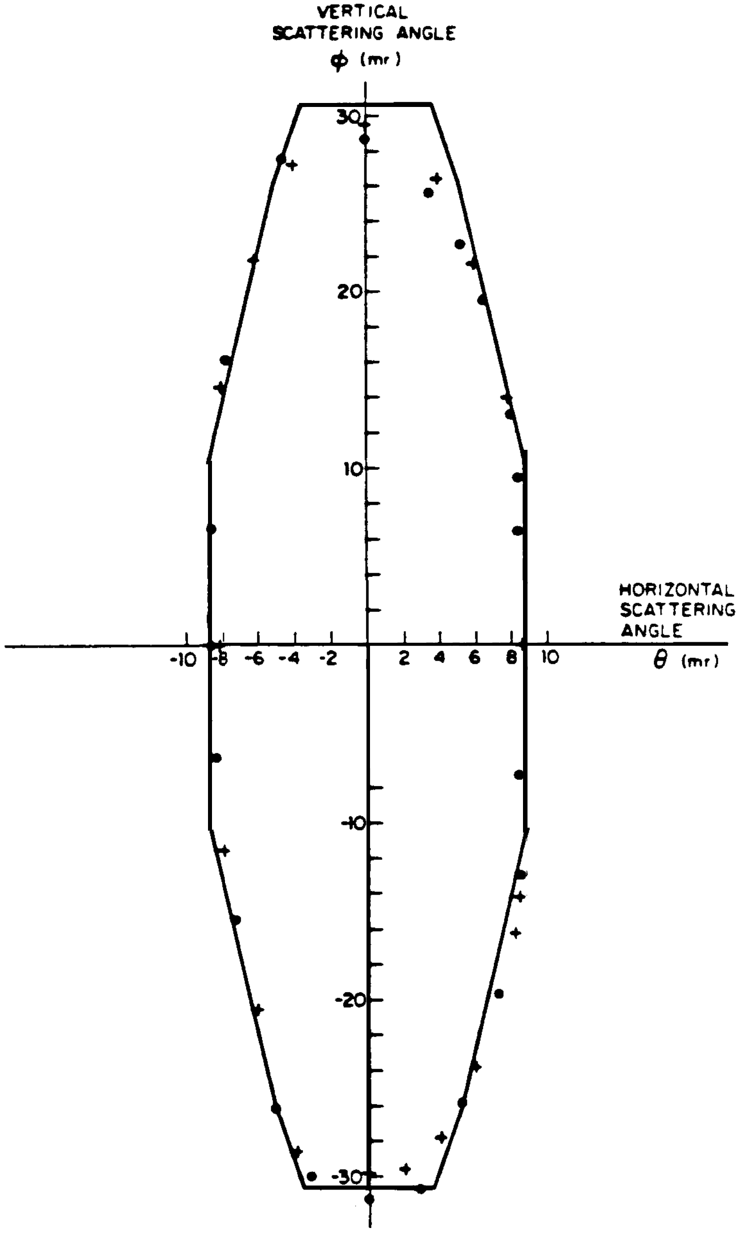


Fig. 33. Angular acceptance of the 8 GeV spectrometer for electrons from the center of the target and with the spectrometer set so that the incoming beam followed the central axis. The points are for two different beam energies (● = 8 GeV , + = 6 GeV). The solid line is the aperture from computer calculations.

The solid angle of the spectrometers entered directly into the calculation of the cross section, and we wanted to check the calculations of the 8 GeV aperture. A special run with beam was planned to study the optics of the spectrometer and the acceptance. The spectrometer was placed at 0° so that the beam entered the spectrometer along the central orbit. The beam energy was adjusted to the setting of the spectrometer and the beam was observed with scintillation screens mounted at the focal planes. Magnets located at the target position steered the beam, tracing out orbits and verifying the optical properties of the spectrometer's magnetic fields. By determining the limiting orbits in the spectrometer the solid angle could be measured. Fig. 33 shows the results for the central momentum case. The agreement with the predictions was quite good, but there were some slight discrepancies with the calculated aperture limits for the extreme rays. After the initial run, lead masks were introduced into the spectrometer to better define the aperture.

Following the optics tests, the counters and shielding were installed along with the hydrogen target and the beam current monitors. By the month of May the first runs of the elastic scattering proposal were underway. The accelerator was operating rather well by this time, though still struggling to meet all of the design specifications.

It is an exciting moment when a new experimental facility is put into operation at a new accelerator, especially when the new accelerator opens up extended new regions of energy for exploration. We were about to use

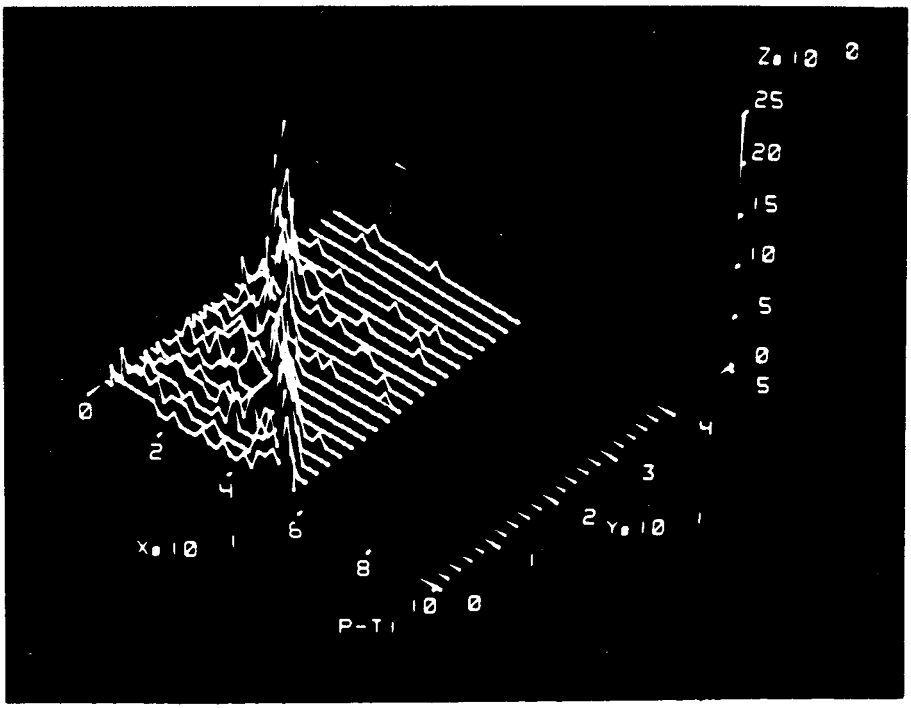


Fig. 34. Computer display of the focal plane location of particles passing through the elements of the p and theta hodoscopes of the 8 GeV spectrometer. The line corresponding to elastic scattering is evident.

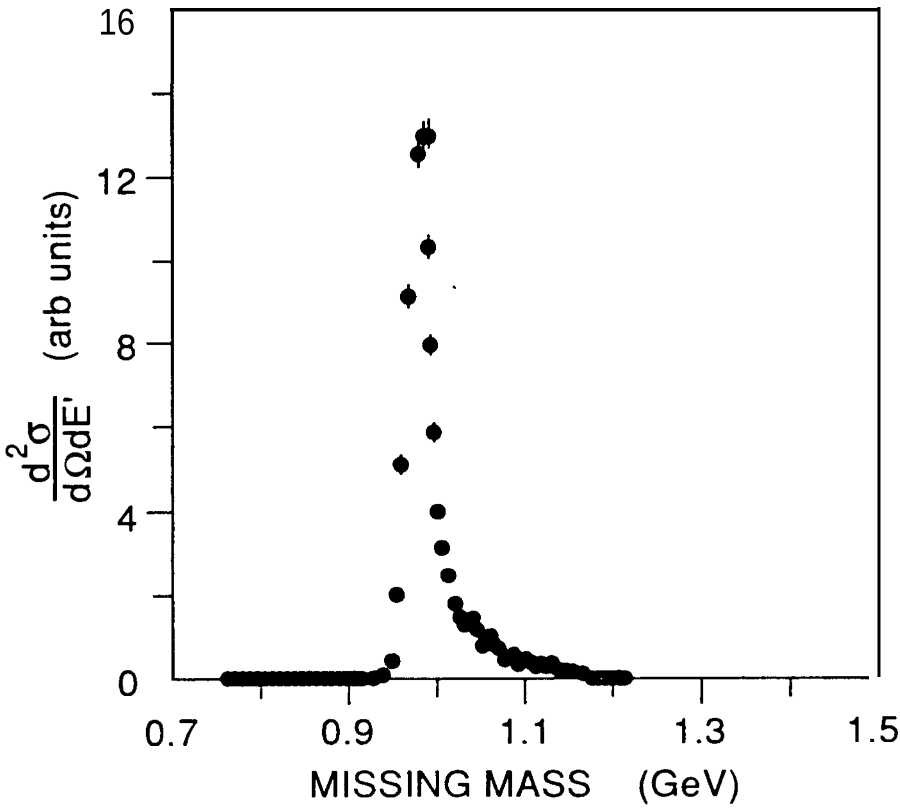


Fig. 35. The same data as in Figure 34, plotted against the calculated missing mass of each event. (The peak is displaced from the mass of the proton at 938 MeV by a slight mismatch in energy calibrations between the switchyard and the spectrometer.)

the biggest physics project ever built to look into places where no one had ever looked before. Nearly a decade of thinking and hard work by hundreds of people would be tested by the events of that evening. Such moments are often spoiled by last minute difficulties, but we were fortunate. Preparations proceeded smoothly, the target was filled with hydrogen and soon the computer was analyzing events. Within a few minutes a respectable elastic peak was showing in the "*p*-θ" display which sorted events into bins corresponding to the counters hit in the momentum and scattering angle hodoscopes (Fig. 34). The data in this 3-dimensional plot can be converted to a 2-dimensional plot of counts vs. missing mass (Fig. 35) and then to cross sections and form factors. For the next couple of weeks we accumulated data and ran various checks. The system worked well-we could accumulate data fairly rapidly and change both energy and angle from the counting house. The investments made for the sake of efficiency were proving to be valuable, and we were happy with the functioning of our apparatus and the operation of the accelerator.

A preliminary analysis of the data obtained was made within a few months for presentation at the Electron-Photon Symposium held at SLAC in Au-

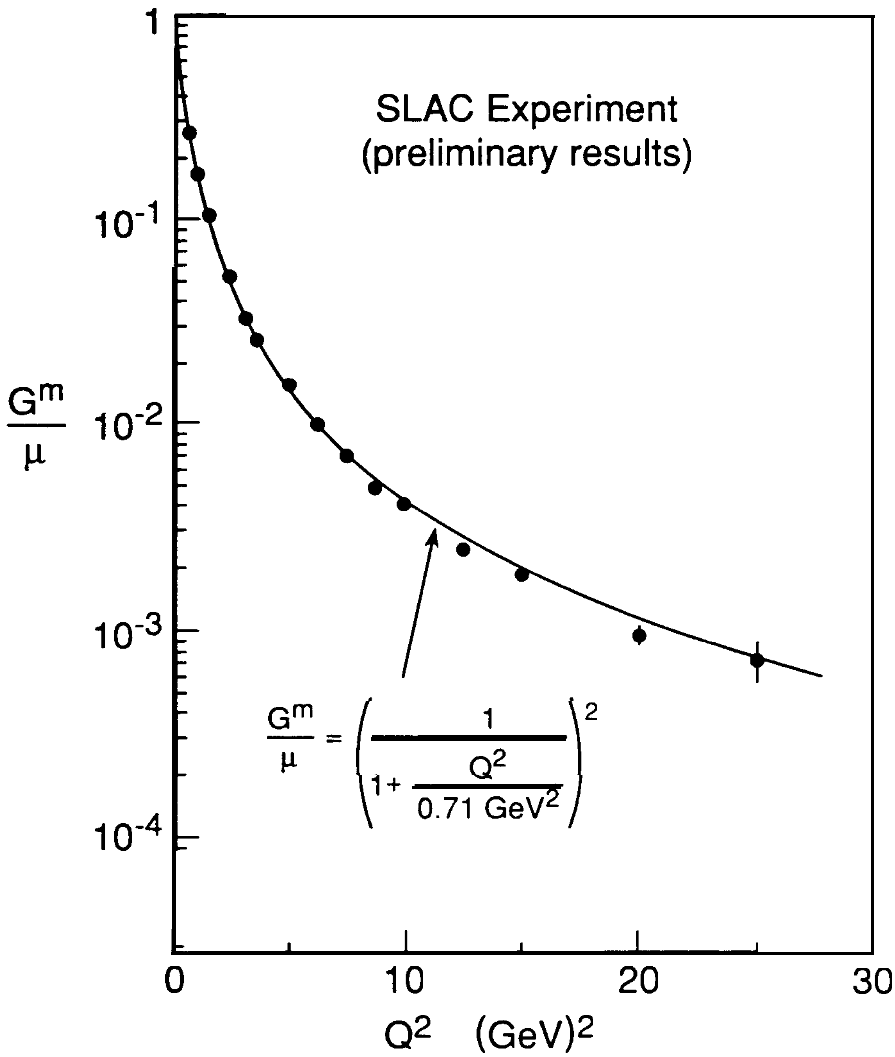


Fig. 36. Magnetic form factor measurement at SLAC in 1967. The dipole curve is the same as in Figure 25, here extended to $Q^2 = 25$ GeV^2. Again, the agreement is imperfect but the curve describes the general behavior of the data quite well.

gust, 1967.[35] The elastic cross sections measured at SLAC behaved in much the same way as those measured at lower energies-falling on the same simple extrapolation of the earlier fits as the CEA and DESY data (Fig. 36). We collected data for G_{MP} at values of Q^2 up to 25 GeV^2.

The first opportunity to find something new and unexpected with the spectrometer facility and the SLAC beam had been a disappointment. This is quite normal in experimental physics. Most measurements increment knowledge by just a small amount. Sometimes enough of those small increments eventually result in insights that change our point of view. The sudden observation of unexpected phenomena that result in major new insights is an uncommon event in science. One tries to be ready for such observations, but usually has to be content with adding a small brick of knowledge to the existing edifice. In any case, we had very little time to philosophize over the elastic results because we were busy preparing for the first inelastic scattering experiments. They began in August 1967, using the 20 GeV spectrometer.

In this talk I have tried to point out the importance of advances in accelerators and experimental equipment for the long series of electron scattering experiments at Stanford and elsewhere. The utility of large scale facilities would continue to be demonstrated in later work on nuclear structure with muons and neutrinos at Fermilab and CERN. Large facilities are now commonplace in high energy physics, partially because of the early successes of such facilities in the field of electron scattering.

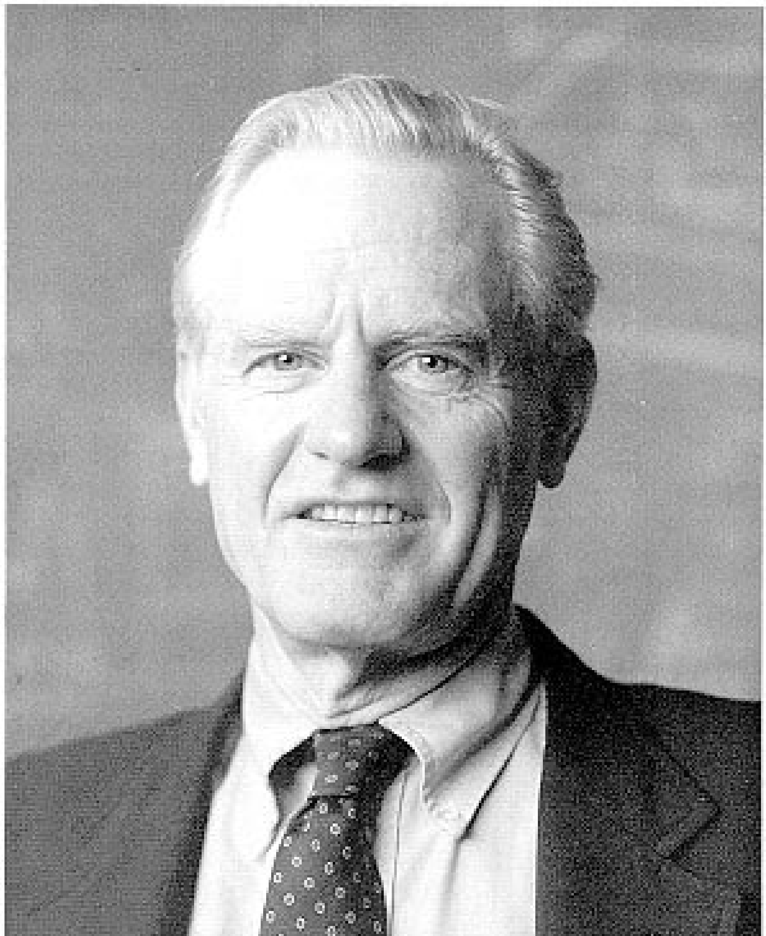
The Stanford Linear Accelerator and the associated initial complement of experimental equipment were generously supported by U.S. Goverment funding administered by (what is now) the Department of Energy. We were given a chance to build apparatus that was well suited to the opportunities provided by the new linear accelerator. The vast changes in the scale of scientific endeavors during this century have not changed one of the principal preoccupations of the experimental physicist- the building of quality experimental equipment which is matched to the task at hand. In those days the cost-effectiveness of apparatus was considered more important than arbitrary cost-ceilings, and we hope that the physics output of the facilities in End Station A has justified the considerable expense incurred in building them.

In the summer of 1967, SLAC was embarking on a long and productive program of experiments. The story of one of those experiments will be continued in Professor Kendall's lecture.

REFERENCES

1. H. W. Kendall, Deep Inelastic Scattering: Experiments on the Proton and the Observation of Scaling. *Les Prix Nobel 1990.*
2. J. I. Friedman, Deep Inelastic Scattering: Comparisons with the Quark Model. *Les Prix Nobel 1990.*
3. J. I. Friedman, H. W. Kendall, R. E. Taylor, Deep Inelastic Scattering: Acknowledgments. *Les Prix Nobel 1990.*
4. H. Geiger and E. Marsden, Proc. Roy. Soc. 82, 495 (1909).
5. E. Rutherford, Phil. Mag. 21, 669 (1911).
6. J. Franck and G. Hertz, Verh. Dtsch. Phys. Ges. 16, 457 (1914).
7. M. E. Rose, Phys. Rev. 73, 279 (1948).
8. L. I. Schiff, *Summary of Possible Experiments with a High Energy Linear Electron Accelerator,* SUML- 102, Stanford University, Microwave Laboratory, 1949 (unpublished).
9. M. N. Rosenbluth, Phys. Rev. 79, 615 (1950).
10. E. M. Lyman, A. 0. Hanson, and M. B. Scott, Phys. Rev. 84, 626 (1951).
11. J. H. Fregeau and R. Hofstadter, Phys. Rev. 99, 1503 (1955).

12. R. Hofstadter, H. R. Fechter and J. A. McIntyre, Phys. Rev. 91, 422 (1953).
13. R. Hofstadter and R. W. McAllister, Phys. Rev. 98, 217 (1955).
14. R. Hofstadter, Rev. Mod. Phys. **28,** 214 (1956) and op. *cit.* (This article summarizes the work at HEPL up to 1956 and contains a fairly complete set of references to the early work in the field.)
15. Proposal for a Two Mile Linear Electron Accelerator, Stanford University, April **1957.**
16. R. B. Neal, ed., *The Stanford Two Mile Accelerator* (W. A. Benjamin, NY, 1968).
17. C. D. Buchanan *et al., in Proc. 1965 Int. Symp. on Electron and Photon Interactions at High Energies,* Hamburg, Germany, G. Hohler *et al.*, eds. (Hamburg, Germany, Deutsche Phys. Geselleschaft, 1965). pp. 20-42; presented by R. Hofstadter, and op. *cit.*
18. R. R. Wilson *et* al., Nature **188, 94** (1960).
19. R. R. Wilson, Nucl. Instrum. **1,** 101 (1957).
20. K. Berkelman *et al.*, Phys. Rev. 130, 2061 (1965).
21. J. R. Dunning *et* al., Phys. Rev. Lett. 13, 631 (1964) and op. *cit.*
22. H. J. Behrend *et* al., Nuovo Cimento **A38, 140** (1967) and op. *cit.*
23. W. Bartel *et* al., Phys. Rev. Lett. 17, 608 (1966) and op. *cit.*
24. J. Schwinger, Phys. Rev. 75, 898 (1949).
25. W. K. H. Panofsky, C. Newton, and G. B. Yodh, Phys. Rev. 98, 751 (1955).
26. W. K. H. Panofsky, W. M. Woodward, and G. B. Yodh, Phys. Rev. 102, 1392 (1956).
27. G. B. Yodh and W. K. H. Panofsky, Phys. Rev. 105, 731 (1957).
28. R. A. Alvarez *et al.,* Rev. Sci. Instrum. 31, 556 (1960).
29. W. K. H. Panofsky and E. A. Allton, Phys. Rev. **110,** 1155 (1958).
30. G. G. Ohlsen, Phys. Rev. 120, 584 (1960).
31. S. D. Drell and J. D. Walecka, Ann. Phys. (NY) 28, 18 (1964).
32. L. Hand, Phys. Rev. 129, 1584 (1963).
33. A. A. Cone *et al.,* Phys. Rev. Lett. 14, 326 (1965).
34. F. W. Brasse *et al.,* Nuovo Cimento 55, 679 (1968).
35. R. E. Taylor in *Proc. of the 1967 Int. Symp. on Electron and Photon Interactions at High Energies* (Stanford Linear Accelerator Center, 1967) pp. 70 - 101.



Henry W. Kendall

HENRY W. KENDALL

I was born on December 9, 1926 in Boston, Massachusetts. My parents were Henry P. Kendall, a Boston businessman, and Evelyn Way Kendall, originally from Canada.

I lived in Boston until the early 1930s when the family - there were five, for by then I had a younger brother and a younger sister - moved to a small town outside Boston, where the three of us grew up and where I still live.

I went briefly to a local grade school but was held back by a reading disability which was cured after I was moved to a school some miles distant. From age 14 to 18, most of the period of World War II, I spent at Deerfield Academy, a college preparatory school. My academic work was poor for I was more interested in non-academic matters and was bored with school work. I had developed - or had been born with - an active curiosity and an intense interest in things mechanical, chemical and electrical and do not remember when I was not fascinated with them and devoted to their exploration. Father was a great encouragement in these projects except when they involved hazards, such as the point, at about age 11, when I embarked on the culture of pathogenic bacteria. He also instilled in both me and my brother a love and respect for the outdoors, especially the mountains and the sea.

I entered the US Merchant Marine Academy in the summer of 1945. I was there, in basic training, when the first atom bombs were exploded over Japan. I was unaware of the human side of these events and only recall a feeling that some of the last secrets of nature had been penetrated and that little would be left to explore. I spent the winter of 1945 -46 on a troop transport on the North Atlantic (a most interesting experience), returning to the Academy for advanced training in the spring of 1946. I resigned in October, 1946, to start as a freshman at Amherst College. Although a mathematics major at college, my interest in physics was great and I did undergraduate research and a thesis in that field. But history, English and biology were all most attractive and there was a period, early on, when any one of these might have ended up as the major subject. Non-college enterprises, in the summers particularly, absorbed considerable time. I and a Deerfield friend became interested in diving and two summers were spent in organizing and running a small diving and salvage operation. We wrote our first books after that; one on shallow water diving, another on underwater photography, with a considerable success for both. These activities, mostly self-taught, were a good introduction to two skills very helpful in later experimental work: seeing projects through to successful conclusions and doing them safely.

On the urging of Karl Compton, a family friend and then President of MIT, I applied for, and was accepted at that institution's school of physics in 1950. The years at graduate school were a continuing delight - the first sustained immersion in science at a full professional level. My thesis, carried out under the supervision of Martin Deutsch, was an attempt to measure the Lamb shift in positronium, a transient atom discovered by Deutsch a few years before. The attempt was unsuccessful but it served as a very interesting introduction to electromagnetic interactions and the power of the underlying theory.

The two years after receiving the PhD degree were spent as a National Science Foundation Postdoctoral Fellow at MIT and at Brookhaven National Laboratory, followed by a trip west to join the research group of Robert Hofstadter and the faculty of the Stanford University physics department. Hofstadter was engaged in the study of the proton and neutron structure that was later to bring him the Nobel Prize, work that even at the time was clearly of the greatest interest and importance. The principal facility used in this research was a 300 ft. linear electron accelerator, a precursor to the 2 mile machine at the Stanford Linear Accelerator Center (SLAC), later built in the hills behind the University. Here I met and worked with Jerome Friedman, got to know Richard Taylor, then a graduate student in another group and W. K. H. Panofsky, the driving force behind SLAC. Friedman, Taylor and I were later to join in the long series of measurements on deep inelastic scattering at SLAC.

As in the college years, absorbing non-physics matters claimed a portion of my leisure time: mountaineering and mountain photography. Stanford and the San Francisco Bay area offered a number of skilled climbs as well as Yosemite Valley not far away. After two years of rock and mountain climbing, I was invited on the first -of several expeditions to the Andes. Later there have been trips to the Himalayas and the Arctic, with cameras of increasing size to capture some of the astonishing beauty of those remote places. Many of the friends made during those years have remained through life.

After five years at Stanford I moved back to MIT as a member of the faculty. Friedman had gone there a year earlier and we reestablished our collaboration. By 1964, the joint work with Taylor, by then a research group leader at SLAC, was initiated. This collaboration was surely the most enjoyable of any physics I have ever done. It was a pleasure shared by most people in the effort and well recognized at the time. All three of us have remained, up to the present, in the universities we were at then. I have been involved in research in later years, after the SLAC effort wound down in the middle 1970s, at the proton accelerator at Fermilab and since 198 1, again at SLAC. The most interesting physics for me has always been the searches for new phenomena or new effects. With colleagues I have searched for limits to quantum electrodynamics, heavy electrons, parity breakdown in electron properties, and other such things. Unfortunately, the ever-growing size, scale, and duration of particle experiments, as well as the much larger collaborations, have made such programs less and less congenial to me over the years, circumstances that disturb many in the physics community.

At the start. of the 1960s troubled by the massive build-up of the superpower's nuclear arsenals, I joined a group of academic scientists advising the U.S. Defense Department. The opportunity to observe the operation of the Defense establishment from the "inside," both in the nuclear weapons area and in the counterinsurgency activities that later expanded to be the U.S. military involvement in South East Asia proved a valuable experience, helpful in later activities in the public domain. It was clear that changing unwise Government policies from inside, especially those the Government is deeply attached to, involves severe, often insurmountable, problems.

In 1969, I was one of a group founding the Union of Concerned Scientists (UCS), and have played a substantial role in its activities in the years hence. UCS is a public interest group, supported by funds raised from the general public, that presses for control of technologies which may be harmful or dangerous. The organization has had an important national role in the controversies over nuclear reactor safety, the wisdom of the US Strategic Defense Initiative, the B2 (Stealth) bomber, and the challenge posed by fossil fuel burning and possible greenhouse warming of the atmosphere, among others. I have been Chairman of the organization since 1974. The activities of the organization are part of a slowly growing interest among scientists to take more responsibility for helping society control the exceedingly powerful technologies that scientific research has spawned. It is hard to conclude that scientists are in the main responsible for the damage and risks that are now so apparent in such areas as environmental matters and nuclear armaments; these have been largely the consequence of governmental and industrial imperatives, both here and abroad. Yet it seems clear that without scientists' participation in the public debates, the chances of great injury to all humanity is much enhanced. In my view, the scientific community has not participated in this effort at a level commensurate with the need, nor with the special responsibilities that scientists ineluctably have in this area.

This expenditure of effort and the sense of responsibility to help achieve control of aberrant technologies which drives it, stems in no small measure from the example set by my Father, who, throughout his life, spent a great deal of time and no small amount of energy on quiet, pro bono work. He was not alone among his own friends - nor among his own contemporaries - in this; it has been a tradition in New England of very long standing. In continuing to pursue such objectives, my expectation is that the challenges facing both me and the Union will be made substantially easier by the award of the Nobel Prize. This is perhaps the most attractive part of having gained this exceptional honor.

DEEP INELASTIC SCATTERING: EXPERIMENTS ON THE PROTON AND THE OBSERVATION OF SCALING

Nobel Lecture, December 8, 1990

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I *Introduction*

A. Overview of the Electron Scattering Program

In late 1967 the first of a long series of experiments on highly inelastic electron scattering was started at the two mile accelerator at the Stanford Linear Accelerator Center (SLAC) using liquid hydrogen and, later, liquid deuterium targets. Carried out by a collaboration from the Massachusetts Institute of Technology (MIT) and SLAC, the object was to look at large energy loss scattering of electrons from the nucleon (the generic name for the proton and neutron), a process soon to be dubbed deep inelastic scattering. Beam energies up to 21 GeV, the highest electron energies then available, and large electron fluxes, made it possible to study the nucleon to very much smaller distances than had previously been possible. Because quantum electrodynamics provides an explicit and well-understood description of the interaction of electrons with charges and magnetic moments, electron scattering had, by 1968, already been shown to be a very powerful probe of the structures of complex nuclei and individual nucleons.

Hofstadter and his collaborators had discovered, by the mid-1960s that as the momentum transfer in the scattering increased, the scattering cross section dropped sharply relative to that from a point charge. The results showed that nucleons were roughly 10^{-13} cm in size, implying a distributed structure. The earliest MIT-SLAC studies, in which California Institute of Technology physicists also collaborated, looked at elastic electron-proton scattering, later ones at electro-production of nucleon resonances with excitation energies up to less than 2 GeV. Starting in 1967, the MIT-SLAC collaboration employed the higher electron energies made available by the newly completed SLAC accelerator to continue such measurements, before beginning the deep inelastic program.

Results from the inelastic studies arrived swiftly: the momentum transfer dependence of the deep inelastic cross sections was found to be weak, and the deep inelastic form factors - which embodied the information about the proton structure - depended unexpectedly only on a single variable rather than the two allowed by kinematics alone. These results were inconsistent with the current expectations of most physicists at the time. The general belief had been that the nucleon was the extended object found in elastic electron scattering but with the diffuse internal structure seen in pion and proton scattering. The new experimental results suggested point-like constituents but were puzzling because such constituents seemed to contradict well-established beliefs. Intense interest in these results developed in the theoretical community and, in a program of linked experimental and theoretical advances extending over a number of years, the internal constituents were ultimately identified as **quarks,** which had previously been devised in 1964 as an underlying, quasi-abstract scheme to justify a highly successful classification of the then-known hadrons. This identification opened the door to development of a comprehensive field theory of hadrons (the strongly interacting particles), called Quantum Chromodynamics ((LCD), that replaced entirely the earlier picture of the nucleons and mesons. QCD in conjunction with electroweak theory, which describes the interactions of leptons and quarks under the influence of the combined weak and electromagnetic fields, constitutes the Standard Model, all of whose predictions, at this writing, are in satisfactory agreement with experiment. The contributions of the MIT-SLAC inelastic scattering program were recognized by the award of the 1990 Nobel Prize in Physics.

B. Organization of lectures

There are three lectures that, taken together, describe the MIT-SLAC experiments. The first, written by R.E.Taylor (Reference l), sets out the early history of the construction of the two mile accelerator, the proposals made for the construction of the electron scattering facility, the antecedent physics experiments at other laboratories, and the first of our scattering experiments which determined the elastic proton structure form factors. This paper describes the knowledge and beliefs about the nucleon's internal structure in 1968, including the conflicting views on the validity of the quark model and the "bootstrap" models of the nucleon. This is followed by a review of the inelastic scattering program and the series of experiments that were carried out, and the formalism and variables. Radiative corrections are described and then the results of the inelastic electron-proton scattering measurements and the physics picture - the naive parton model that emerged. The last lecture, by J. I. Friedman (Reference 2), is concerned with the later measurements of inelastic electron-neutron and electron-proton measurements and the details of the physical theory - the constituent quark model - which the experimental scattering results stimulated and subsequently, in conjunction with neutrino studies, confirmed.

II *Nucleon and Hadronic Structure in 1968*

At the time the MIT-SLAC inelastic experiments started in 1968, there was no detailed model of the internal structures of the hadrons. Indeed, the very notion of "internal structure" was foreign to much of the then-current theory. Theory attempted to explain the soft scattering - that is, rapidly decreasing cross sections as the momentum transfer increased - which was the predominant characteristic of the high energy hadron-hadron scattering data of the time, as well as the hadron resonances, the bulk of which were discovered in the late 1950s and 1960s. Quarks had been introduced, quite successfully, to explain the static properties of the array of hadrons. Nevertheless, the available information suggested that hadrons were "soft" inside, and would yield primarily distributions of scattered electrons reflecting diffuse charge and magnetic moment distributions with no underlying point-like constituents. Quark constituent models were gleams in the eyes of a small handful of theorists, but had serious problems, then unsolved, which made them widely unpopular as models for the high energy interactions of hadrons.

The need to carry out calculations with forces that were known to be very strong introduced intractable difficulties: perturbation theory, in particular, was totally unjustified. This stimulated renewed attention to S-matrix theory (Reference 3), an attempt to deal with these problems by consideration of the properties of a matrix that embodied the array of strong interaction transition amplitudes from all possible initial states to all possible final states.

A. Theory: Nuclear Democracy

An approach to understanding hadronic interactions, and the large array of hadronic resonances, was the bootstrap theory (Reference 4), one of several elaborations of S-matrix theory. It assumed that there were no "fundamental" particles: each was a composite of the others. Sometimes referred to as "nuclear democracy," the theory was at the opposite pole from constituent theories.

Regge theory (Reference 5), a very successful phenomenology, was one elaboration of S-matrix theory which was widely practiced. Based initially on a new approach to non-relativistic scattering, it was extended to the relativistic S-matrix applicable to high energy scattering (Reference 6). The known hadrons were classified according to which of several "trajectories" they lay on. It provided unexpected connections between reactions at high energies to resonances in the crossed channels, that is, in disconnected sets of states. For scattering, Regge theory predicted that at high energy, hadron-hadron scattering cross sections would depend smoothly on s, the square of the center of mass energy, as $A(s) \sim s^{(\alpha(0))}$, and would fall exponentially with t, the square of the space-like momentum transfer, as

$$A(t) \backsim \exp(\alpha' t \ln(s/s_0))$$

Regge theory led to duality, a special formulation of which was provided by Veneziano's dual resonance model (Reference 7). These theories still provide the best description of soft, low momentum transfer scattering of pions and nucleons from nucleons, all that was known in the middle 1960s. There was a tendency, in this period, to extrapolate these low momentum transfer results so as to conclude there would be no hard scattering at all.

S-matrix concepts were extended to the electromagnetic processes involving hadrons by the Vector Meson Dominance (VMD) model (Reference 8). According to VMD, when a real or virtual photon interacts with a hadron, the photon transforms, in effect, into one of the low mass vector mesons that has the same quantum numbers as the photon (primarily the rho, omega and phi mesons). In this way electromagnetic amplitudes were related to hadronic collision amplitudes, which could be treated by S-matrix methods. The VMD model was very successful in phenomena involving real photons and many therefore envisaged that VMD would also deal successfully with the virtual photons exchanged in inelastic electron scattering. Naturally, this also led to the expectation that electron scattering would not reveal any underlying structure.

All of these theories, aside from their applications to hadron-hadron scattering and the properties of resonances, had some bearing on nucleon structure as well, and were tested against the early MIT-SLAC results.

B. Quark Theory of 1964

The quark' was born in a 1964 paper by Murray Gell-Mann (Reference 9) and, independently, by George Zweig (Reference 10). For both, the quark (a term Zweig did not use until later) was a means to generate the symmetries of SU(3), the "Eightfold Way," Gell-Mann and Ne'emann's (Reference 11) highly successful 1961 scheme for classifying the hadrons. Combinations of spin 1/2 quarks, with fractional electric charges, and other appropriate quantum numbers, were found to reproduce the multiplet structures of all the observed hadrons. Fractional charges were not necessary but provided the most elegant and economical scheme. Three quarks were required for baryons, later referred to as "valence" quarks, and quark-antiquark pairs for mesons. Indeed the quark picture helped solve some difficulties with the earlier symmetry groupings (Reference 12). The initial successes of the theory stimulated numerous free quark searches. There were attempts to produce them with accelerator beams, studies to see if they were produced in cosmic rays, and searches for "primordial" quarks by Millikan oil drop techniques sensitive to fractional charges. None of these has ever been successful (Reference 13).

C. Constituent Quark Picture

There were serious problems in having quarks as physical constituents of nucleons and these problems either daunted or repelled the majority of the theoretical community, including some of its most respected members (Reference 14). The idea was distasteful to the S-matrix proponents. The problems were, first, that the failure to produce quarks had no precedent in

The word *quork* was invented by Murray Cell-Mann, who later found *quark* in the novel Finnegan's *Wake,* by James Joyce, and adopted what has become the accepted spelling. Joyce apparently employed the word as a corruption of the word *quart*. The author is grateful to Murray Gell-Mann for a discussion clarifying the matter.

physicists' experience. Second, the lack of direct production required the quarks to be very massive, which, for the paired quark configurations of the mesons, meant that the binding had to be very great, a requirement that led to predictions inconsistent with hadron-hadron scattering results. Third, the ways in which they were combined to form the baryons, meant that they could not obey the Pauli exclusion principle, as required for spin one-half particles. Fourth, no fractionally charged objects had ever been unambiguously identified. Such charges were very difficult for many to accept, for the integer character of elementary charges was long established. Enterprising theorists did construct quark theories employing integrally charged quarks, and others contrived ways to circumvent the other objections. Nevertheless, the idea of constituent quarks was not accepted by the bulk of the physics community, while others sought to construct tests that the quark model was expected to fail (Reference 15).

Some theorists persisted, nonetheless. Dalitz (Reference 16) carried out complex calculations to help explain not only splittings *between* hadron multiplets but the splittings *within* them also, using some of the theoretical machinery employed in nuclear spectroscopy calculations. Calculations were carried out on other aspects of hadron dynamics, for example, the successful prediction that Δ^+ decay would be predominantly magnetic dipole (Reference 17). Owing to the theoretical difficulties just discussed, the acceptance of quarks as the basis of this successful phenomenology was not carried over to form a similar basis for high energy scattering.

Gottfried studied electron-proton scattering with a model assuming point quarks, and argued that it would lead to a total cross section (elastic plus inelastic) at fixed momentum transfer, identical to that of a point charge, but he expressed great skepticism that this would be borne out by the forthcoming data (Reference 18). With the exception of Gottfried's work and one by Bjorken stimulated by current algebra, discussed below, all of the published constituent quark calculations were concerned with low energy processes or hadron characteristics rather than high energy interactions. Zweig carried out calculations assuming that quarks were indeed hadron constituents but his ideas were not widely accepted (Reference 19).

Thus, one sees that the tide ran against the constituent quark model in the 60s (Reference 20). One reviewer's summary of the style of the 60s was that "quarks came in handy for coding information but should not be taken seriously as physical objects" (Reference 21). While quite helpful in low energy resonance physics, it was for some "theoretically disreputable," and was felt to be largely peripheral to a description of high energy soft scattering (Reference 22).

D. Current Algebra

Following his introduction of quarks, Gell-Mann, and others, developed "current algebra," which deals with hadrons under the influence of weak and electromagnetic interactions. Starting with an assumption of free quark fields, he was able to find relations between weak currents that reproduced the current commutators postulated in constructing his earlier hadronic symmetry groups. Current algebra had become very important by 1966. It exploited the concept of *local observables* - the current and charge densities of the weak and electromagnetic interactions. These are field theoretic in character and could only be incorporated into S-matrix cum bootstrap theory by assumptions like VMD. The latter are plausible for moderate momentum transfer, but hardly for transfer large compared to hadron masses. As a consequence, an important and growing part of the theoretical community was thinking in field theoretic terms.

Current algebra also gave rise to a small but vigorous "sum rule" industry. Sum rules are relationships involving weighted integrals over various combinations of cross sections. The predictions of some of these rules were important in confirming the deep inelastic electron and neutrino scattering results, after these became available (Reference 23).

Gell-Mann made clear that he was not suggesting that hadrons were made up of quarks (Reference 24), although he kept open the possibility that they might exist (Reference 25). Nevertheless, current algebra reflected its constituent-quark antecedents, and Bjorken used it to demonstrate that sum rules derived by him and others required large cross sections for these to be satisfied. He then showed that such cross sections arose naturally in a quark constituent model (Reference 26), in analog to models of nuclei composed of constituent protons and neutrons, and also employed it to predict the phenomena of scaling, discussed at length below. Yet Bjorken and others were at a loss to decide how the point-like properties that current algebra appeared to imply were to be accommodated (Reference 27).

E. Theoretical Input to The Scattering Program

In view of the theoretical situation as set out above, there was no consideration that a possible point-like substructure of the nucleon might be observable in electron scattering during the planning and design of the electron scattering facility. Deep inelastic processes were, however, assessed in preparing the proposal submitted to SLAC for construction of the facility (Reference 28). Predictions of the cross sections employed a model assuming off-mass-shell photo-meson production, using photoproduction cross sections combined with elastic scattering structure functions, in what was believed to be the best guide to the yields expected. These were part of extensive calculations, carried out at MIT, designed to find the magnitude of distortions of inelastic spectra arising from photon radiation, necessary in planning the equipment and assessing the difficulty of making radiative corrections. It was found ultimately that these had underpredicted the actual yields by between one and two orders of magnitude.

III *The Scattering Program*

The linear accelerator that provided the electron beam employed in the inelastic scattering experiments was, and remains to the date of this paper, a

Fig. 1. View of the Stanford Linear Accelerator. The electron injector is at the top, the experimental area in lower center. The deep inelastic scattering studies were carried out in End Station A, the largest of the buildings in the experimental area.

device unique among high energy particle accelerators. See Figure 1. An outgrowth of the smaller, 1 GeV accelerator employed by Hofstadter in his studies of the charge and magnetic moment distributions of the nucleon, it relied on advanced klystron technology devised by Stanford scientists and engineers to provide the high levels of microwave power necessary for one-pass acceleration of electrons. Proposed in 1957, approved by the Congress in 1962, its construction was initiated in 1963. It went into operation in 1967, on schedule, having cost $114M (Reference 29).

The experimental collaboration began in 1964. After 1965, R. E. Taylor was head of SLAC Group A with J.I.Friedman and the present author sharing responsibility for the M.I.T. component. A research group from California Institute of Technology joined in the construction cycle and the elastic studies but withdrew before the inelastic work started in order to pursue other interests.

The construction of the facility to be employed in electron scattering was nearly concurrent with the accelerator's construction. This facility was large for its time. A 200 ft. by 125 ft. shielded building housed three magnetic spectrometers with an adjacent "counting house" containing the fast electronics and a computer, also large for its time, where experimenters controlled the equipment and conducted the measurements. See Figure 2a and 2b. The largest spectrometer would focus electrons up to 20 GeV and was employed at scattering angles up to 10°. A second spectrometer, useful to 8

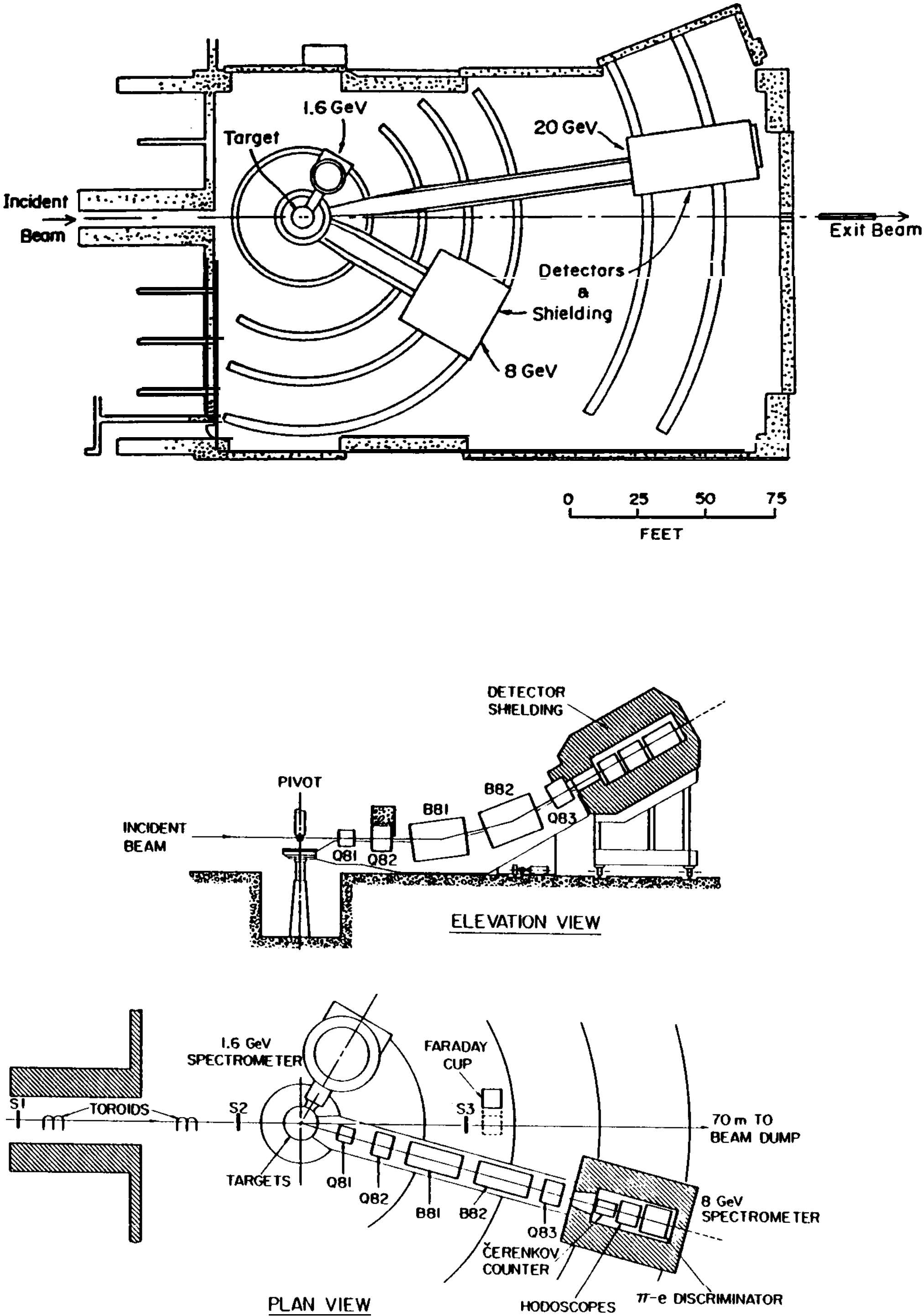


Fig. 2. (a) Plan view of End Station A and the two principal magnetic spectrometers employed for analysis of scattered electrons. (b) Configuration of the 8 GeV spectrometer, employed at scattering angles greater than 12°.

GeV, was used initially out to 34°, and a third, focusing to 1.6 GeV, constructed for other purposes, was employed in one set of large angle measurements to help determine the uniformity in density of the liquified target gases. The detectors were designed to detect only scattered electrons. The very short duty cycle of the pulsed beam precluded studying the recoil systems in coincidence with the scattered electrons: it would have given rise to unacceptable chance coincidence rates, swamping the signal.

The elastic studies started in early 1967 with the first look at inelastic processes from the proton late the same year. By the spring of 1968, the first inelastic results were at hand. The data were reported at a major scientific meeting in Vienna in August and published in 1969 (Reference 30). Thereafter, a succession of experiments were carried out, most of them, from 1970 on, using both deuterium and hydrogen targets in matched sets of measurements so as to extract neutron scattering cross sections with a minimum of systematic error. These continued well into the 1970s. One set of measurements (Reference 31) studied the atomic-weight dependence of the inelastic scattering, primarily at low momentum transfers, studies that were extended to higher momentum transfers in the early 1980s, and involved extensive reanalysis of earlier MIT-SLAC data on hydrogen, deuterium and other elements (Reference 32).

The collaboration was aware from the outset of the program that there were no accelerators in operation, or planned, that would be able to confirm the entire range of results. The group carried out independent data analyses at MIT and at SLAC to minimize the chance of error. One consequence of the absence of comparable scattering facilities was that the collaboration was never pressed to conclude either data taking or analysis in competitive circumstances. It was possible throughout the program to take the time necessary to complete work thoroughly.

IV *Scattering Formalism and Radiative Corrections*

A. Fundamental Processes

The relation between the kinematic variables in elastic scattering, as shown in Figure 3, is:

$$\nu = E\text{-}E' = q^2/(2M) \qquad q^2 = 2EE'\ (1\text{-}\cos\theta) \tag{1}$$

where E is the initial and E' the final electron energy, θ the laboratory angle of scattering, ν the electron energy loss, q the four-momentum transferred to the target nucleon, and M the proton mass.

The cross section for elastic electron-proton scattering has been calculated by Rosenbluth (Reference 33) in first Born approximation, that is, to leading order in $\alpha = 1/137$:

$$\frac{d\sigma}{d\Omega}(E) = \sigma_M(E)\left\{\frac{E'}{E}\right\}\left\{\frac{G_{Ep}^2(q^2) + \tau G_{Mp}^2(q^2)}{1+\tau} + 2\tau G_{Mp}^2 \tan^2(\theta/2)\right\} \tag{2}$$

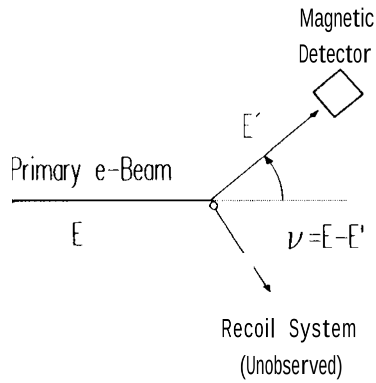


Fig. 3. Scattering kinematics.

where

$$\sigma_M = \frac{4\alpha^2 E'^2}{q^4} \cos^2 \left(\frac{\theta}{2}\right)$$

is the Mott cross section for elastic scattering from a point proton, and

$$\tau = q^2/(4M^2)$$

In these equations, and in what follows, $\hbar$ = c = 1, and the electron mass has been neglected. The functions $G_{Ep}(q^2)$ and $G_{Mp}(q^2)$, the electric and magnetic form factors, respectively, describe the time-averaged structure of the proton. In the non-relativistic limit the squares of these functions are the Fourier transforms of the spatial distributions of charge and magnetic moment, respectively. As can be seen from Equation (2) magnetic scattering is dominant at high q^2. Measurements (Reference 34) show that G_{Mp} is roughly described by the "dipole" approximation:

$$G_{Mp}/\mu = 1/(1 + q^2/0.71)^2$$

where q^2 is measured in $(\mathrm{GeV})^2$ and μ = 2.79 is the proton's magnetic moment. Thus, at large q^2 an additional $1/q^8$ dependence beyond that of σ_M is imposed on the elastic scattering cross section as a consequence of the finite size of the proton. This is shown in Figure 4.

In inelastic scattering, energy is imparted to the hadronic system. The invariant or missing mass W is the mass of the final hadronic state. It is given by:

$$W^2 = (2M\nu + M^2 - q^2)$$

When only the electron is observed the composition of the hadronic final state is unknown except for its invariant mass W. On the assumption of one photon exchange (Figure 5), the differential cross section for electron scattering from the nucleon target is related to two structure functions W_1 and W_2 according to (Reference 35):

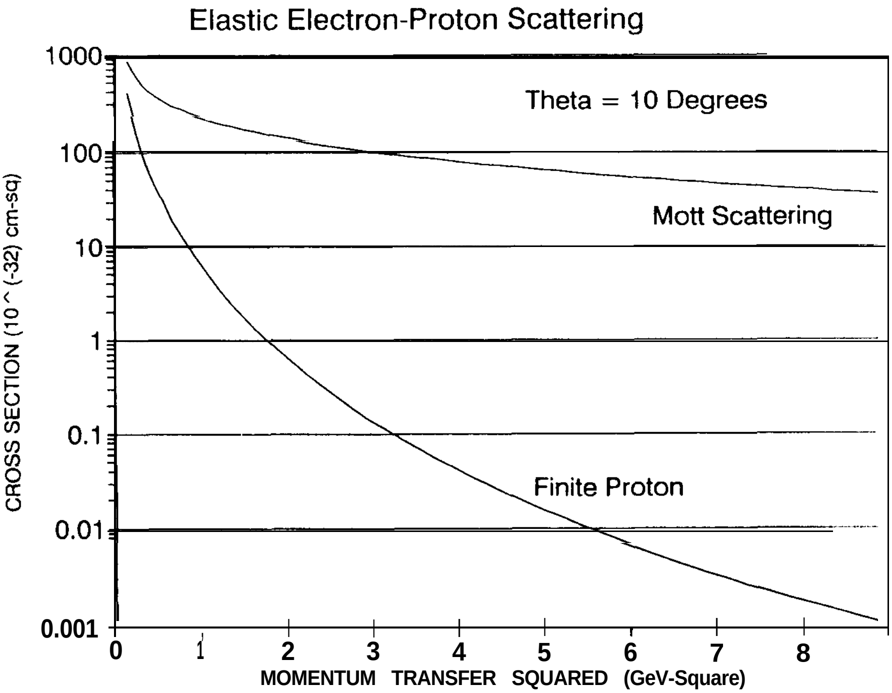


Fig. 4. Elastic scattering cross sections for electrons from a "point" proton and for the actual proton. The differences are attributable to the finite sire of the proton.

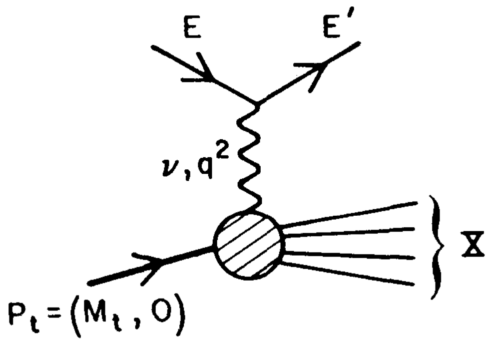


Fig. **5. Feynman diagram for inelastic electron scattering.**

$$\frac{d^2\sigma}{d\Omega\, dE'}(E,E',\theta) = \sigma_M \left[W_2(\nu,q^2) + 2W_1(\nu,q^2)\tan^2(\theta/2)\right] \tag{3}$$

This expression is the analog of the Rosenbluth cross section given above. The structure functions W_1 and W_2 are similarly defined by Equation (3) for the proton, deuteron, or neutron; they summarize all the information about the structure of the target particles obtainable by scattering unpolarized electrons from an unpolarized target.

Within the single-photon-exchange approximation, one may view inelastic electron scattering as photoproduction by "virtual" photons. Here, as opposed to photoproduction by real photons, the photon mass q^2 is variable and the exchanged photon may have a longitudinal as well as a transverse polarization. If the final state hadrons are not observed, the interference between these two components averages to zero, and the differential cross section for inelastic electron scattering is related to the total cross sections for absorption of transverse, σ_T, and longitudinal, σ_L, virtual photons according to (Reference 36)

$$\frac{d^2\sigma}{d\Omega\, dE'}(E,E',\theta) = \Gamma\left[\sigma_T(\nu,q^2) + \varepsilon\,\sigma_L(\nu,q^2)\right] \tag{4}$$

where

$$\Gamma = \frac{a}{4\pi^2}\,\frac{KE'}{q^2 E}\left(\frac{2}{1-\varepsilon}\right)$$

$$\varepsilon = [1 + 2(1 + \nu^2/q^2)\tan^2(\theta/2)]^{-1}$$

and

$$K = (W^2 - M^2)/(2M)$$

The quantity Γ is the flux of transverse virtual photons and ε is the degree of longitudinal polarization. The cross sections σ_T and σ_L are related to the structure functions W_1 and W_2 by

$$\begin{aligned} W_1(\nu,q^2) &= \frac{K}{4\pi^2 a}\,\sigma_T(\nu,q^2) \\ W_2(\nu,q^2) &= \frac{K}{4\pi^2 a}\left(\frac{q^2}{q^2+\nu^2}\right)[\sigma_T(\nu,q^2) + \sigma_L(\nu,q^2)] \end{aligned} \tag{5}$$

In the limit $q^2 \to 0$, gauge invariance requires that $\sigma_L \to 0$ and $\sigma_T \to \sigma_\gamma$ (v), where σ_γ (v) is the photoproduction cross section for real photons. The quantity R, defined as the ratio σ_L/σ_T is related to the structure functions by

$$R(\nu,q_2) \equiv \sigma_L/\sigma_T = (W_2/W_1)(1 + \nu^2/q^2) - 1 \tag{6}$$

A separate determination of the two inelastic structure functions W, and W_2 (or, equivalently, σ_L and σ_T) requires values of the differential cross section at several values of the angle σ for fixed ν and q^2. According to Equation (4) σ_L is the slope and σ_T is the intercept of a linear fit to the quantity Σ where:

$$\Sigma = \frac{1}{\Gamma}\,\frac{d^2\sigma}{d\Omega\, dE'}(\nu,q^2,\theta)$$

The structure functions W, and W_2 are then directly calculable from Eq. (5). Alternatively, one can extract W, and W_2 from a single differential cross-section measurement by inserting a particular functional form for R in the equations

$$W_1 = \frac{1}{\sigma_M}\,\frac{d^2\sigma}{d\Omega\, dE'}\left[(1+R)\left(\frac{q^2}{q^2+\nu^2}\right)+2\tan^2\left(\frac{\theta}{2}\right)\right]^{-1}$$
$$W_2 = \frac{1}{\sigma_M}\,\frac{d^2\sigma}{d\Omega\, dE'}\left[1+\left(\frac{2}{1+R}\right)\left(\frac{q^2+\nu^2}{q^2}\right)\tan^2\left(\frac{\theta}{2}\right)\right]^{-1} \tag{7}$$

Equations (5) through (7) apply equally well for the proton, deuteron, or neutron.

In practice, it was convenient to determine values of σ_L and σ_T from straight line fits to differential cross sections as functions of ε. R was determined from the values of σ_L and σ_T, and W_1 and W_2 were, as shown above, determined from R.

B. Scale Invariance and Scaling Variables.

By investigating models that satisfied current algebra, Bjorken (Reference 37) had conjectured that in the limit of q^2 and ν approaching infinity, with the ratio $\omega = 2M\nu/q^2$ held fixed, the two quantities νW_2 and W_1 become functions of ω only. That is:

$$2MW_1(\nu, q^2) = F_1(\omega)$$
$$\nu W_2(\nu, q^2) = F_2(\omega)$$

It is this property that is referred to as "scaling" in the variable ω in the "Bjorken limit." The variable $x = 1/w$ came into use soon after the first inelastic measurements; we will use both in this paper.

Since W_1 and W_2 are related by

$$\nu W_2/W_1 = (1+R)/(1/\nu + \omega/(2M))$$

it can be seen that scaling in W_1 accompanies scaling in νW_2 only if R has the proper functional form to make the right hand side of the equation a function of ω. In the Bjorken limit, it is evident that the ratio $\nu W_2/W_1$ will scale if R is constant or is a function of ω only.

C. Radiative Corrections

Radiative corrections must be applied to the measured cross sections to eliminate the effects of the radiation of photons by electrons which occurs during the nucleon scattering itself and during traversals of material before and after scattering. These corrections also remove higher order electrodynamic contributions to the electron-photon vertex and the photon propagator. Radiative corrections as extensive as were required in the proposed scattering program had been little studied previously (Reference 38). Friedman (Reference 39), in 1959 had calculated the elements of the required "triangle," discussed in more detail below, in carrying out corrections to the inelastic scattering of 175 MeV electrons from deuterium. Isabelle and Kendall (Reference 40), studying the inelastic scattering of electrons of energy up to 245 MeV from Bi^{209} in 1962, had measured inelastic spectra over a number of triangles and had developed the computer procedures necessary to permit computation of the corrections. These studies provided

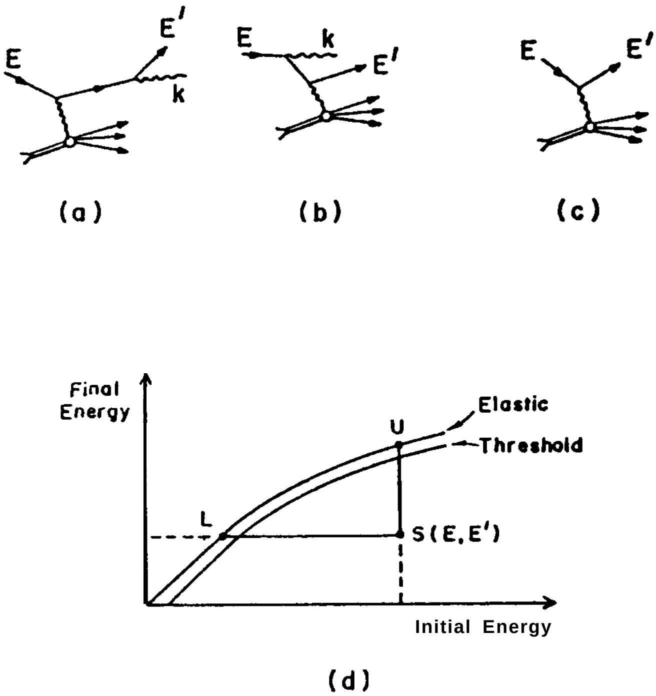


Fig. 6. Diagrams showing radiation in electron scattering (a) after exchange of a virtual photon (b) before exchange of a virtual photon. Figure (6c) is the diagram with radiative effects removed. Figure (6 d) is the kinematic plane relevant to the radiative corrections program. The text contains a further discussion of corrections procedures. A "triangle" as discussed in the text is formed by points L, U, and S.

confidence that the procedures were tractable and the resulting errors of acceptable magnitude.

The largest correction has to be made for the radiation during scattering, described by diagrams (a) and (b) in Figure 6. A photon of energy k is emitted in (a) after the virtual photon is exchanged, and in (b) before the exchange. Diagram (c) is the cross section which is to be recovered after appropriate corrections for (a) and (b) have been made. A measured cross section at fixed *E*, E^{1}, and θ will have contributions from (a) and (b) for all values of k which are kinematically allowed. The lowest value of k is zero, and the largest occurs in (b) for elastic scattering of the virtual electron from the target particle. Thus, to correct a measured cross section at given values of *E* and *E'*, one must know the cross section over a range of incident and scattered energies.

To an excellent approximation, the information necessary to correct a cross section at an angle θ may all be gathered at the same value of θ. Diagram (d) of Figure 6 shows the kinematic range in *E* and E^{1} of cross sections which can contribute by radiative processes to the fundamental cross section sought at point S, for fixed θ. The range is the same for contributions from bremsstrahlung processes of the incident and scattered electrons. For single hard photon emission, the cross section at point S will have contributions from elastic scattering at points U and L, and from inelastic scattering along the lines SL and SU, starting at inelastic threshold. If two or more photons are radiated, contributions can arise from line LU and the inelastic region bounded by lines SL and SU. The cross sections needed for these corrections must themselves have been corrected for radiative effects. However, if uncorrected cross sections are available over the whole of the "triangle" LUS, then a one-pass radiative correction procedure may be employed, assuming the peaking approximation (Reference 41), which will produce the approximately corrected cross sections over the entire triangle, including the point S.

The application of radiative corrections required the solution of another difficulty, as it was generally not possible to take measurements sufficiently closely spaced in the *E-E'* plane to apply them directly. Typically live to ten spectra, each for a different *E,* were taken to determine the cross sections over a "triangle." Interpolation methods had to be developed to supply the missing cross sections and had to be tested to show that they were not the source of unexpected error. Figure 7 shows the triangles, and the locations of the spectra, for data taken in one of the experiments in the program.

In the procedures that were employed, the radiative tails from elastic electron-proton scattering were subtracted from the measured spectra before the interpolations were carried out. In the MIT-SLAC radiative correction procedures, the radiative tails from elastic scattering were calculated using the formula of Tsai (Reference 42), which is exact to lowest order in α. The calculation of the tail included the effects of radiative energy degradation of the incident and final electrons, the contributions of multiple photon processes, and radiation from the recoiling proton. After the subtraction of the elastic peak's radiative tail, the inelastic radiative tails were removed in a one-pass unfolding procedure as outlined above. The particular form of the peaking approximation used was determined from a lit to an exact calculation of the inelastic tail to lowest order which incorporated a model that approximated the experimental cross sections. One set of formulas and procedures are described by Miller *et al.* (Reference 43) and were employed in the SLAC analysis. The measured cross sections were also corrected in a separate analysis, carried out at MIT, using a somewhat different set of approximations (Reference 44). Comparisons of the two gave corrected cross sections which agreed to within a few percent. Reference 45 contains a complete description of the MIT radiative corrections procedures that were applied, the cross checks that were carried out, and the assessment of errors arising both from the radiative corrections and from other sources of uncertainty in the experiment. Figure 8 shows the relative magnitude of the radiative corrections as a function of *W* for a typical spectrum with a hydrogen target. While radiative corrections were the largest corrections to the data, and involved a considerable amount of computation, they were understood to a confidence level of 5% to 10% and did not significantly increase the total error in the measurements.

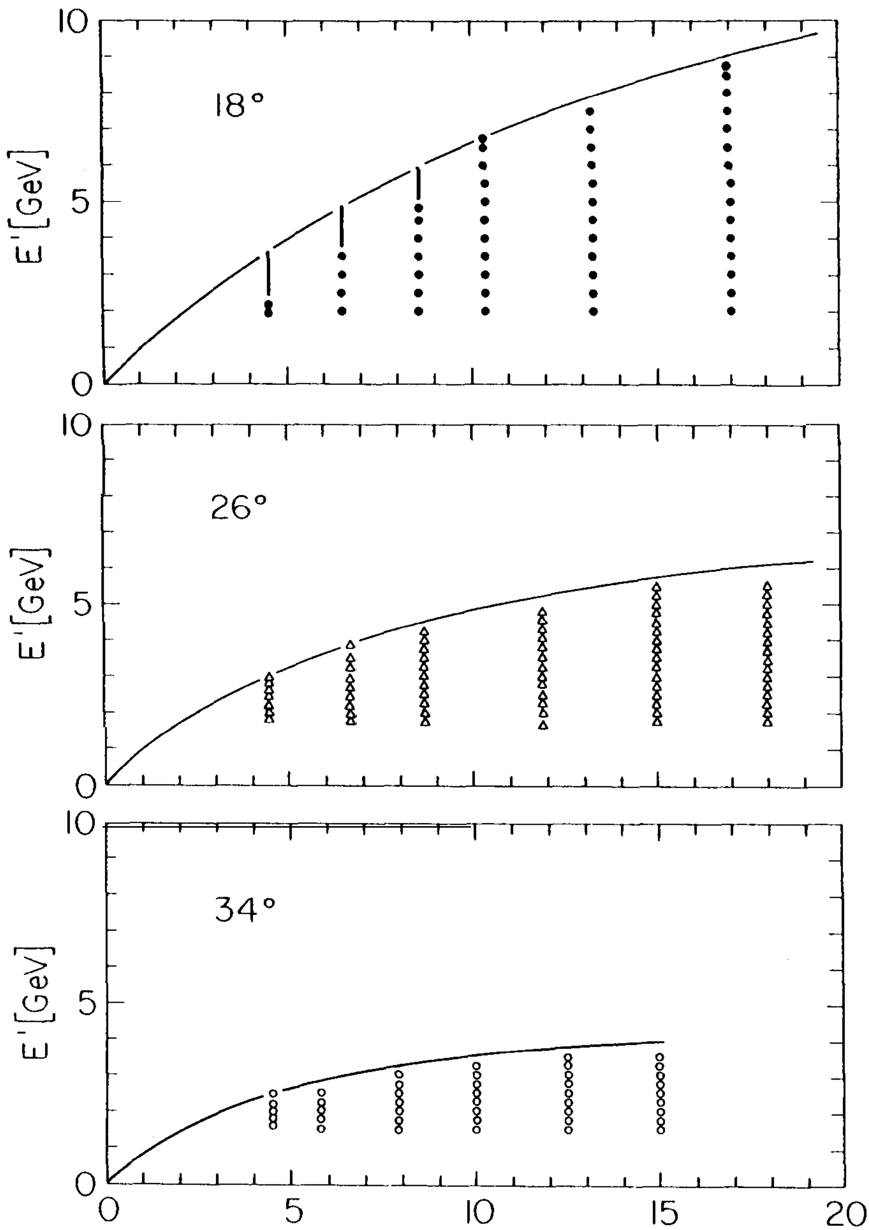


Fig. 7. Inelastic measurements: where spectra were taken to determine "triangles" employed in making radiative corrections for three angles selected for some of the later experiments. The solid curves represent the kinematics of elastic electron-proton scattering.

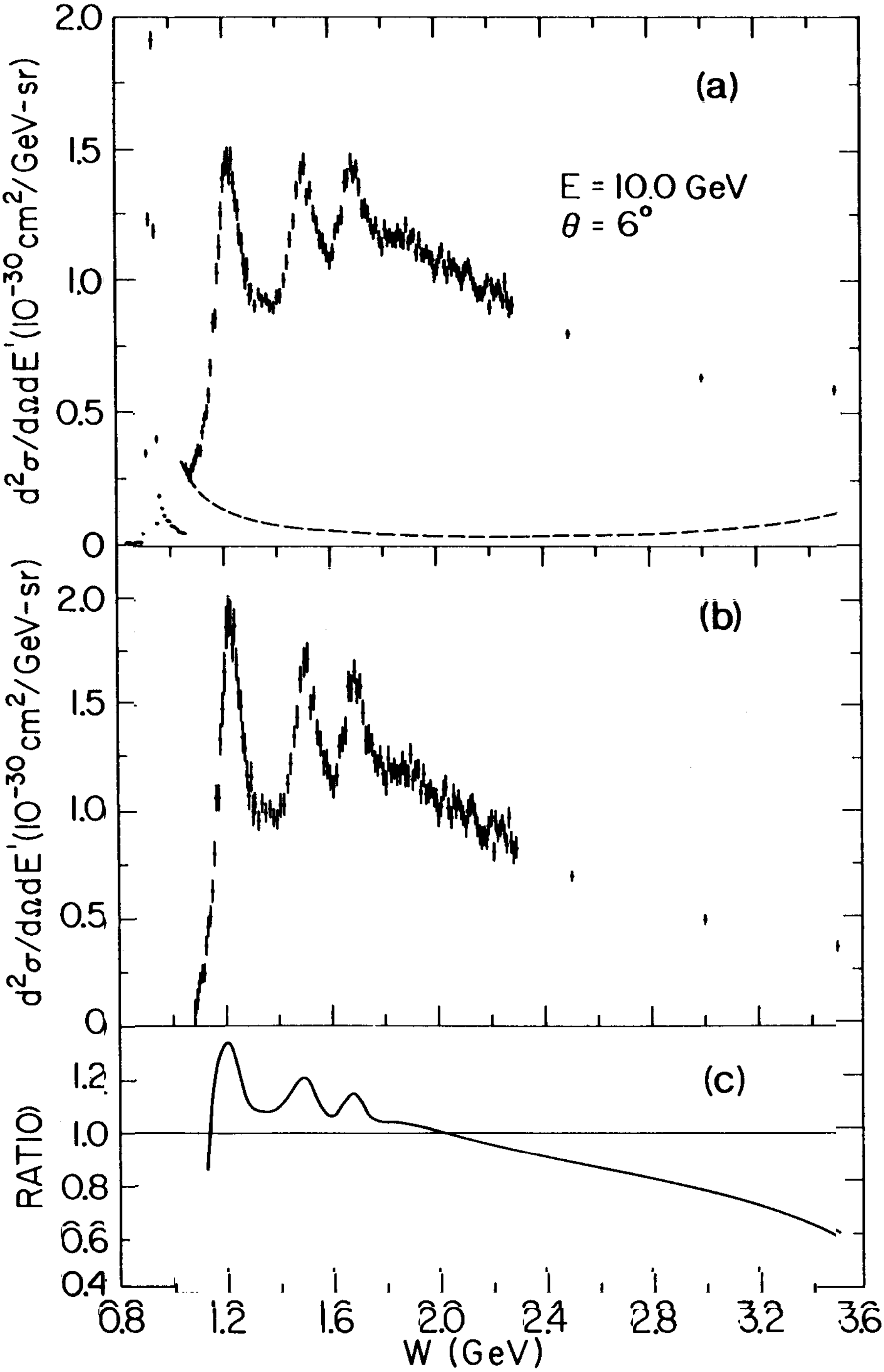


Fig. 8. Spectra of 10 GeV electrons scattered from hydrogen at 6^0, as a function of the final hadronic state energy W. Figure (8a) shows the spectrum before radiative corrections. The elastic peak has been reduced in scale by a factor of 8.5. The computed radiative "tail" from the elastic peak is shown. Figure (8 b) shows the same spectrum with the elastic peak's tail subtracted and inelastic corrections applied. Figure (8c) shows the ratio of the inelastic spectrum before, to the spectrum after, radiative corrections.

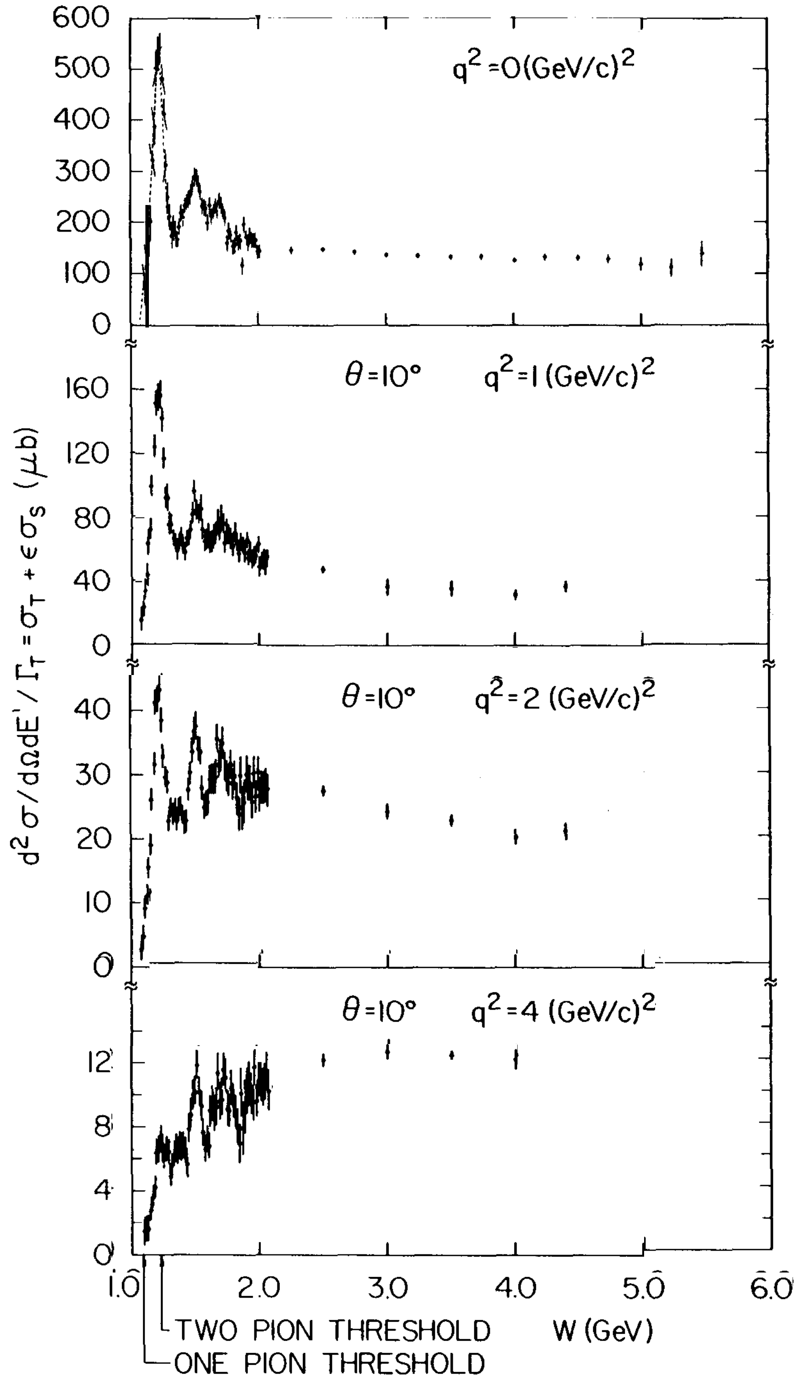


Fig. 9. Spectra of electrons scattered from hydrogen at q^2 up to 4 (GeV/c)^2. The curve for $q^2 = 0$ represents an extrapolation to $q^2 = 0$ of electron scattering data acquired at $\theta = 1.5°$. Elastic peaks have been subtracted and radiative corrections have been applied.

V *Electron Proton Scattering: Results.*

The scattered electron spectra observed in the experiments had a number of features whose prominence depended on the initial and final electron energies and the scattering angle. At low q^2 both the elastic peak and resonance excitations were large, with little background from non-resonant continuum scattering either in the resonance region or at higher missing masses. As q^2 increased, the elastic and resonance cross sections decreased rapidly, with the continuum scattering becoming more and more dominant. Figure 9 shows four spectra of differing q^2. Data points taken at the elastic peak and in the resonance region were closely spaced in E' so as to allow fits to be made to the resonance yields, but much larger steps were employed for larger excitation energies.

Figures 10a and 10b show visual fits to spectra over a wide range in energy and scattering angle (including one spectrum from the accelerator at the Deutsches Electronen Synchrotron (DEW)), illustrating the points discussed above.

Two features of the non-resonant inelastic scattering that appeared in the first continuum measurements were unexpected. The first was a quite weak q^2 dependence of the scattering at constant W. Examples for W = 2.0 and W = 3.0 GeV, taken from data of the first experiment, are shown in Figure 11 as a function of q^2. For comparison the q^2 dependence of elastic scattering is shown also.

The second feature was the phenomenon of scaling. During the analysis of the inelastic data, J. D. Bjorken suggested a study to determine if νW_2 was a function of ω alone. Figure 12a shows the earliest data so studied: W_2, for six values of q^2, as a function of v. Figure 12b shows $F_2 = \nu W_2$ for 10 values of q^2, plotted against ω. Because R was at that time unknown, F_2 was shown for the limiting assumptions, R = 0 and R = CO. It was immediately clear that the Bjorken scaling hypothesis was, to a good approximation, correct. This author, who was carrying out this part of the analysis at the time, recalls wondering how Balmer may have felt when he saw, for the first time, the striking agreement of the formula that bears his name with the measured wavelengths of the atomic spectra of hydrogen.

More data showed that, at least in the first regions studied and within sometimes large errors, scaling held nearly quantitatively. As we shall see, scaling holds over a substantial portion of the ranges of v and q^2 that have been studied. Indeed the earliest inelastic e-p experiments (Reference 30) showed that approximate scaling behavior occurs already at surprisingly non-asymptotic values of $q^2 \geq$ 1 .O GeV^2 and $W \geq 2.6$ GeV.

The question quickly arose as to whether there were other scaling variables that converged to ω in the Bjorken limit, and that provided scaling behavior over a larger region in v and q^2 than did the use of ω. Several were proposed (Reference 46) before the advent of QCD, but because this theory predicts small departures from scaling, the search for such variables was abandoned soon after.

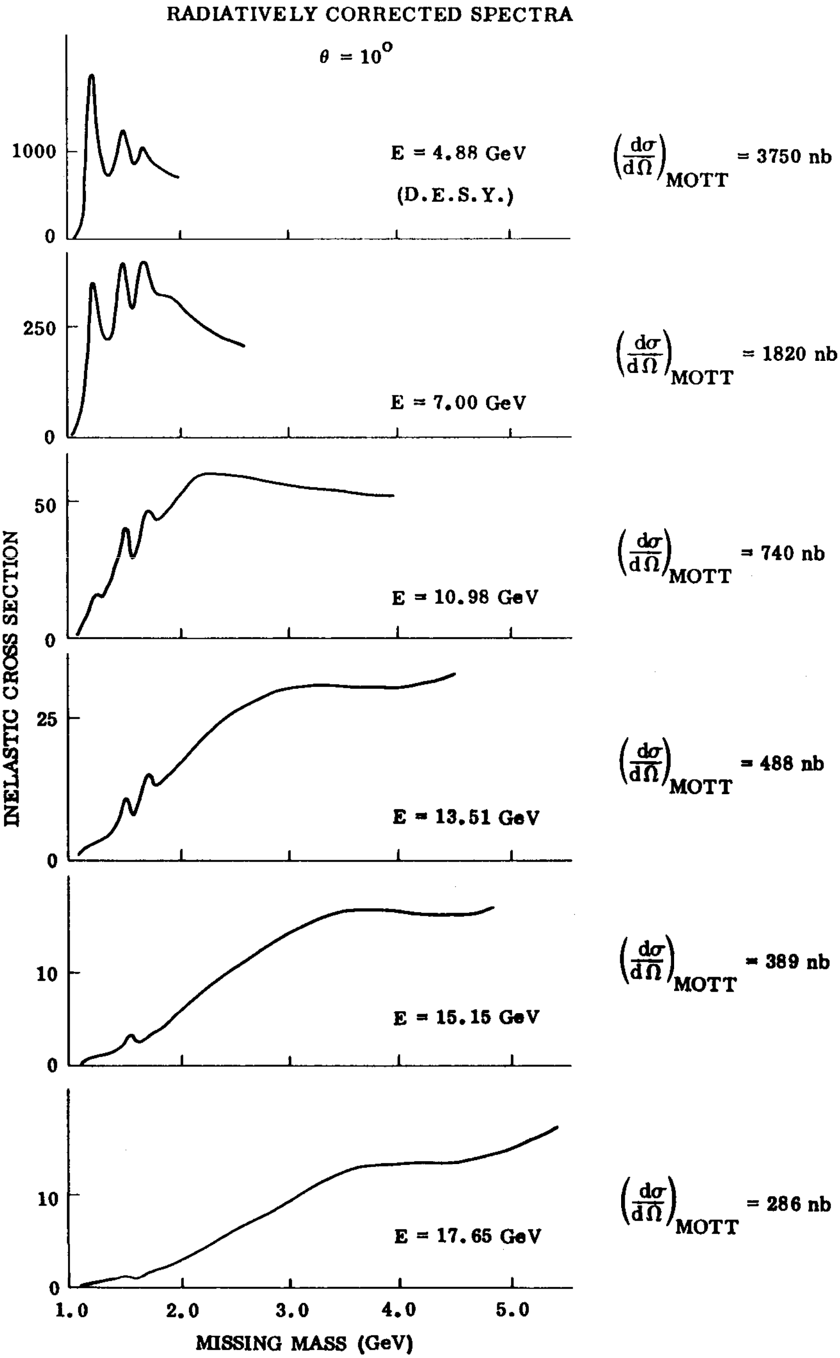


Fig. 10a. Visual fits to spectra showing the scattering of electrons from hydrogen at 10° for primary energies, *E,* from 4.88 GeV to 17.5 GeV. The elastic peaks have been subtracted and radiative corrections applied. The cross sections are expressed in nanobarns per GeV per steradian. The spectrum for *E* = 4.88 GeV was taken at DESY; W. Bartel, et al., Phys. Lett., B28 148 (1968).

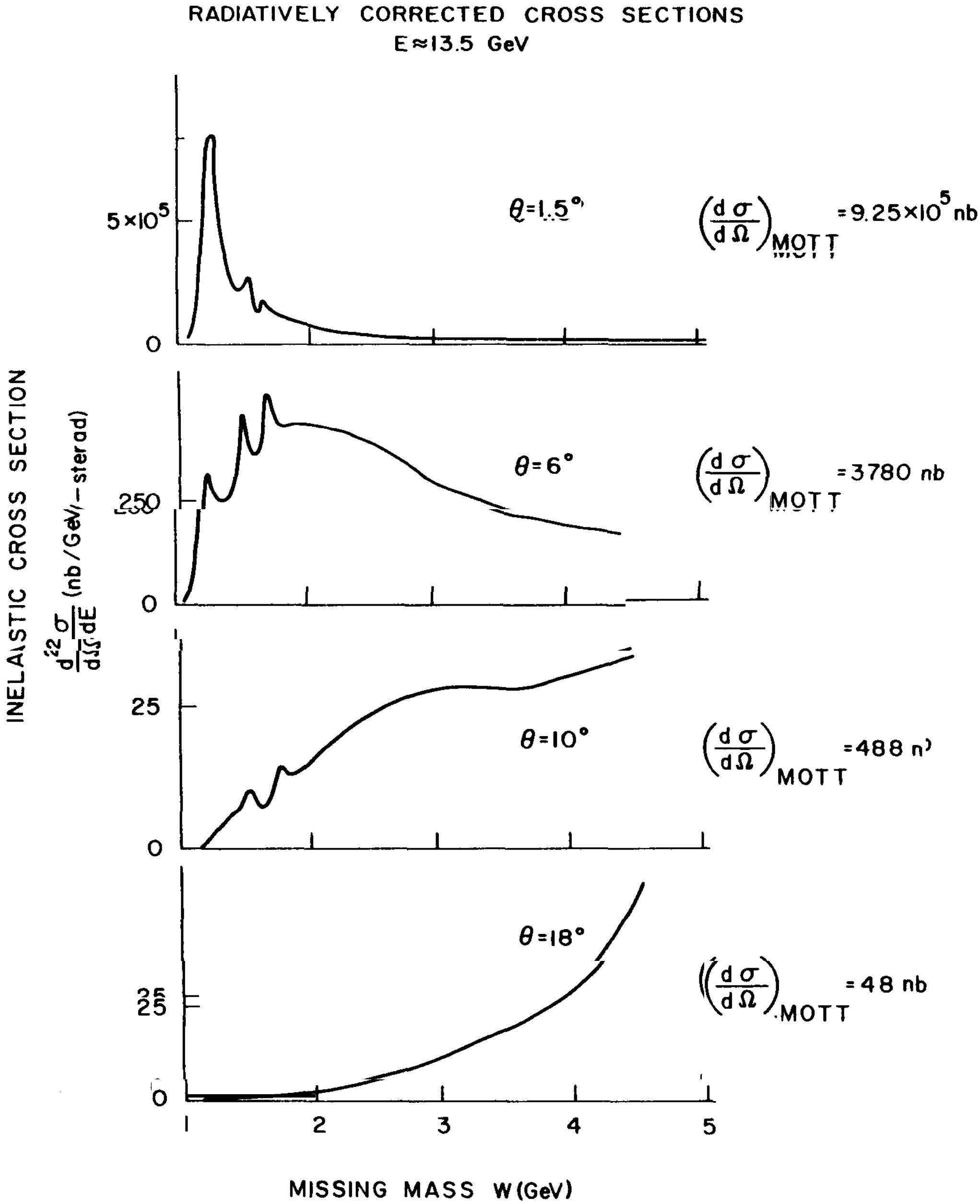


Fig. 10b. Visual fits to spectra showing the scattering of electrons from hydrogen at a primary energy E of approximately 13.5 GeV, for scattering angles from 1.5° to 18°. The 1.5° curve is taken from MIT-SLAC data used to obtain photoabsorption cross sections.

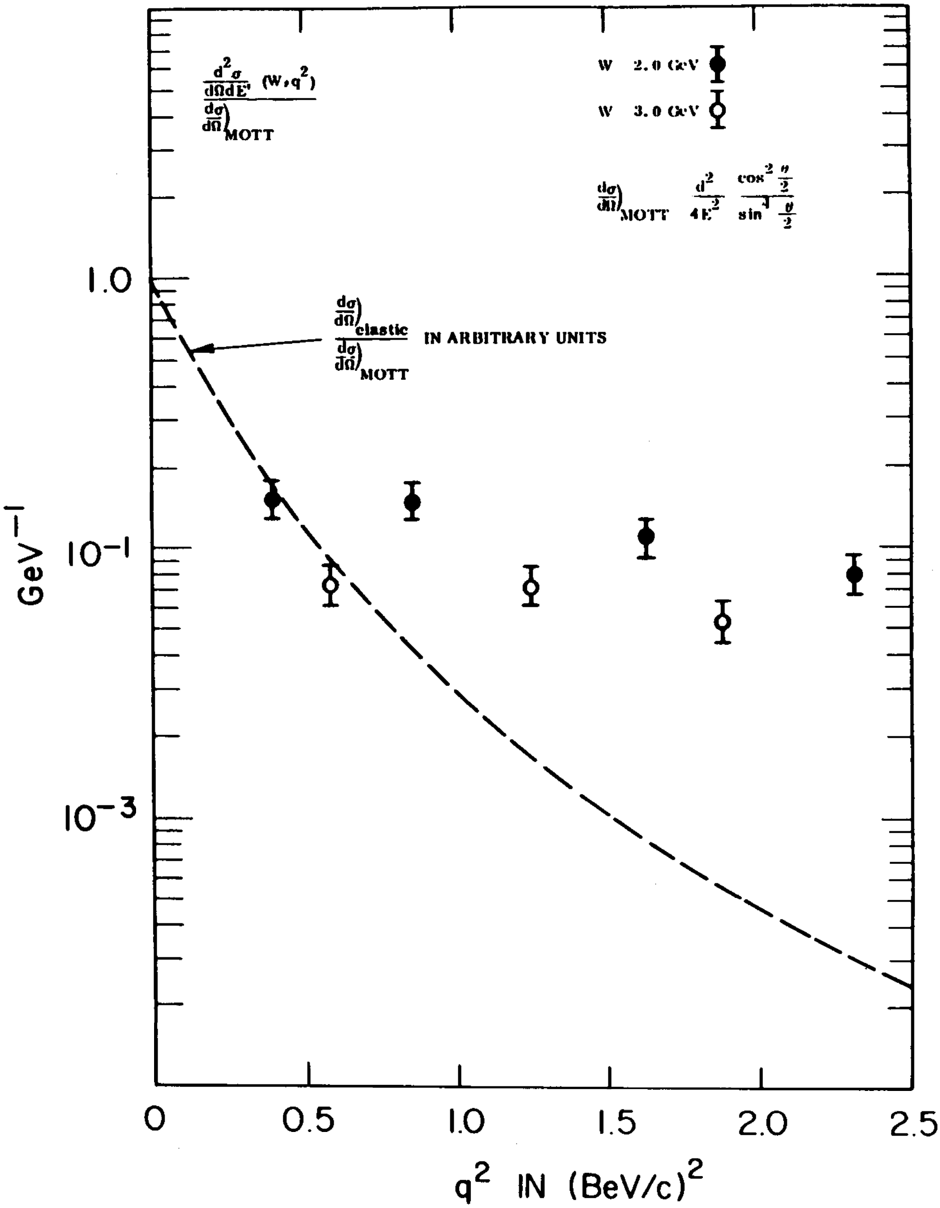


Fig. 11. **Inelastic data for $W = 2$ and 3 GeV as a function of q^2. This was one of the earliest examples of the relatively large cross sections and weak q^2 dependence that were later found to** characterize the deep inelastic scattering and which suggested point-like nucleon constituents. The q^2 dependence of elastic scattering is shown also; these cross sections have been divided by σ_M

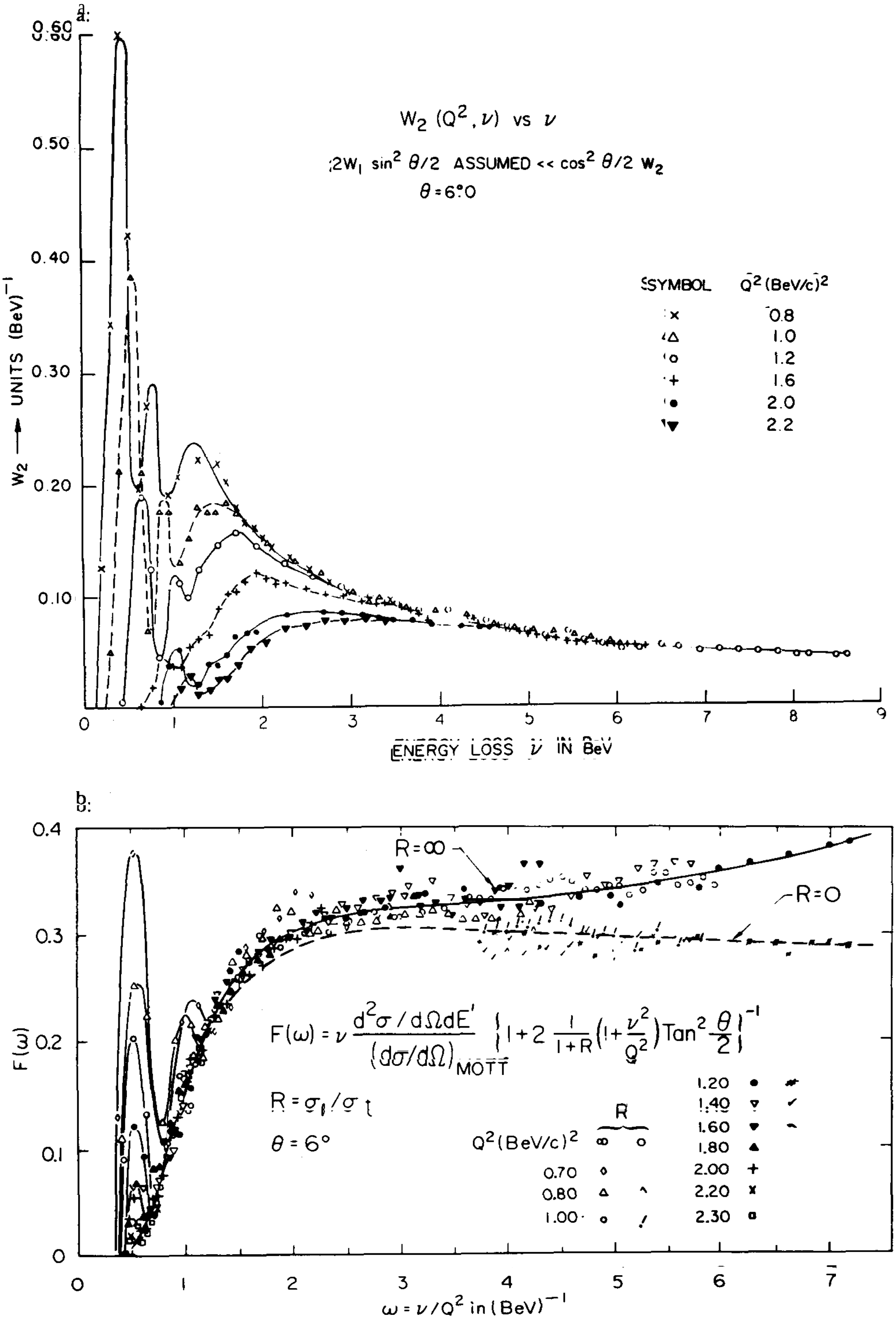


Fig. 12. **(a) The inelastic structure function $W_2(\nu,q^2)$ plotted against the electron energy loss ν.** (b) The quantity $F_1 = \nu W_2(\omega)$. The "nesting" of the data observed here was the first evidence of scaling. The figure is discussed further in the text.

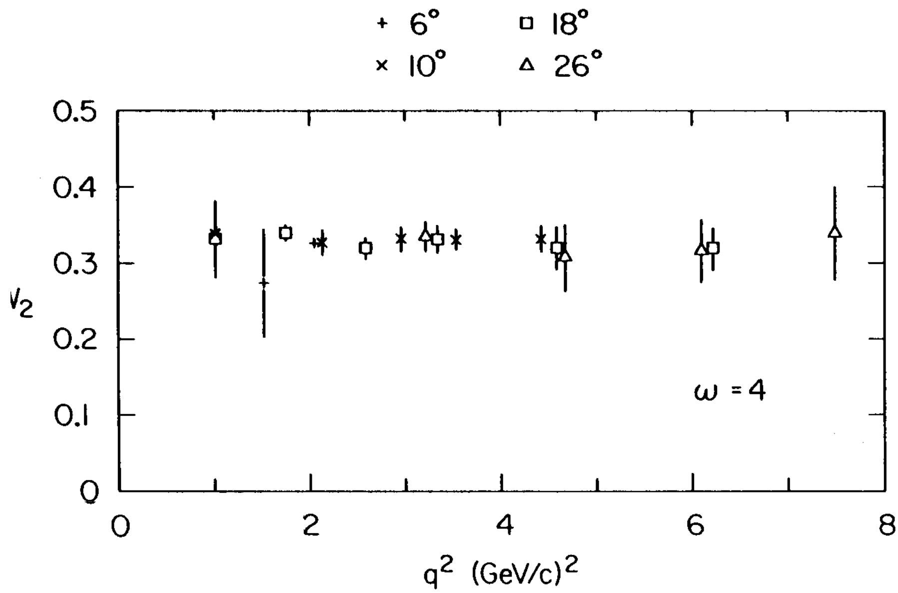


Fig. 13. An early observation of scaling: νW_2 for the proton as a function of q^2 for W > 2 GeV, at ω = 4.

Figure 13 shows early data on νW_2, for ω = 4, as a function of q^2. Within the errors there was no q^2 dependence.

A more complex separation procedure was required to determine R and the structure functions, as discussed above. The kinematic region in q^2 - W^2 space available for the separation is shown in Figure 14. This figure also shows the 75 kinematic points where, after the majority of the experiments were complete, separations had been made. Figure 15 displays sample least-square fits to $\Sigma(\nu,q^2,\theta)$ vs $\varepsilon(\nu,q^2,\theta)$, as defined earlier, in comparison with data, from which σ_L and σ_T and then R, were found.

A rough evaluation of scaling is provided by, for example, inspecting a plot of the data taken by the collaboration on νW_2 against x as shown in Figure 16. These data, to a fair approximation, describe a single function of x. Some deviations, referred to as scale breaking, are observed. They are more easily inspected by displaying the q^2 dependence of the structure functions. Figure 17 shows separated values of $2MW_1$ and νW_2 from data taken late in the program, plotted against q^2 for a series of constant values of x. With extended kinematic coverage and with smaller experimental errors, sizeable scale breaking was observed in the data.

VI *Theoretical Implications of the Electron-Proton Inelastic Scattering Data.*

As noted earlier, the discovery, during the first inelastic proton measurements, of the weak q^2 dependence of the structure function νW_2, coupled with the scaling concept inferred from current algebra and its roots in the quark theory, at once suggested new possibilities concerning nucleon structure. At the 1968 Vienna Meeting, where the results were made public for

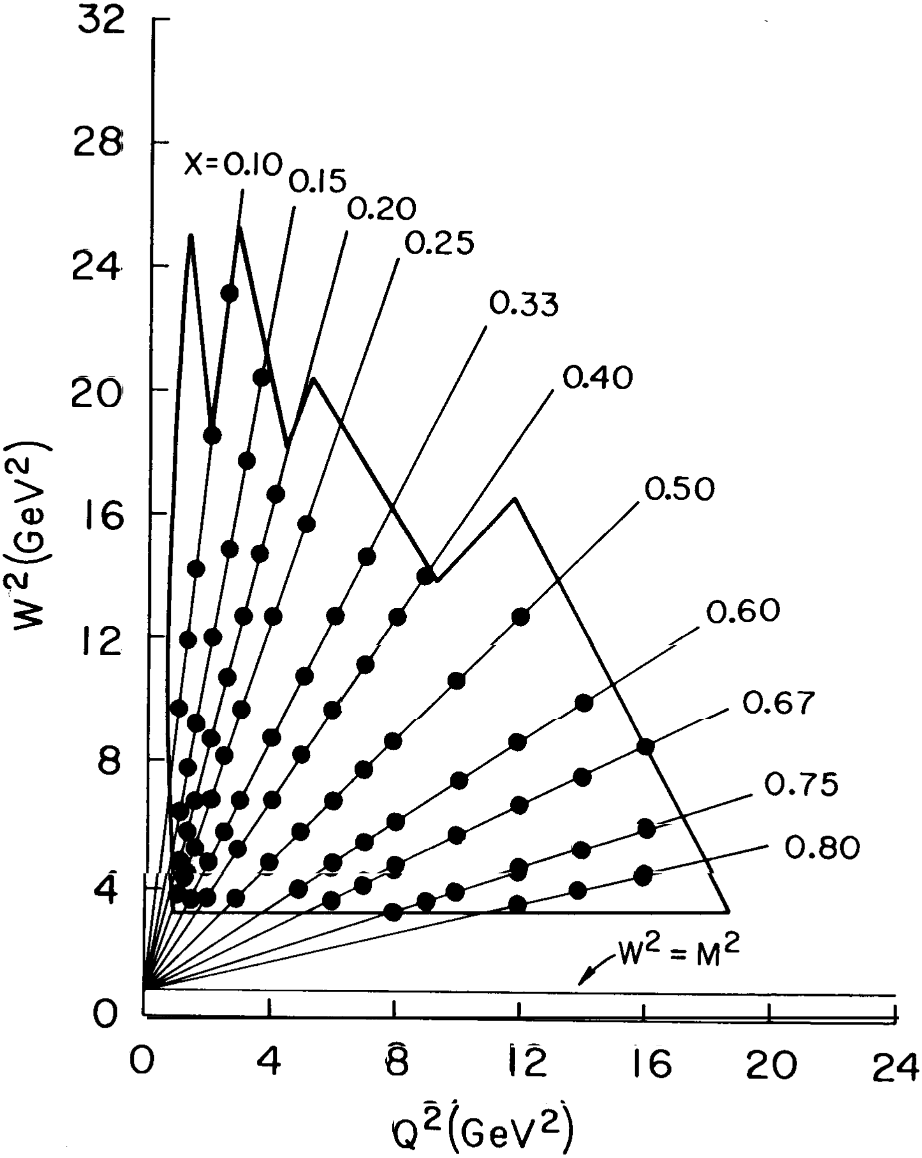


Fig. 14. The kinematic region in $q^2 - W^2$ space available for the extraction of R and the structure functions. Separations were made at the 75 kinematic points (ν, q^2) shown.

William A Fowler

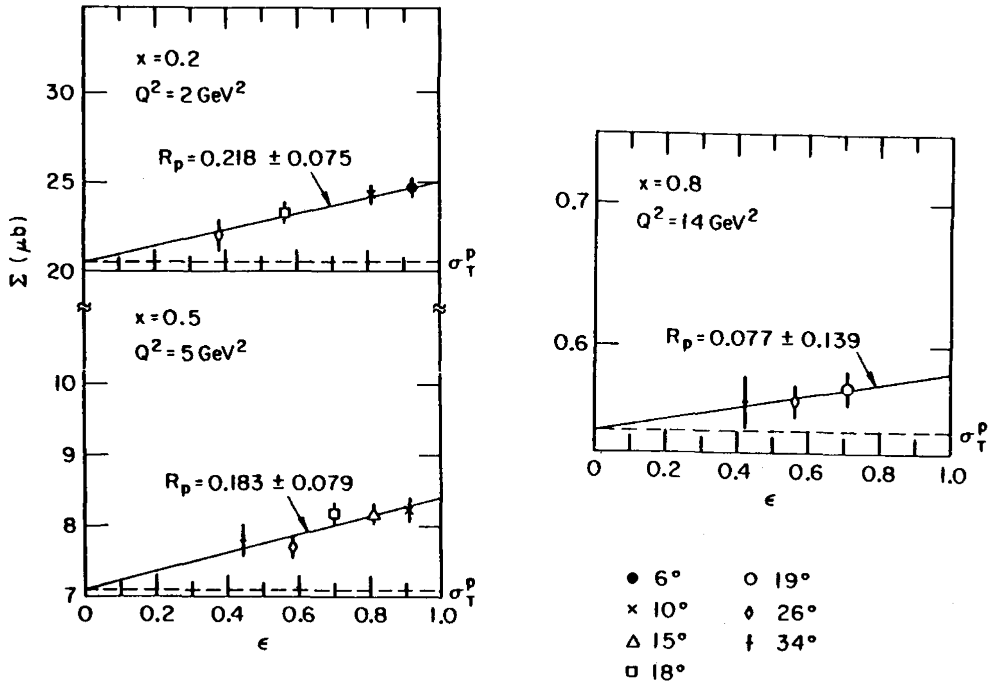


Fig. 15. **Sample least-square fits to Σ vs ε in comparison with data from the proton. The** quantities R and σ_T were available from the fitting parameters, and from them σ_L was determined.

the first time, the rapporteur, W. K. H. Panofsky, summed up the conclusions (Reference 47): "Therefore theoretical speculations are focussed on the possibility that these data might give evidence on the behavior of point-like, charged structures within the nucleon."

Theoretical interest at SLAC in the implications of the inelastic scattering increased substantially after an August 1968 visit by R. P. Feynman. He had been trying to understand hadron-hadron interactions at high energy assuming constituents he referred to as partons. On becoming aware of the inelastic electron scattering data, he immediately saw in partons an explanation both of scaling and the weak q^2 dependence. In his initial formulation (Reference 48), now called the naive parton theory, he assumed that the proton was composed of point-like partons, from which the electrons scattered incoherently. The model assumed an infinite momentum frame of reference, in which the relativistic time dilation slowed down the motion of the constituents. The transverse momentum was neglected, a simplification relaxed in later elaborations. The partons were assumed not to interact with one another while the virtual photon was exchanged: the impulse approximation of quantum mechanics. Thus, in this theory, electrons scattered from constituents that were "free," and therefore the scattering reflected the properties and motions of the constituents. This assumption of a near-vanishing of the par-ton-parton interaction during lepton scattering, in the

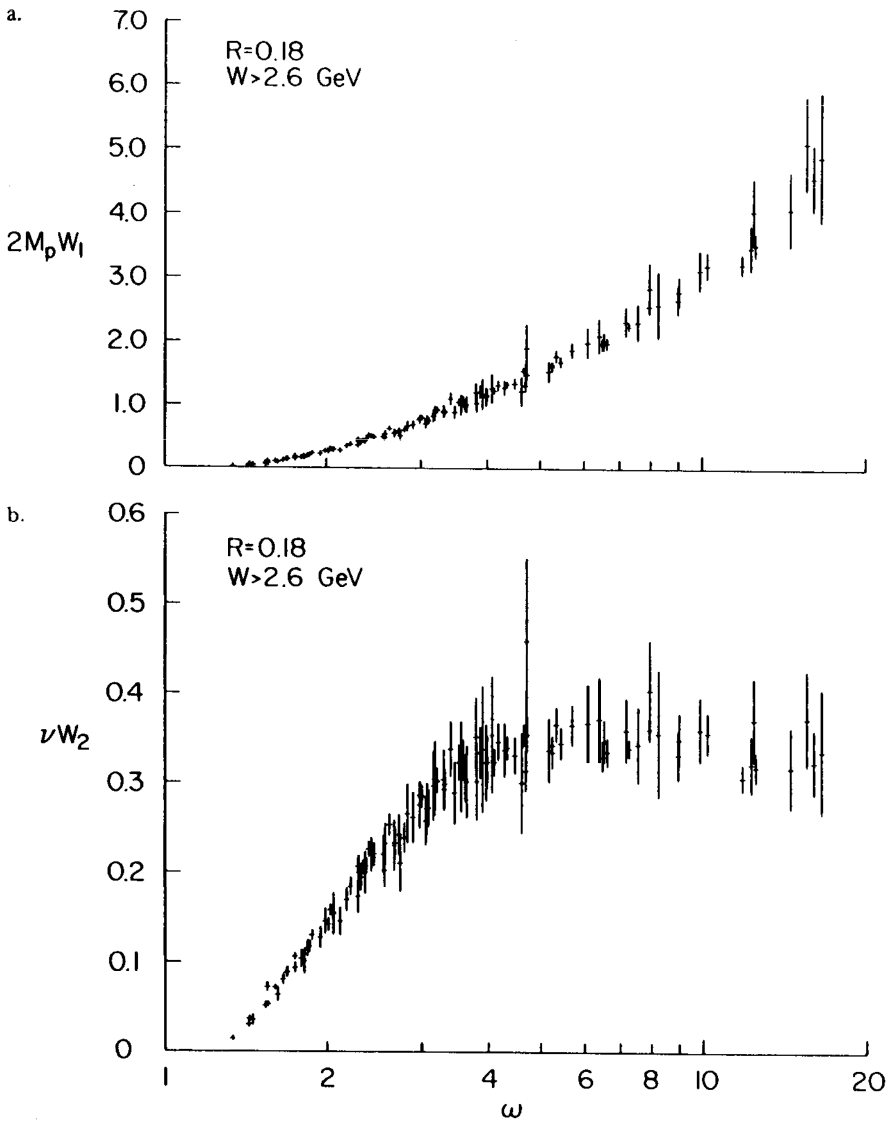


Fig. 16. (a,b) Scaling: $F_1 = 2MW_1(\omega)$ vs ω, and $F_2 = \nu W_2(\omega)$ vs ω, for the proton.

Bjorken limit, was subsequently shown to be a consequence of QCD known as *asymptotic freedom*. Feynman came to Stanford again, in October 1968, and gave the first public talk on his parton theory, stimulating much of the theoretical work which ultimately led to the identification of his partons with quarks.

In November 1968, Curt Callan and David Gross (Reference 49) showed that *R*, given in Equation (6), depended on the spins of the constituents in a parton model and that its kinematic variation constituted an important test

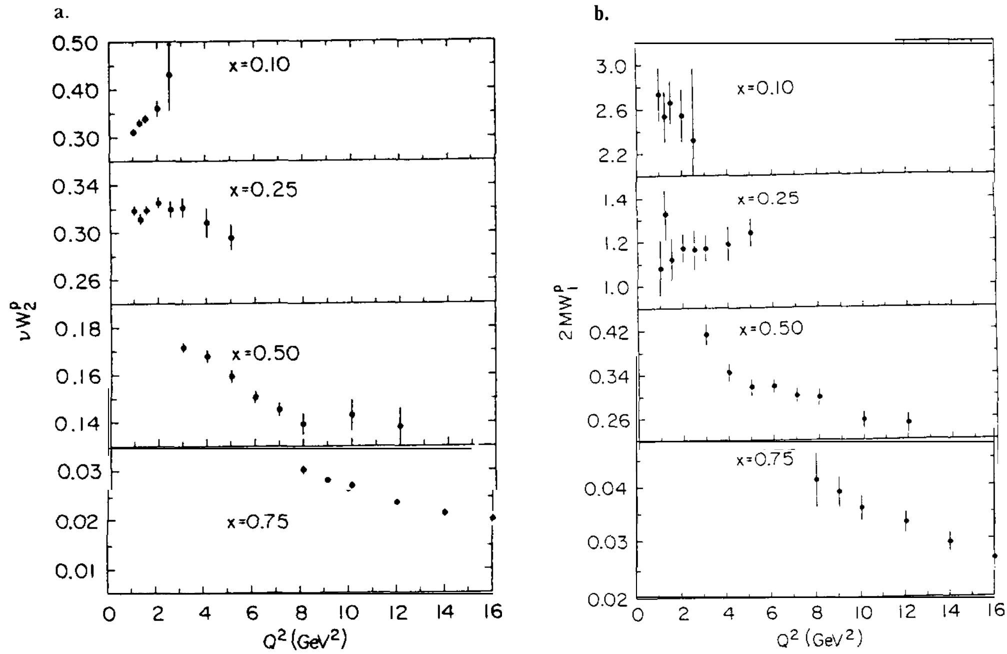


Fig. 17. (a,b) F_1 and F_2 as functions of q^2, for fixed values of x, for the proton.

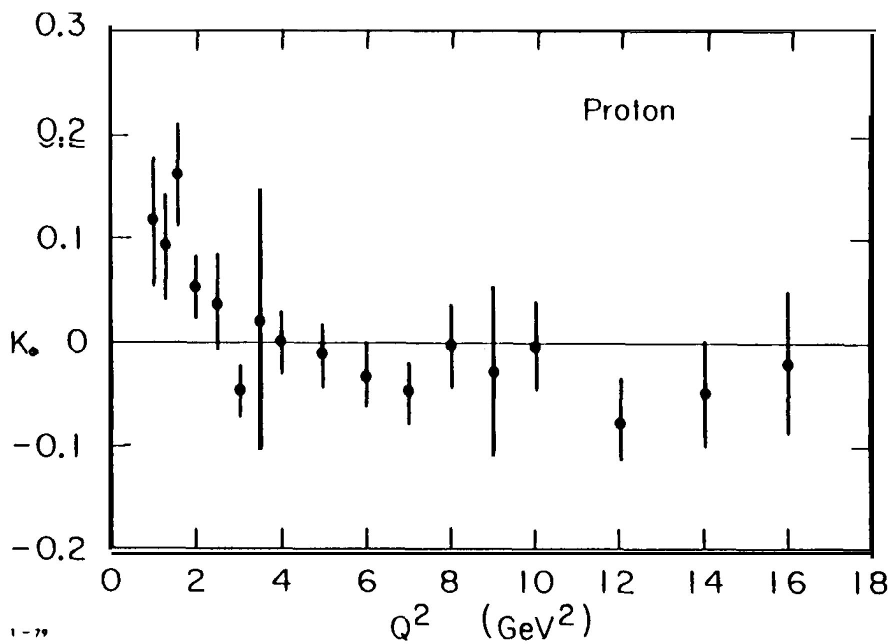


Fig. 18. The Callan-Gross relation: K_0 vs q^2, where K_0 is defined in the text. These results established the spin of the partons as 1/2.

of such models. For spin 1/2, R was expected to be small, and, for the naive parton model, where the constituents are assumed unbound in the Bjorken limit, $R = q^2/\nu^2$ (ie, $F_2 = xF_1$). More generally, for spin 1/2 partons, $R = g(x)(q^2/\nu^2)$. This is equivalent to the scaling of νR.

Spin zero or one partons led to the prediction $R \neq 0$ in the Bjorken limit, and would indicate that the proton cloud contains elementary bosons. Small values of R were found in the experiment and these were totally incompatible with the predictions of Vector Meson Dominance. Later theoretical studies (Reference 50) showed that deviations from the general Callan-Gross rule would be expected at low x and low q^2. A direct evaluation of the Callan-Gross relation for the naive parton model may be found from

$$K_0 = F_2/(xF_1) - 1$$

which vanishes when the relation is satisfied. K_0 is shown in Figure 18, as a function of q^2. Aside from the expected deviations at low q^2, K_0 is consistent with zero, establishing the parton spin as 1/2.

VII *Epilogue*

After the initial inelastic measurements were completed, deuteron studies were initiated to make neutron structure functions accessible. Experiments were made over a greater angular range and statistical, radiative, and systematic errors were reduced. The structure functions for the neutron were found to differ from the proton's. Vector Meson Dominance was abandoned and by 1972 all diffractive models, and nuclear democracy, were found to be inconsistent with the experimental results. Increasingly detailed parton calculations and sum rule comparisons, now focussing on quark constituents, required sea quarks - virtual quark-antiquark pairs - in the nucleon, and, later, gluons - neutral bosons that provided the inter-quark binding.

On the theoretical front, a special class of theories was found that could incorporate asymptotic freedom and yet was compatible with the binding necessary to have stable nucleons. Neutrino measurements confirmed the spin 1/2 assignment for partons and that they had fractional, rather than integral electric charge. The number of "valence" quarks was found to be 3, consistent with the original 1964 assumptions.

By 1973, the picture of the nucleon had clarified to such an extent that it became possible to construct a comprehensive theory of quarks and gluons and their strong interactions: QCD. This theory was built on the concept of "color," whose introduction years before (Reference 51) made the nucleons' multi-quark wave functions compatible with the Pauli principle, and, on the assumption that only "color-neutral" states exist in nature, explained the absence of all unobserved multi-quark configurations (such as quark-quark and quark-quark-antiquark) in the known array of hadrons. Furthermore, as noted earlier, QCD was shown to be asymptotically free (Reference 52).

By that year the quark-parton model, as it was usually called, satisfactorily explained electron-nucleon and neutrino-nucleon interactions, and provided a rough explanation for the very high energy "hard" nucleon-nucleon scattering that had only recently been observed. The experimenters were seeing quark-quark collisions.

By the end of the decade, the fate of quarks recoiling within the nucleon in high energy collisions had been understood; for example, after quark pair production in electron-positron colliders, they materialized as back-to-back jets composed of ordinary hadrons (mainly pions), with the angular distributions characteristic of spin l/2 objects. Gluon-jet enhancement of quark jets was predicted and then observed, having the appropriate angular distributions for the spin 1 they were assigned within QCD. Theorists had also begun to deal, with some success, with the problem of how quarks remained confined in stable hadrons.

Quantum Chromodynamics describes the strong interactions of the hadrons and so can account, in principle at least, for their ground state properties as well as hadron-hadron scattering. The hadronic weak and electromagnetic interactions are well described by electroweak theory, itself developed in the late 1960s. The picture of the nucleon, and the other hadrons, as diffuse, structureless objects was gone for good, replaced by a successful, nearly complete theory.

ACKNOWLEDGEMENTS

There were many individuals who made essential contributions to this work. An extensive set of acknowledgements is given in Reference 53.

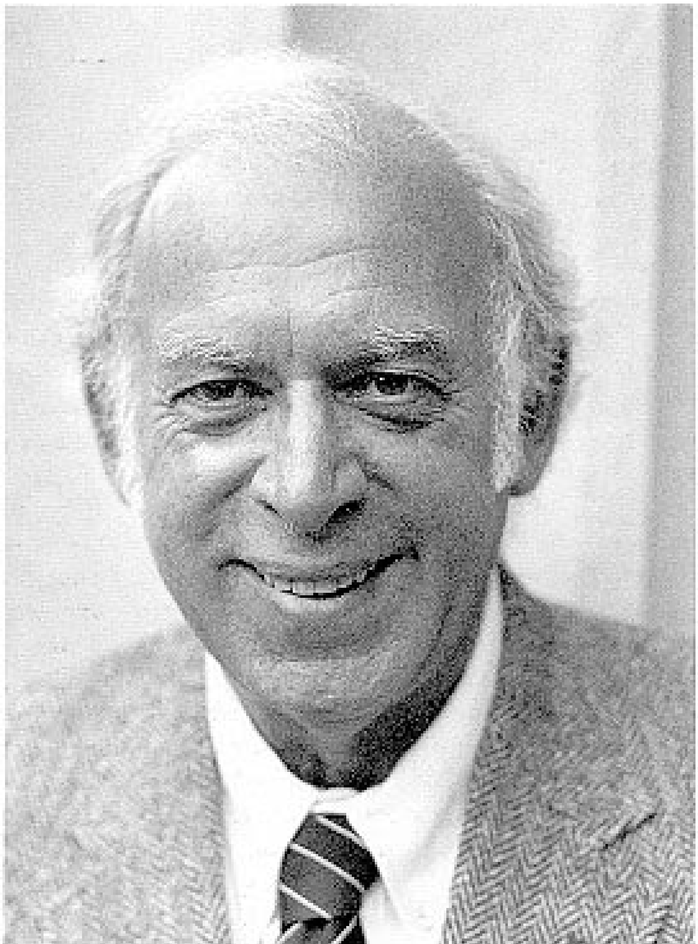
REFERENCES

1. R.E.Taylor, Deep Inelastic Scattering: The Early Years. Les Prix *Nobel 1990.* Hereafter "Taylor."
2. J. I. Friedman, Deep Inelastic Scattering: Comparisons with the Quark Model. Les *Prix Nobel* 1990. Hereafter "Friedman."
3. S. C. Frautschi, *Regge Poles and S-Matrix Theory,* W. A. Benjamin (1963). Hereafter "Frautschi."
4. G. F. Chew and S. C. Frautschi, Phys. Rev. Lett. 8, 394 (1961).
5. P. D. B. Collins and E. J. Squires, *Regge Poles in Particle Physics,* Springer-Verlag, Berlin (1968). For a broad review of the strong interaction physics of the period see Martin L. Perl, *High Energy Hadron Physics,* John Wiley & Sons, (New York 1974). See also Frautschi.
6. G. F. Chew, S. C. Frautschi, and S. Mandelstam, Phys. Rev. 126, 1202 (1962).
7. G. Veneziano, Nuovo Cim. 57A, 190 (1968). See also J. H. Schwarz, Phys. Rep. 8, 269 (1973).
8. J.J.Sakurai, Phys. Rev. Lett. 22, 981 (1969).
9. M. Cell-Mann, Phys. Lett. 8, 214 (1964).
10. G. Zweig, CERN-8182/Th.401 (Jan. 1964) and CERN-8419/Th.412 (Feb. 1964), both unpublished. Hereafter "Zweig."
11. M. Gell-Mann, C. I. T. Synchrotron Lab. Rep't, CTSL-20 (unpublished) and Y. Ne'eman, Nuc. Phys. 26, 222 (1961). See also M. Gell-Mann and Y. Ne'eman, *The Eightfold Way,* W. A. Benjamin (1964).

12. The quark model explained why triplet, sextet, and 27-plets of then-current SU(3) were absent of hadrons. With rough quark mass assignments, it could account for observed mass splittings within multiplets, and it provided an understanding of the anomalously long lifetime of the phi meson (discussed later in this paper).
13. Lawrence W. Jones, Rev. Mod. Phys. 49, 717 (1977).
14. ".we know that.. .[mesons and baryons] are mostly, if not entirely, made up out of one another. . . The probability that a meson consists of a real quark pair rather than two mesons or a baryon and antibaryon must be quite small." M. Cell-Mann, *Proc.XIIIth Inter. Conf. on High En. Phys.,* Berkeley, California 1967.
15. "Additional data is necessary and very welcome in order to destroy the picture of elementary constituents." J. D. Bjorken. "I think Prof. Bjorken and I constructed the sum rules in the hope of destroying the quark model." Kurt Gottfried. Both quotations from *Proc. 1967 Internat. Symp.* on *Electron and Photon Interac. at High Energy,* Stanford, California, Sept. 5 -9, 1967.
16. R. Dalitz, Session 10, Rapporteur. *Proc. XIIIth Inter. Conf: High En. Phys.,* Berkeley, 1966. (University of California, Berkeley).
17. C. Becchi and G. Morpurgo, Phys. Lett. 17, 352 (1965).
18. K. Gottfried, Phys. Rev. Lett. 18, 1174 (1967).
19. Zweig believed from the outset that the nucleon was composed of "physical" quark constituents. This was based primarily on his study of the properties of the phi meson. It did not decay rapidly to ***p-n*** as expected but rather decayed roughly two orders of magnitude slower to kaon-antikaon, whose combined mass was near the threshold for the decay. He saw this as a dynamical effect; one not explainable by selection rules based on the symmetry groups and explainable only by a constituent picture in which the initial quarks would "flow smoothly" into the final state. He was "severely criticized" for his views, in the period before the MIT-SLAC results were obtained. Private communication, February 1991.
20. According to a popular book on the quark search, Zweig, a junior theorist visiting at CERN when he proposed his quark theory, could not get a paper published describing his ideas until the middle 1970s, well after the constituent model was on relatively strong ground; M. Riordan, *The Hunting of the Quark,* Simon and Schuster, New York (1987). His preprints (cf. Zweig) did, however, reach many in the physics community and helped stimulate the early quark searches.
21. A. Pais, *Inward* Bound, Oxford University Press, New York City (1986).
22. "Throughout the 1960s, into the 1970s, papers, reviews, and books were replete with caveats about the existence of quarks." Andrew Pickering, *Constructing* Quarks, University of Chicago Press (Chicago 1984).
23. Further discussion of sum rules and their comparisons with data is to be found in Friedman.
24. "Such particles [quarks] presumably are not real but we may use them in our field theory anyway." Physics 1, 63 (1964).
25. "Now what is going on? What are these quarks? It is possible that real quarks exist, but if so they have a high threshold for copious production, many BeV; ..." *Proc. XIIIth Inter. Conf. on High En. Phys.,* Berkeley, California, 1967.
26. "We shall find these results [sum rules requiring cross sections of order Rutherford scattering from a point particle] so perspicuous that, by an appeal to history, an interpretation in terms of 'elementary constituents' of the nucleon is suggested." He pointed out that high energy lepton-nucleon scattering could resolve the question of their existence and noted that "it will be of interest to look at very large inelasticity and dispose, without ambiguity, of the model completely." "Current Algebra at Small Distances," lecture given at International School of Physics, "Enrico Fermi," XLI Course, Varenna, Italy, July

1967. SLAC Pub. 338, August 1967 (unpublished) and *Proceedings of the International School of Physics "Enrico Fermi", Course XLI: Selected Topics in Particle Physics,* J. Steinberger, ed. (Academic Press, New York, 1968).
27. T. D. Lee: "I'm certainly not the person to defend the quark models, but it seems to me that at the moment the assumption of an unsubtracted dispersion relation [the subject of the discussion] is as ad *hoc* as the quark model. Therefore, instead of subtracting the quark model one may also subtract the unsubtracted dispersion relation." J. Bjorken: "I certainly agree. I would like to dissociate myself a little bit from this as a test of the quark model. I brought it in mainly as a desperate attempt to interpret the rather striking phenomena of a point-like behavior. One has this very strong inequality on the integral over the scattering cross section. It's only in trying to interpret how that inequality could be satisfied that the quarks were brought in. There may be many other ways of interpreting it." Discussion in *Proc. 1967 Internat. Symp. on Electron and Photon Interac. at High Energy,* Stanford, Sept 5 -9, 1967.
28. *Proposal for Spectrometer Facilities at SLAC,* submitted by SLAC Groups A and C, and physicists from MIT and CIT. (Stanford, California, undated, unpublished). *Proposal for Initial Electron Scattering Experiments* Using *the SLAC Spectrometer Facilities:* Proposal 4b "The Electron-Proton Inelastic Scattering Experiment," submitted by the SLAC-MIT-CIT Collaboration, 1 January 1966 (unpublished).
29. *The Stanford Two-Mile Accelerator* R. B. Neal, General Editor, W. A. Benjamin (New York 1968).
30. *14th Int. Conf. High Energy Phys.,* Vienna, Aug., 1968. E. D. Bloom et al., Phys. Rev. Lett. 23, 930 (1969); M. Breidenbach et al., ibid 23, 935 (1969).
31. W. R. Ditzler, et al., Phys. Lett. 57B, 201 (1975).
32. L. W. Whitlow, et al., Phys. Lett. B250, 193 (1990) and L. W. Whitlow, SLAC Report 357, March 1990 (unpublished).).
33. M. Rosenbluth, Phys. Rev. 79, 615 (1950).
34. P. N. Kirk, et al., Phys. Rev. D8, 63 (1973).
35. S. D. Drell and J. D. Walecka, Ann. Phys. 28, 18 (1964).
36. L. Hand, Phys. Rev. 129, 1834 (1963).
37. J. D. Bjorken, Phys. Rev. 179, 1547 (1969). Although the conjecture was published after the experimental results established the existence of scaling, the proposal that this might be true was made prior to the measurements as discussed later in the text.
38. J. D. Bjorken, Ann. Phys. 24, 201 (1963).
39. J. I. Friedman, Phys. Rev. 116, 1257 (1959).
40. D. Isabelle and H. W. Kendall, Bull. Am. Phys. Soc. 9, 95 (1964). The final report on the experiment is S. Klawansky et al., Phys. Rev. C7, 795 (1973).
41. G. Miller et al., Phys. Rev. D5, 528 (1972); L. W. Mo and Y. S. Tsai, Rev. Mod. Phys. 41, 205 (1969).
42. Y. S. Tsai, *Proc. Nucleon Struct. Conf. Stanford* 1963, p. 22 1. Stanford Univ. Press (Stanford 1964), edited by R. Hofstadter and L. I. Schiff.
43. G. Miller et al., Phys. Rev. D5, 528 (1972).
44. Poucher, J. S. 1971. PhD thesis, MIT, (unpublished).
45. A. Bodek et al., Phys. Rev. D20, 1471 (1979).
46. J. I. Friedman and H. W. Kendall, Ann. Rev. Nuc. Sci., 22, 203 (1972). A portion of this publication is used in the present paper.
47. W.K.H.Panofsky, in 14th *Int. Conf. High Energy Phys.,* Vienna, Aug., 1968, edited by J. Prentki and J. Steinberger (CERN, Geneva), p 23.
48. R. P. Feynman, Phys. Rev. Lett. 23, 1415 (1969).
49. C. Callan and D. J. Gross, Phys. Rev. Lett. 21, 311 (1968).
50. R. P. Feynman, *Photon-Ha&on Interactions,* W. A. Benjamin (1972).
51. M. Y. Han and Y. Nambu, Phys. Rev. 139B, 1006 (1965).

52. D. Gross and F. Wilczek, Phys. Rev. Lett. 30, 1343 (1973), D. Politzer, ibid., 1346.
53. J. I. Friedman, H. W. Kendall, and R. E. Taylor, Deep Inelastic Scattering: Acknowledgements, *Les Prix Nobel 1990*.



Jerome I. Friedman

JEROME I. FRIEDMAN

I was born in Chicago, Illinois on March 28, 1930, the second of two children of Selig and Lillian Friedman, nee Warsaw, who were immigrants from Russia. My father came to the United States in 1913 and later served in the U.S. Army Artillery Corps in World War I. After the war he was employed by the Singer Sewing Machine Co. and later established his own business, repairing and selling used commercial and home sewing machines. My mother arrived in the United States in 19 14 on one of the last voyages of the Lusitania. She supported herself until she was married by working in a garment factory. My parents had little formal education, except for courses in English after they arrived in the United States, but were self taught and had wide ranging interests. My father was an avid reader, having interests in science and political history, and our home was filled with books. My mother, who had a lovely singing voice, loved music and, in particular, opera. The education of my brother and myself was of paramount importance to my parents, and in addition to their strong encouragement, they were prepared to make any sacrifice to further our intellectual development. When there were financial difficulties they still managed to provide us with music and art lessons. They greatly respected scholarship in itself, but they also impressed upon us that there were great opportunities available for those who were well educated. I received my primary and secondary education in Chicago. As I very much liked to draw and paint as a child, I entered a special art program in high school, which was very much like being in an art school imbedded in a regular high school curriculum. While I always had some interest in science, I developed a strong interest in physics when I was in high school as a result of reading a short book entitled *Relativity,* by Einstein. It opened a new vista for me and deepened my curiosity about the physical world. Instead of accepting a scholarship to the Art Institute of Chicago Museum School and against the strong advice of my art teacher, I decided to continue my formal education and sought admission to the University of Chicago because of its excellent reputation and because Enrico Fermi taught there. I was fortunate to have been accepted with a full scholarship. As my parents had limited means, my university training would not have been possible without such help. After finishing my requirements in an highly innovative and intellectually stimulating liberal arts program (established by Robert M. Hutchins who was then President of the University), I entered the Physics Department in 1950, receiving a Master's degree in 1953 and a Ph.D. in 1956. It is difficult to convey the sense of excitement that pervaded the Department at that time. Fermi's brilliance, his stimulating, crystal clear lectures that he gave in numerous seminars and courses, the outstanding faculty in the Department, the many notable physicists who frequently came to visit Fermi, and the pioneering investigations of pion proton scattering at the newly constructed cyclotron all combined to create an especially lively atmosphere. I was indeed fortunate to have seen the practice of physics carried out at its "very best" at such an early stage in my development. I also had the great privilege of being supervised by Fermi, and I can remember being overwhelmed with a sense of my good fortune to have been given the opportunity to work for this great man. It was a remarkably stimulating experience that shaped the way I think about physics. My thesis project was an investigation in nuclear emulsion of proton polarization produced in scattering from nuclei at cyclotron energies. The objective was to determine whether the polarization resulted from elastic or inelastic scattering. Professor Fermi tragically died in 1954 after a short illness. What an immense loss it was to all of us. My thesis work was not yet completed, and John Marshall kindly took over my supervision and signed my thesis. After I received my Ph.D., I continued working as a post-dot at the University of Chicago nuclear emulsion laboratory, which was then led by Valentine Telegdi. That year Val Telegdi and I did an emulsion experiment in which we searched for parity violation in muon decay. We were one of the first groups to observe this surprising effect which had been suggested by T.D. Lee and C.N. Yang. Val was not only an excellent mentor but he was instrumental in getting me my first real job with Robert Hofstadter.

In 1957, I joined Hofstadter's group at the High Energy Physics Laboratory at Stanford University as a Research Associate. This was where I learned counter physics and the techniques of electron scattering. While there I did a number of experiments studying elastic and inelastic electron-deuteron scattering. In an experiment to measure a weighted sum-rule for inelastic electron deuteron scattering which was related to the n-p interaction I had to confront the problem of making radiative corrections to inelastic spectra, and I developed a technique which proved to be valuable in my later work. Henry Kendall independently developed a similar technique and later we combined efforts to develop a radiative corrections program for our deep inelastic scattering work at SLAC. It was in Hofstadter's group that I began my long collaboration with Henry Kendall who was also a member of the group. During this period I became acquainted with Richard Taylor, who was just finishing his thesis in another group, and with other future collaborators in the deep inelastic program at SLAC, Dave Coward and Hobey DeStaebler. One of the highlights of this period was attending the wonderfully informal and informative high energy physics seminars in the home of W.K.H. Panofsky, who was Director of the Laboratory.

In 1960, I was hired as a faculty member in the Physics Department of the Massachusetts Institute of Technology. When I arrived I joined David Ritson's research group. A short time later he accepted a position at Stanford University and I inherited a small group. With these resources I soon began working on collaborative effort to measure muon pair production at the Cambridge Electron Accelerator (CEA) in order to test the validity of Quantum Electra-Dynamics. Henry Kendall joined my group in 1961 and we have been collaborators at MIT since that time. The last measurement we did at the CEA was a measurement of the deuteron form factor at the highest momentum transfers that could be reached at that accelerator to get some limits on the size of relativistic effects and meson currents.

In 1963, Henry Kendall and I started a collaboration with W.K.H. Panofsky, Richard Taylor and other physicists from the Stanford Linear Accelerator Center and the California Institute of Technology to develop electron scattering facilities for a physics program at the Stanford Linear Accelerator, a 20 GeV electron linac that was being constructed under the leadership of Panofsky. This required that we both travel between MIT and SLAC on a regular basis. The MIT Physics Department gave us special support by reducing our teaching responsibilities. We soon set up a small MIT group at SLAC and for extended periods of time one of us was always there. We had a rare opportunity. We were part of a group of physicists who were provided a new accelerator, given the support to design and construct optimal experimental facilities, and had the opportunity to participate in the exploration of a new energy range with electrons. From 1967 to about 1975 the MIT and SLAC groups carried out a series of measurements of inelastic electron scattering from the proton and neutron which provided the first direct evidence of the quark sub-structure of the nucleon. It was a very exciting time for all of us. This program is described in detail in the adjoining Physics Nobel Lectures.

As the program at SLAC was nearing completion we joined a collaborative effort at Fermilab involving a number of institutions to build a beam line and a single-arm spectrometer in the Meson Laboratory. During the latter half of the 1970's this collaboration carried out a series of experiments to investigate elastic scattering, Feynman scaling and production mechanisms in inclusive hadron scattering. When this work was completed, our group joined another collaboration to build a large neutrino detector at Fermilab. The objective of this program was to study the weak neutral currents in measurements of inclusive neutrino and anti-neutrino nucleon scattering, which were done in the first half of the 1980's. These investigations confirmed the predictions of the Standard Model.

In 1980, I became Director of the Laboratory for Nuclear Science at MIT and then served as Head of the Physics Department from 1983 to 1988. During the time I was in these administrative positions I managed to maintain a foothold in research, which greatly eased my transition back to full-time teaching and research in 1988. While it was a very interesting period in my life, I was happy to get back to more direct contact with students in the classroom and in my research projects. Currently, our MIT group is participating in the construction of a large detector to study electron-positron annihilations at the Stanford Linear Collider and has also been engaged in design work for a detector for the Superconducting Super Collider, which is now under construction.

Over the years I have served on a number of program and scientific policy advisory committees at various accelerators. I also was a member of the Board of the University Research Association for six years, serving as Vice-President for three years. I am currently a member of the High Energy Advisory Panel for the Department of Energy and also Chairman of the Scientific Policy Committee of the Superconducting Super Collider Laboratory.

Experimental high energy physics research is a group effort. I have been very fortunate to have had outstanding students and colleagues who have made invaluable contributions to the research with which I have been associated. I thank them not only for their contributions, but also for their friendship.

My life has been enhanced by my marriage to Tania Letetsky-Baranovsky who has broadened my horizons and has been an unfaltering source of support. She has endured with cheerful resignation my many absences when I have had to travel to distant particle accelerators. There are four grown children in our family, Ellena, Joel, Martin, and Sandra who pursue their activities in various parts of the country.

With regard to my non-vocational activities, in addition to getting much pleasure from various cultural activities, such as theater, music, ballet, etc., I enjoy painting and study Asian ceramics.

DEEP INELASTIC SCATTERING: COMPARISONS WITH THE QUARK MODEL

Nobel Lecture, December 8, 1990

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JEROME I. FRIEDMAN

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EARLY RESULTS

In the latter half of 1967 a group of physicists from the Stanford Linear Accelerator Center (SLAC) and the Massachusetts Institute of Technology (MIT) embarked on a program of inelastic electron proton scattering after completing an initial study' of elastic scattering with physicists from the California Institute of Technology. This work was done on the newly completed 20 GeV Stanford linear accelerator. The main purpose of the inelastic program was to study the electro-production of resonances as a function of momentum transfer. It was thought that higher mass resonances might become more prominent when excited with virtual photons, and it was our intent to search for these at the very highest masses that could be reached. For completeness we also wanted to look at the inelastic continuum since this was a new energy region which had not been previously explored. The proton resonances that we were able to measure' showed no unexpected kinematic behavior. Their transition form factors fell about as rapidly as the elastic proton form factor with increasing values of the four momentum transfer, q. However, we found two surprising features when we investigated the continuum region (now commonly called the deep inelastic region).

(1) Weak q^2 Dependence

The first unexpected feature of these early results[3] was that the deep inelastic cross-sections showed a weak fall off with increasing q^2. The scattering yields at the larger values of q^2 were between one and two orders of magnitude greater than expected.

The weak momentum transfer dependence of the inelastic cross-sections for excitations well beyond the resonance region is illustrated in Fig. 1. The differential cross section divided by the Mott cross section,[4] σ_{Mott}, is plotted as a function of the square of the four-momentum transfer, $q^2 = 2EE'(1-\cos\theta)$, for constant values of the invariant mass of the recoiling target system, W, where $W^2 = 2M(E-E') + M^2-q^2$. The quantity E is the energy of the incident electron, E' is the energy of the final electron, and θ is the scattering angle, all defined in the laboratory system; M is the mass of the proton. The cross section is divided by the Mott cross section in order to remove the major part of the well-known four-momentum transfer depen-

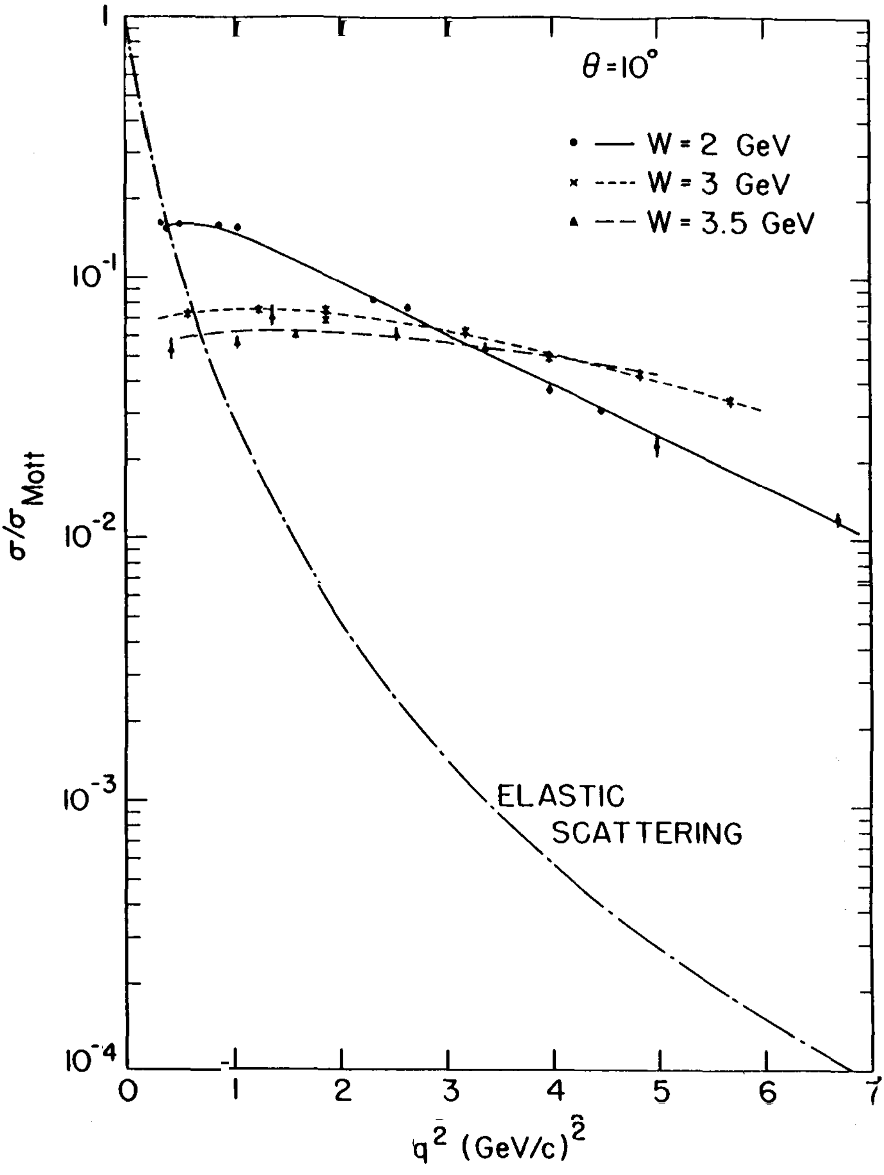

Fig. 1: $(d^2\sigma/d\Omega dE')/\sigma_{\mathrm{Mott}}$, in GeV^{-1}, vs. q^2 for W = 2, 3 and 3.5 GeV. The lines drawn through the data are meant to guide the eye. Also shown is the cross section for elastic e-p scattering divided by σ_{Mott}, $(d\sigma/d\Omega)/\sigma_{\mathrm{Mott}}$, calculated for $\theta = 10°$, using the dipole form factor. The relatively slow variation with q^2 of the inelastic cross section compared with the elastic cross section is clearly shown.

dence arising from the photon propagator. The q^2 dependence that remains is related primarily to the properties of the target system. Results from 10° are shown in the figure for each value of W. As W increases, the q^2 dependence appears to decrease. The striking difference between the behavior of the deep inelastic and elastic cross sections is also illustrated in this figure, where the elastic cross section, divided by the Mott cross section for $\theta = 10°$. is shown.

When the experiment was planned, there was no clear theoretical picture of what to expect. The observations of Hofstadter' in his pioneering studies of elastic electron scattering from the proton showed that the proton had a size of about 10^{-13} cm and a smooth charge distribution. This result, plus the theoretical framework that was most widely accepted at the time, suggested to our group when the experiment was planned that the deep inelastic electron proton cross-sections would fall rapidly with increasing q^2.

(2) Scaling

The second surprising feature in the data, scaling, was found by following a suggestion by Bjorken.[6] To describe the concept of scaling, one has to introduce the general expression for the differential cross section for unpolarized electrons scattering from unpolarized nucleons with only the scattered electrons detected.'

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{\mathrm{Mott}} \left[W_2 + 2W_1 \tan^2 \frac{\theta}{2} \right].$$

The functions W_1 and W_2 are called structure functions and depend on the properties of the target system. As there are two polarization states of the virtual photon, transverse and longitudinal, two such functions are required to describe this process. In general, W_1 and W_2 are each expected to be functions of both q^2 and ν, where ν is the energy loss of the scattered electron. However, on the basis of models that satisfy current algebra, Bjorken conjectured that in the limit of q^2 and ν approaching ∞, the two quantities νW_2 and W_1 become functions only of the ratio $\omega = 2M\nu/q^2$; that is

$$\begin{aligned} 2MW_1 (\nu, q^2) &\longrightarrow F_1(\omega) \\ \nu W_2 (\nu, q^2) &\longrightarrow F_2(\omega). \end{aligned}$$

The scaling behavior of the structure functions is shown in Fig. 2, where experimental values of νW_2 and $2MW_1$ are plotted as a function of ω for values of q^2 ranging from 2 to 20 GeV^2. The data demonstrated scaling within experimental errors for $q^2 > 2\ \mathrm{GeV}^2$ and $W > 2.6$ GeV.

The dynamical origin of scaling was not clear at that time, and a number of models were proposed to account for this behavior and the weak q^2 dependence of the inelastic cross section. While most of these models were firmly imbedded in S-matrix and Regge pole formalism, the experimental results caused some speculation regarding the existence of a possible point-like structure in the proton. In his plenary talk at the XIV International Conference on High Energy Physics held in Vienna in 1968, where preliminary results on the weak q^2 dependence and scaling were first presented, Panofsky[2] reported "... theoretical speculations are focused on the possibility that these data might give evidence on the behavior of point-like charged structures in the nucleon." However, this was not the prevailing point of view. Even if one had proposed a constituent model at that time it was not

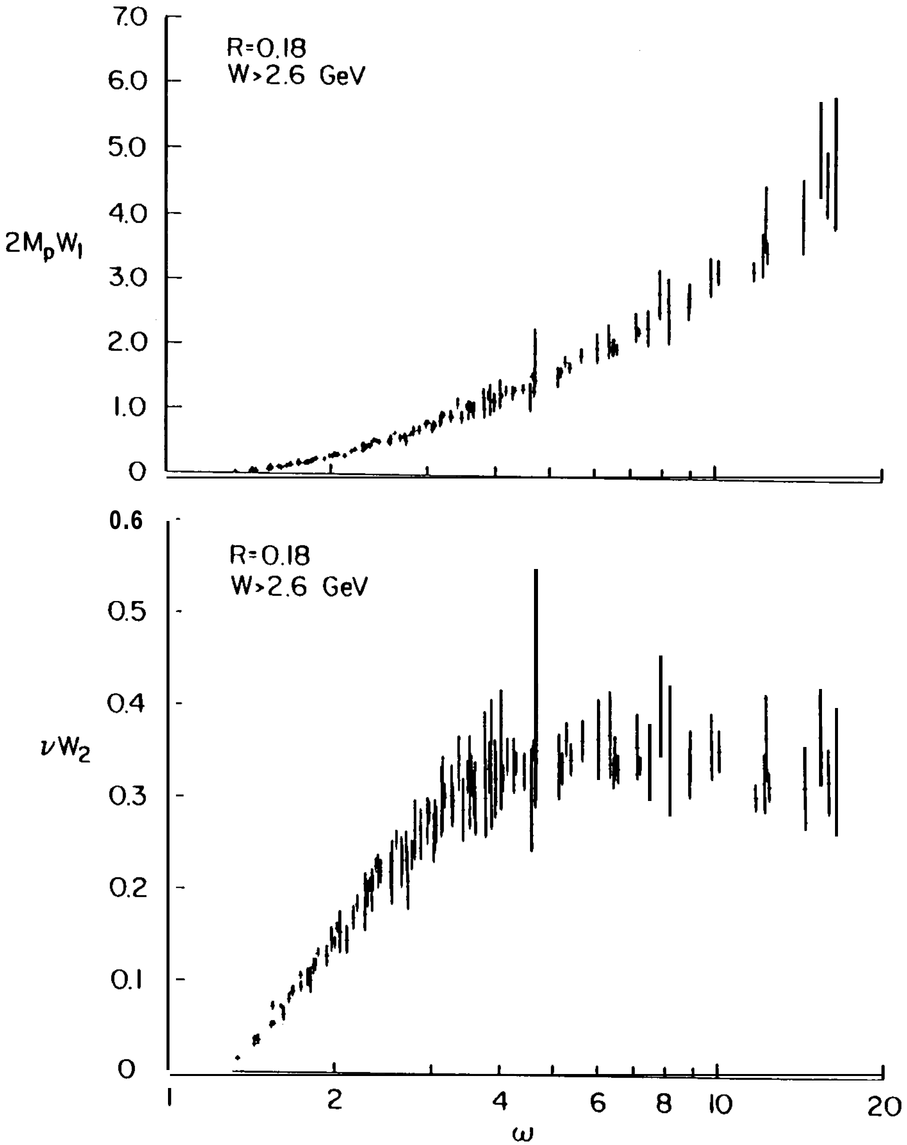

Fig. 2: $2MW_1$ and νW_2 for the proton as functions of ω for $W > 2.6$ GeV, $q^2 > 1(\mathrm{GeV}/c^2)$, and using R = 0.18. Data from Ref. [34]. The quantity R is discussed in the section of this paper entitled *Models*.

clear that there were reasonable candidates for the constituents. Quarks, which had been proposed independently by Gell-Mann[8] and Zweig[9] as the building blocks of unitary symmetry[10] in 1964, had been sought in numerous accelerator and cosmic ray investigations and in the terrestrial environment without success. Though the quark model provided the best available tool for understanding the properties of the many recently discovered hadronic resonances, it was thought by many to be merely a mathematical representation of some deeper dynamics, but one of heuristic value. Considerably more experimental and theoretical results had to be accumulated before a clear picture emerged. More detailed descriptions of the develop ment of the deep inelastic program and its early results are given in the written versions of the 1990 Physics Nobel Lectures of R. E. Taylor[11] and H. W. Kendall.[12]

NON-CONSTITUENT MODELS

The initial deep inelastic measurements stimulated a flurry of theoretical work, and a number of non-constituent models based on a variety of theoretical approaches were put forward to explain the surprising features of the data. One approach related the inelastic scattering to forward virtual Compton scattering, which was described in terms of Regge exchange[13-17] using the Pomeranchuk trajectory, or a combination of it and non-diffractive trajectories. Such models do not require a weak q^2 dependence, and scaling had to be explicitly inserted. Resonance models were also proposed to explain the data. Among these was a Veneziano-type model" in which the density of resonances increases at a sufficiently rapid rate to compensate for the decrease of the contribution of each resonance with increasing q^2. Another type of resonance model[19] built up the structure functions from an infinite series of N and A resonances. None of these models was totally consistent with the full range of data accumulated in the deep inelastic program.

One of the first attempts[20] to explain the deep inelastic scattering results employed the Vector Dominance Model, which had been used to describe photon-hadron interactions over a wide range of energies. This model, in which the photon is assumed to couple to a vector meson which then interacts with a hadron, was extended, using p meson dominance, to deep inelastic electron scattering. It reproduced the gross features of the data in that νW_2 approached a function of ω for ν much greater than M_p the mass of the p meson. The model also predicted that

$$R = \frac{\sigma_S}{\sigma_T} = \left(\frac{\varepsilon q^2}{M_\rho^2}\right)\left(1 - \frac{q^2}{2M\nu}\right),$$

where R is the ratio of σ_S and σ_T, the photo-absorption cross-sections of longitudinal and transverse virtual photons, respectively, and ε is the ratio of the vector meson-nucleon total cross sections for vector mesons with polarization vectors respectively parallel and perpendicular to their direction of motion. Since the parameter ε is expected to have a value of about 1 at high energies, this theory predicted very large values of R for values of $q^2 > M_\rho^2$. The ratio R can be related to the structure functions in the following way

$$R = \frac{W_2}{W_1}\left(1 + \frac{\nu^2}{q^2}\right) - 1.$$

The measurements of deep inelastic scattering over a range of angles and energies allowed W_1 and W_2 to be separated and R to be determined experimentally. Early results for R and the predictions of the vector dominance model are shown in Fig. 3. The results showed that R is small and does not increase with q^2. This eliminated the model as a possible description of deep inelastic scattering.

Various attempts[21] to save the vector meson dominance point of view were made with the extension of the vector meson spectral function to higher masses, including approaches which included a structureless continuum of higher mass states. These calculations of the Generalized Vector Dominance model failed in general to describe the data over the full kinematic range.

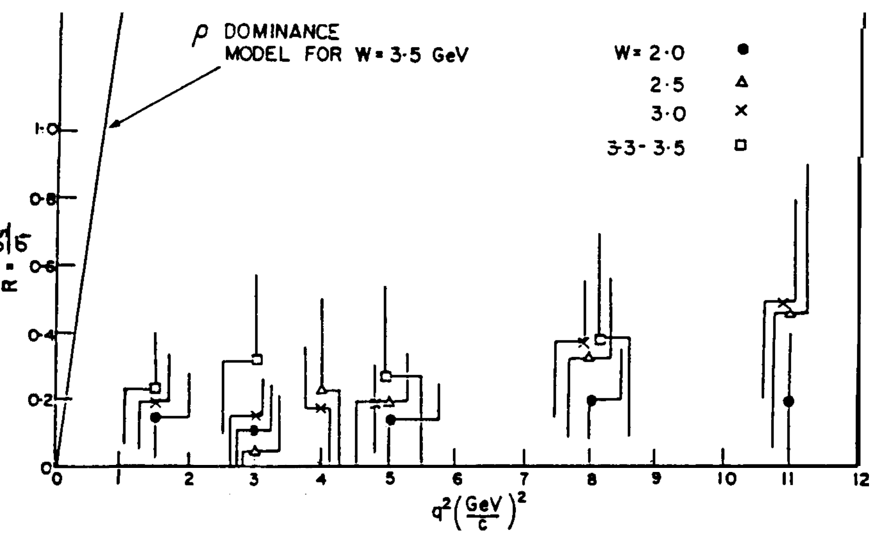

Fig. 3: Measured values of $R = \sigma_S/\sigma_T$ as a function of q^2 for various values of W. The p meson dominance prediction is also shown, calculated for $W = 3.5$ (see Ref. [20]).

CONSTITUENT MODELS

The first suggestion that deep inelastic electron scattering might provide evidence of elementary constituents was made by Bjorken in his 1967 Varenna lectures.[22] Studying the sum rule predictions derived from current algebra,[23] he stated, ". . . We find these relations so perspicuous that, by an appeal to history, an interpretation in terms of elementary constituents is suggested." In essence, Bjorken observed that a sum rule for neutrino scattering derived by Adler[24] from the commutator of two time components of the weak currents led to an inequality[25] for inelastic electron scattering,

$$\int_{q^2/2M}^{\infty} d\nu \left[W_2^p(\nu, q^2) + W_2^n(\nu, q^2)\right] \geq \frac{1}{2},$$

where W_2^p and W_2^n are structure functions for the proton and neutron, respectively.

This is equivalent to:

$$\lim_{E\to\infty}\left[\frac{d\sigma_{ep}}{dq^2}+\frac{d\sigma_{en}}{dq^2}\right]\geq\frac{2\pi\alpha^2}{q^4}.$$

The above inequality states that as the electron energy goes to infinity the sum of the electron-proton plus electron-neutron total cross sections (elastic plus inelastic) at fixed large q^2 is predicted to be greater than one-half the cross section for electrons scattering from a point-like particle. Bjorken also derived a similar result for backward electron scattering.[26] These results were derived well before our first inelastic results appeared. In hindsight, it is clear that these inequalities implied a point-like structure of the proton and large cross sections at high q^2, but Bjorken's result made little impression on us at the time. Perhaps it was because these results were based on current algebra, which we found highly esoteric, or perhaps it was that we were very much steeped in the physics of the time, which suggested that hadrons were extended objects with diffuse substructures.

The constituent model which opened the way for a simple dynamical interpretation of the deep inelastic results was the parton model of Feynman. He developed this model to describe hadron-hadron interactions,[27] in which the constituents of one hadron interact with those of the other. These constituents, called partons, were identified with the fundamental bare particles of an unspecified underlying field theory of the strong interactions. He applied this model to deep inelastic electron scattering after he had seen the early scaling results that were to be presented a short time later at the 14th International Conference on High Energy Physics, in Vienna, in the late-summer of 1968. Deep inelastic electron scattering was an ideal process for the application of this model. In electron-hadron scattering the electron's interaction and structure were both known, whereas in hadron-hadron scattering neither the structures nor the interactions were understood at the time.

In this application of the model the proton is conjectured to consist of point-like partons from which the electron scatters. The model is implemented in a frame approaching the infinite momentum frame, in which the relativistic time dilation slows down the motions of the constituents nearly to a standstill. The incoming electron thus "sees" and incoherently scatters from partons which are noninteracting with each other during the time the virtual photon is exchanged. In this frame the impulse approximation is assumed to hold, so that the scattering process is sensitive only to the properties and momenta of the partons. The recoil parton has a final state interaction in the nucleon, producing the secondaries emitted in inelastic scattering. A diagram of this model is shown in Fig. 4.

Consider a proton of momentum P, made up of partons, in a frame approaching the infinite momentum frame. The transverse momenta of any parton is negligible and the i^{th} parton has the momentum $P_i = x_i P$, where x_i is a fraction of the proton's momentum. Assuming the electron scatters

from a point-like parton of charge Qi (in units of e), leaving it with the same mass and charge, the contribution to $W_2(\nu,q^2)$ from this scattering is

$$W_2^{(i)}(\nu, q^2) = Q_i^2\,\delta(\nu - q^2/2Mx_i) = \frac{Q_i^2 x_i}{\nu}\,\delta(x_i - q^2/2M\nu).$$

The expression for νW_2 for a distribution of partons is given by

$$\nu W_2(\nu, q^2) = \sum_N \mathrm{P}(N)\left(\sum_{i=1}^{N} Q_i^2\right) x f_N(x) = F_2(\mathrm{x})$$

where

$$x = \frac{q^2}{2M\nu} = \frac{1}{\omega}$$

and where P(N) is the probability of N partons occurring. The sum

$$\left(\sum_{i=1}^{N} (\mathrm{Q}_i)^2\right)$$

is the sum of the squares of the charges of the N partons, and $f_N(x)$ is the distribution of the longitudinal momenta of the charged partons.

It was clear that the parton model, with the assumption of point-like constituents, automatically gave scaling behavior. The Bjorken scaling variable ω was seen to be the inverse of the fractional momentum of the struck parton, x, and νW_2 was shown to be the fractional momentum distribution of the partons, weighted by the squares of their charges.

In proposing the parton model, Feynman was not specific as to what the partons were. There were two competing proposals for their identity.

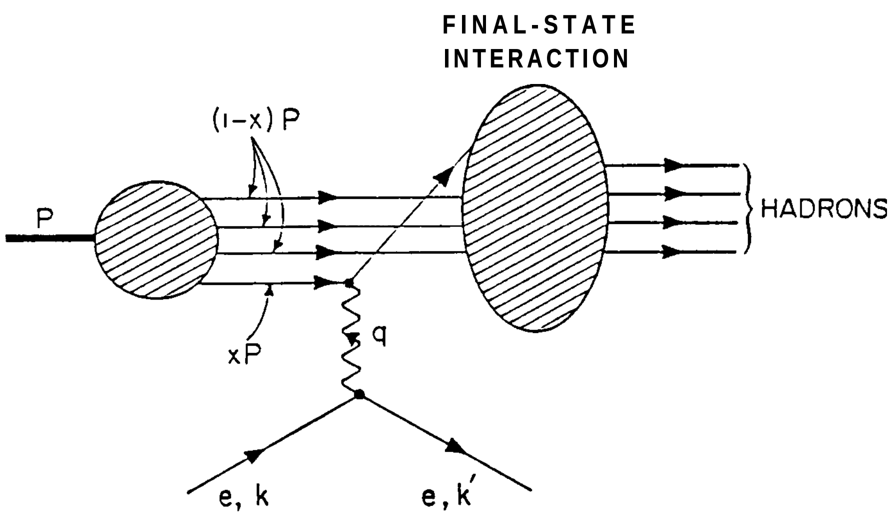

Fig. 4: A representation of inelastic electron nucleon scattering in the parton model. *k* and *k'* are the incident and final momenta of the electron. The other quantities are defined in the text.

Applications of the parton model identified partons with bare nucleons and pions,[28-30] and also with quarks[31-33]. However, parton models incorporating quarks had a glaring inconsistency. Quarks required strong final state interactions to account for the fact that these constituents had not been observed in the laboratory. Before the theory of Quantum Chromodynamics (QCD) was developed, there was a serious problem in making the "free" behavior of the constituents during photon absorption compatible with the required strong final state interaction. One of the ways to get out of this difficulty was to assign quarks very large masses but this was not considered totally satisfactory. This question was avoided in parton models employing bare nucleons and pions because the recoil constituents are allowed to decay into real particles when they are emitted from the nucleon.

Drell, Levy and Yan[28] derived a parton model, in which the partons are bare nucleons and pions, from a canonical field theory of pions and nucleons with the insertion of a cutoff in transverse momenta. The calculations showed that the free point-like constituents which interact with the electromagnetic current in each order of perturbation theory and to leading order in logarithms of $2M\nu/q^2$ are bare nucleons making up the proton and not the pions in the pion cloud.

A further development of the approach that identified bare nucleons and pions as partons was a calculation by Lee and Drell[30] that provided a fully relativistic generalization of the parton model that was no longer restricted to an infinite momentum frame. This theory obtained bound state solutions of the Bethe-Salpeter equation for a bare nucleon and bare mesons, and connected the observed scale invariance with the rapid decrease of the elastic electromagnetic form factors.

When the quark model was proposed in 1964 it contained three types of quarks, up (u), down (d), and strange (s), having charges 2/3, - 1/3, and - 1/3, respectively, and each of these a spin l/2 particle. In this model the nucleon (and all other baryons) is made up of three quarks, and all mesons consist of a quark and an antiquark. As the proton and neutron both have zero strangeness, they are (u,u,d) and (d,d,u) systems respectively. Bjorken and Paschos[31] studied the parton model for a system of three quarks, commonly called valence quarks, in a background of quark-antiquark pairs, often called the sea, and suggested further tests for the model. A more detailed description of a quark-parton model was later given by Kuti and Weisskopf.[32] Their model of the nucleon contained, in addition to the three valence quarks, a sea of quark-antiquark pairs, and neutral gluons, which are quanta of the field responsible for the binding of the quarks. The momentum distribution of the quarks corresponding to large ω was given in terms of the requirements of Regge behavior. Decisive tests of these models were provided by extensive measurements with hydrogen and deuterium targets that followed the early results.

MEASUREMENTS OF PROTON AND NEUTRON STRUCTURE FUNCTIONS

The first deep inelastic electron scattering results[3] were obtained in the period 1967 - 1968 from a hydrogen target with the 20 GeV spectrometer set at scattering angles of 6° and 10°. By 1970 the proton data[34] had been extended to scattering angles of 18°, 26° and 34° with the use of the 8 GeV spectrometer. The measurements covered a range of q^2 from 1 GeV^2 to 20 GeV^2, and a range of W^2 up to 25 GeV^2. By 1970 data[35] had been also obtained at scattering angles of 6° and 10° with a deuterium target. Subsequently, a series of matched measurements[36-36] with better statistics and covering an extended range of q^2 and W^2 were done with hydrogen and deuterium targets, utilizing the 20 GeV, the 8 GeV, and the 1.6 GeV spectrometers. These data sets provided, in addition to more detailed information about the proton structure functions, a test of scaling for the neutron. In addition, the measured ratio of the neutron and proton structure functions provided a decisive tool in discriminating among the various models proposed to explain the early proton results.

Neutron cross sections were extracted from measured deuteron cross sections using the impulse approximation along with a procedure to remove the effects of Fermi motion. The method used was that of Atwood and West,[39] with small modifications[40] representing off-mass-shell corrections. In this method the measured proton structure functions, W_1, and W_2, were kinematically smeared over the Fermi momentum distribution of the deuteron and combined to yield the smeared proton cross section σ_{ps}. Subtracting the smeared proton cross section from the measured deuteron cross section yielded the smeared neutron cross section $\sigma_{ns} = \sigma_d - \sigma_{ps}$. With the use of a deconvolution procedure[37] on σ_{ns}, the unsmeared neutron cross section σ_n was obtained. From this and the measured value of the proton cross section σ_p the ratio σ_n/σ_p, which is free of kinematic smearing, was determined. The results were insensitive to the choice of the deuteron wave function used to calculate the momentum distribution of the bound nucleons, as long as the wave functions were consistent with the known properties of the deuteron and the n-p interaction.

The conclusions that were derived from the analysis of these extensive data sets were the following:

(1) The deuterium and neutron structure functions showed the same approximate scaling behavior as the proton. This is shown in Fig. 5 which presents νW_2 for the proton, neutron, and deuteron as a function of x for data ranging in q^2 from 2 GeV^2 to 20 GeV^2.

(2) The values of R_p, R_n, and R_d were equal within experimental errors. This is shown in Fig. 6, where the difference of R_d and R_p is plotted.

(3) The ratio of the neutron and proton inelastic cross sections falls continuously as the scaling variable x approaches 1. From a value of about 1 near x = 0, the experimental ratio falls to about 0.3, in the neighbor-

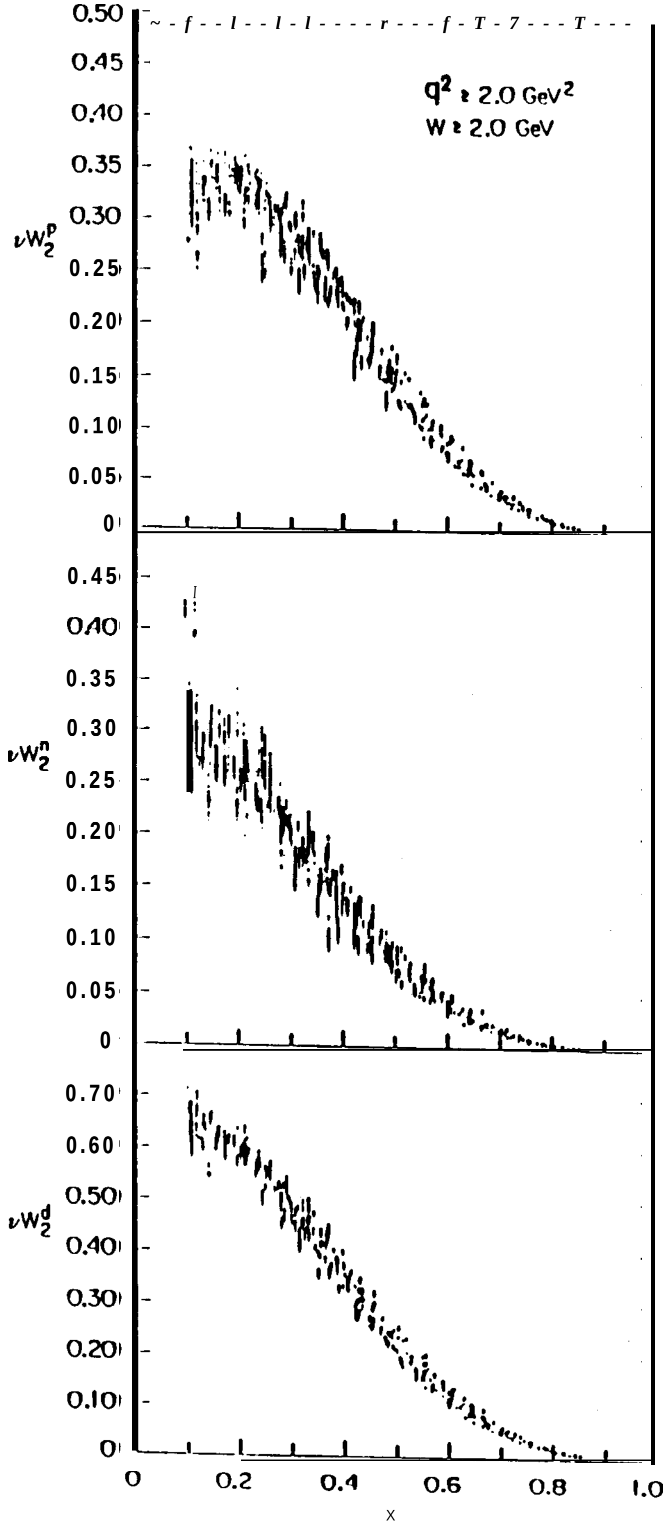

Fig. 5: **Values of $\nu W_2^p, \nu W_2^n$ and νW_2^d plotted against x. Data from Ref. [36]**

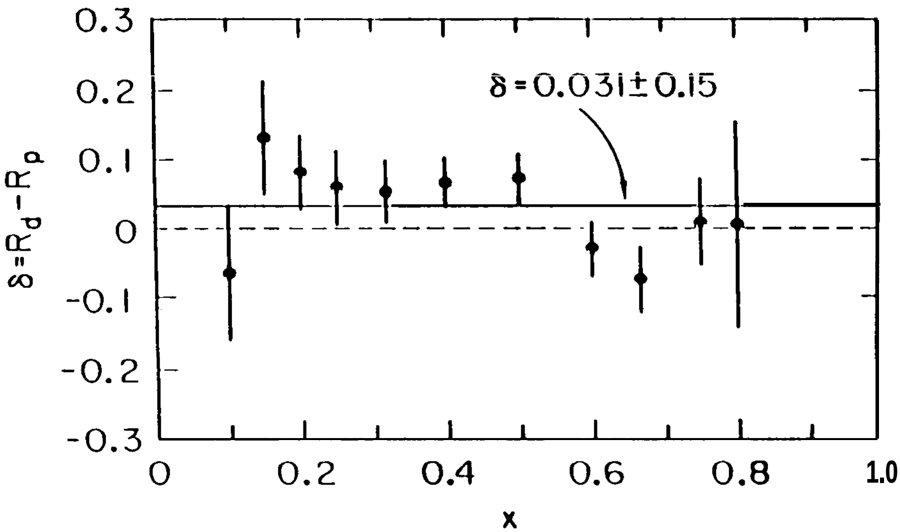

Fig. 6: Average values of the quantity δ = R_d-R_p for each of the 11 values of x studied. Errors shown are purely random. The systematic error in δ is 0.036. Data from Refs. [36] and [37].

hood of x = 0.85. This is shown in Fig. 7 in which σ_n/σ_p is plotted as a function of x. These results put strong constraints on various models of nucleon structure, as discussed later.

SUM RULE RESULTS

A sum rule generally relates an integral of a cross section (or of a quantity derived from it) and the properties of the interaction hypothesized to produce that reaction. Experimental evaluations of such relations thus provide a valuable tool in testing theoretical models. Sum rule evaluations within the framework of the parton model provided an important element in identifying the constituents of the nucleon. The early evaluations of weighted integrals of $\nu W_2(\omega)$ with respect to ω were based on the assumption that the nucleon's momentum is, on the average, equally distributed among the partons. Two important sum rules, which were evaluated for neutrons and protons, were:

$$I_1 = \int_1^\infty \nu W_2(\omega)\,\frac{d\omega}{\omega^2} = \sum_N \mathrm{P}(N)\,\frac{\left(\sum_{i=1}^{N} Q_i^2\right)}{N}$$

$$I_2 = \int_1^\infty \nu W_2(\omega)\,\frac{d\omega}{\omega} = \sum_N \mathrm{P}(N) \sum_{i=1}^{N} Q_i^2 ,$$

where I_2, is the weighted sum of the squares of the parton charges and I_1[31,41], is the mean square charge per parton. The sum I_2 is equivalent to a sum rule derived by Gottfried[42] who showed that for a proton which consists of three nonrelativistic point-like quarks I_2^p equals 1 at a high q^2. The experimental

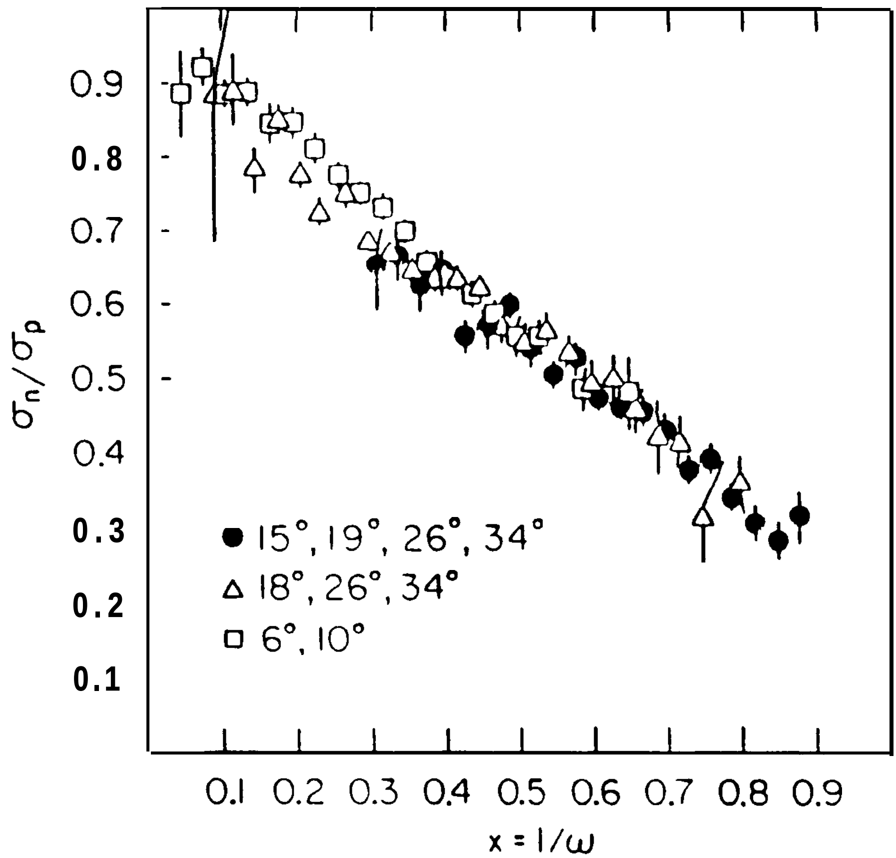

Fig. 7: **Values of σ_n/σ_p as a function of x determined from the results presented in Refs. [36] and [37].**

value of this integral when integrated over the range of the MIT-SLAC data gave:

$$I_2^P = \int_1^{20} \frac{d\omega}{\omega} \nu W_2^p = 0.78 \pm 0.04$$

where the integral was cut off for ω > 20 because of insufficient information about R_p. Since the experimental values of νW_2 at large ω did not exclude a constant value (see Fig. 2), there was some suspicion that this sum might diverge. This would imply that in the quark model scattering occurs from a infinite sea of quark-antiquark pairs as ν approaches ∞. Table 1 gives a summary of the early comparisons of the experimental values of the sum rules with the predictions of various models. Unlike I_2, the experimental value of I_1, was not very sensitive to the behavior of νW_2, for ω > 20. The experimental value was about one-half the value predicted on the basis of the simple three-quark model of the proton, and it was also too small for a proton having three valence quarks in a sea of quark-antiquark pairs. The Kuti-Weisskopf model[32] which included neutral gluons, in addition to the

TABLE 1: Early Sum Rule Results[a] — Theory[b] and Measurements[c]					
	Expected Value[e]		Measurement	ω_m[f]	$q^2(\mathrm{GeV/c})^2$
	3 Quark	3 Quark + "Sea"			
I_1^p	$\frac{1}{3}$	$\frac{2}{9}+\frac{1}{3\langle N\rangle}$	0.159 ± 0.005	20	1.0
			0.165 ± 0.005	20	1.5
			0.172 ± 0.009[d]	20[d]	1.5[d]
			0.154 ± 0.005	12	2.0
I_1^n	$\frac{2}{9}$	$\frac{2}{9}$	0.120 ± 0.008	20	1.0
			0.115 ± 0.008	20	1.5
			0.107 ± 0.009	12	2.0
I_2^p	1	$\frac{1}{3}+\frac{2\langle N\rangle}{9}$	0.739 ± 0.029	20	1.0
			0.761 ± 0.027	20	1.5
			0.780 ± 0.04[d]	20[d]	1.5[d]
			0.607 ± 0.021	12	2.0
I_2^n	$\frac{2}{3}$	$\frac{2\langle N\rangle}{9}$	0.592 ± 0.051	20	1.0
			0.584 ± 0.050	20	1.5
			0.429 ± 0.036	12	2.0
$I_2^p - I_2^n$		$\frac{1}{3}$	0.147 ± 0.059	20	1.0
			0.177 ± 0.057	20	1.5
			0.178 ± 0.042	12	2.0

[a]From J. I. Friedman and H. W. Kendall, Ann. *Rev. Nucl.* Sci. 22, 203 (1972). Excerpts from this publication are used in the present paper.
[b]Reference [31].
[c]Calculated from preliminary results, later published as Refs. [35,36], except where noted.
[d]Data from Ref. [3].
[e]$\langle N\rangle$ expectation value of number of quarks.
[f]w_m is upper limit of integral.

valence quarks and the sea of quark-antiquark pairs, predicted a value of I_1^P that was compatible with this experimental result.

The difference $I_2^p - I_2^n$ was of great interest because it is presumed to be sensitive only to the valence quarks in the proton and the neutron. On the assumption that the quark-antiquark sea is an isotopic scalar, the effects of the sea cancel out in the above difference, giving $I_2^p - I_2^n = 1/3$. Unfortunately, it was difficult to extract a meaningful value from the data because of the importance of the behavior of νW_2, at large ω. Extrapolating $\nu W_2^p - \nu W_2^n$

toward $\omega \rightarrow \infty$ for $\omega > 12$, with the asymptotic dependence $(1/\omega)^{\frac{1}{2}}$ expected on the basis of Regge theory, we obtained a rough estimate of $I_2^p - I_2^n = 0.22 \pm 0.07$. This was compatible with the expected value, given the error and the uncertainties in extrapolation. The difference $\nu W_2^p(x) - \nu W_2^n(x)$, plotted in Fig. 8 shows a peak, which would be expected in theoretical models[31,32] involving quasi-free constituents.

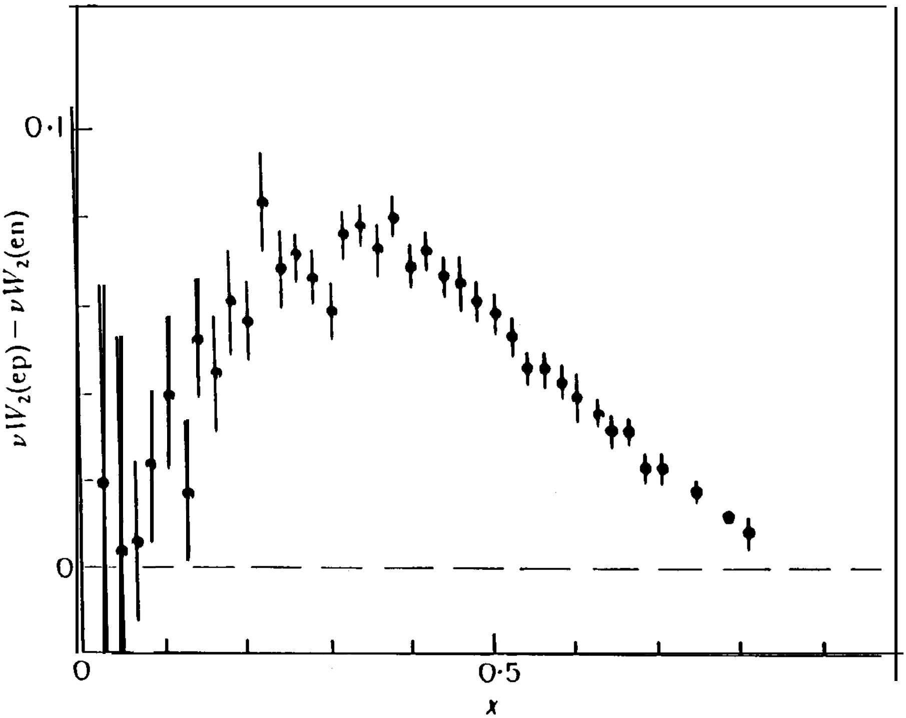

Fig. 8: Values of $\nu W_2^p - \nu W_2^n$ as a function of x.

The Bjorken inequality previously discussed, namely,

$$\int_{q^2/2M}^{\infty} d\nu \left[W_2^p(\nu, q^2) + W_2^n(\nu, q^2)\right] \geqslant \frac{1}{2}$$

was also evaluated. This inequality was found to be satisfied at $\omega \approx 5$.

Extensions of the quark-parton model allowed the weighted sum

$$\int \frac{d\omega}{\omega^2} \nu W_2$$

to be theoretically evaluated without making the assumption that the momentum of the nucleon is equally distributed among different types of partons. If $u_p(x)$ and $d_p(x)$ are defined as the momentum distributions of up and down quarks in the proton then $F_2^p(x)$ is given by

$$F_2^p(x) = \nu W_2^p(x) = x\left[(Q_u^2(u_p(x) + \bar{u}_p(x)) + Q_d^2(d_p(x) + \bar{d}_p(x)))\right]$$

where $\bar{u}_p(x)$ and $\bar{d}_p(x)$ are the distributions for anti-up and anti-down quarks, and Q_u^2 and Q_d^2 are the squares of the charges of the up and down quarks, respectively. The strange quark sea has been neglected.

Using charge symmetry it can be shown that

$$\frac{1}{2}\int_0^1 \left[F_2^p(x) + F_2^n(x)\right] dx = \left[\frac{Q_u^2 + Q_d^2}{2}\right] \int_0^1 x\left[u_p(x) + \bar{u}_p(x) + d_p(x) + \bar{d}_p(x)\right] dx\,.$$

The integral on the right-hand side of the equation is the total fractional momentum carried by the quarks and antiquarks, which would equal 1.0 if they carried the nucleon's total momentum. On this assumption the expected sum should equal

$$\frac{Q_u^2 + Q_d^2}{2} = \frac{1}{2}\left[\frac{4}{9} + \frac{1}{9}\right] = \frac{5}{18} = 0.28\ .$$

The evaluations of the experimental sum from proton and neutron results over the entire kinematic range studied yielded

$$\frac{1}{2}\int \left[F_2^p(x) + F_2^n(x)\right] dx = 0.14 \pm 0.005\ .$$

This again suggested that half of the nucleon's momentum is carried by neutral constituents, gluons, which do not interact with the electron.

IDENTIFICATION OF THE CONSTITUENTS OF THE NUCLEON AS QUARKS

The confirmation of a constituent model of the nucleon and the identification of the constituents as quarks took a number of years and was the result of continuing interplay between experiment and theory. By the time of the XVth International Conference on High Energy Physics held in Kiev in 1970 there was an acceptance in some parts of the high energy community of the view that the proton is composed of point-like constituents. At that time we were reasonably convinced that we were seeing constituent structure in our experimental results, and afterwards our group directed its efforts to trying to identify these constituents and making comparisons with the last remaining competing models.

The electron scattering results which played a crucial role in identifying the constituents of protons and neutrons or which ruled out competing models were the following:

(1) Measurement of *R*

At the Fourth International Symposium on Electron and Photon Interactions at High Energies held in Liverpool in 1969, MIT-SLAC results were presented which showed that R was small and was consistent with being independent of q^2. The subsequent measurements,[36,37] which decreased the errors, were consistent with this behavior.

The experimental result that R was small for the proton and neutron at large values of q^2 and ν required that the constituents responsible for the scattering have spin 1/2, as was pointed out by Callan and Gross.[43] These results ruled out pions as constituents but were consistent with the constituents being quarks or bare protons.

(2) The σ_n/σ_p Ratio

As was discussed in a previous section σ_n/σ_p decreased from 1 at about x = 0 to 0.3 in the neighborhood of x = 0.85. The ratio σ_n/σ_p is equivalent to W_2^n/W_2^p for $R_p = R_n$, and in the quark model a lower bound of 0.25 is imposed on W_2^n/W_2^p. While the experimental values approached and were consistent with this lower bound, Regge and resonance models had difficulty at large x, as they predicted values for the ratio of about 0.6 and 0.7, respectively, near x = I, and pure diffractive models predicted 1.0. The relativistic parton model in which the partons were associated with bare nucleons and mesons predicted a result for W_2^n/W_2^p which fell to zero at x = 1 and was about 0.1 at x = 0.85, clearly in disagreement with our results.

A quark model in which up and down quarks have identical momentum distributions would give a value of W_2^n/W_2^p = 2/3. Thus, the small value observed experimentally requires a difference in these distributions and quark-quark correlations at low x. To get a ratio of 0.25, the lower limit of the quark model, only a down quark from the neutron and an up quark from the proton can contribute to the scattering at the value of x at which the limit occurs.

(3) Sum Rules

As previously discussed, several sum rule predictions suggested point-like structure in the nucleon. The experimental evaluations of the sum rule related to the mean square charge of the constituents were consistent with the fractional charge assignments of the quark model provided that half the nucleon's momentum is carried by gluons.

EARLY NEUTRINO RESULTS

Neutrino deep inelastic scattering produced complementary information that provided stringent tests of the above interpretation. Since charged-current neutrino interactions with quarks were expected to be independent of quark charges but were hypothesized to depend on the quark momentum distributions in a manner similar to electrons, the ratio of the electron and neutrino deep inelastic scattering was predicted to depend on the quark charges, with the momentum distributions cancelling out.

That is

$$\frac{\frac{1}{2}\int\left[F_2^{ep}(x) + F_2^{en}(x)\right]dx}{\frac{1}{2}\int\left[F_2^{\nu p}(x) + F_2^{\nu n}(x)\right]dx} = \frac{Q_u^2 + Q_d^2}{2}$$

where 1/2 $(F_2^{\nu p}(x)+F_2^{\nu n}(x)$ is the F_2 structure function obtained from neutrino-nucleon scattering from a target having an equal number of neutrons and protons. The integral of this neutrino structure function over x is equal to the total fraction of the nucleon's momentum carried by the constituents of the nucleon that interact with the neutrino. This directly measures the fractional momentum carried by the quarks and antiquarks because gluons are not expected to interact with neutrinos.

The first neutrino and anti-neutrino total cross-sections were presented in 1972 at the XVI International Conference on High Energy Physics held at Fermilab and the University of Chicago. The measurements were made at the CERN 24 GeV Synchrotron with the use of the large heavy-liquid bubble chamber "Gargamelle." At this meeting Perkins,[44] who reported these results, stated that, ". . . the preliminary data on the cross-sections provide an astonishing verification for the Gell-Mann/Zweig quark model of hadrons."

These total cross section results, presented in Fig. 9, demonstrate a linear dependence on neutrino energy for both neutrinos and anti-neutrinos that is a consequence of Bjorken scaling of the structure functions in the deep inelastic region. By combining the neutrino and anti-neutrino cross-sections

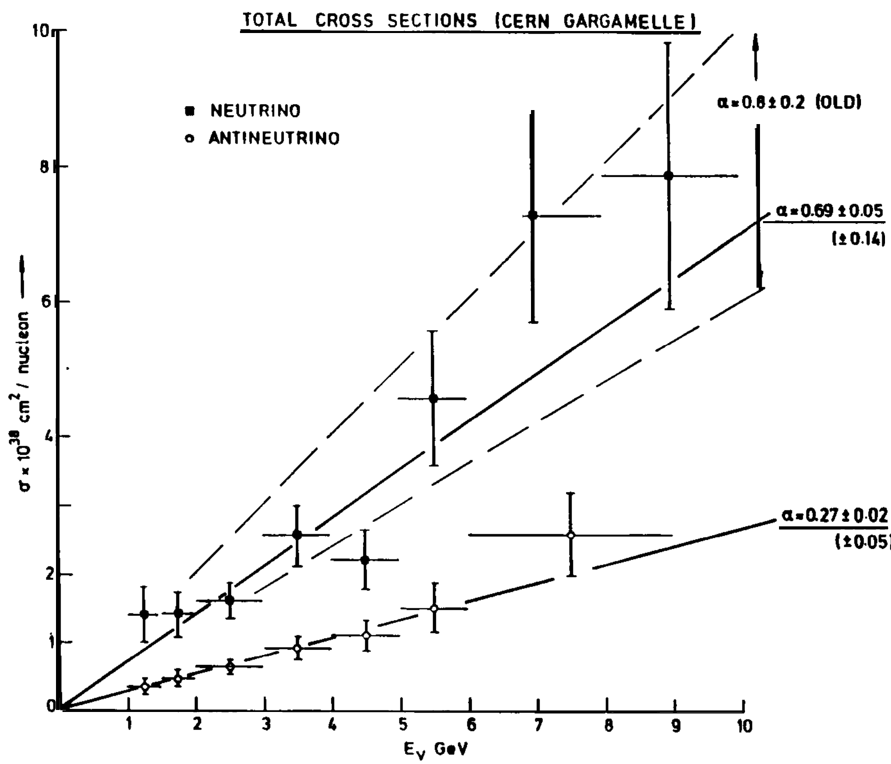

Fig. 9: Early Gargamelle measurements of neutrino nucleon and anti-neutrino nucleon cross sections as a function of energy. These results were presented at the XVI International Conference on High Energy Physics, NAL-Chicago, 1972, Ref. [44].

the Gargamelle group was able to show that

$$\frac{1}{2}\int\left(F_2^{\nu p}(x) + F_2^{\nu n}(x)\right)\,dx = \int x\left[u_p(x) + \bar{u}_p(x) + d_p(x) + \bar{d}_p(x)\right]dx = 0.49 \pm 0.07$$

which confirmed the interpretation of the electron scattering results that suggested that the quarks and antiquarks carry only about half of the nucleon's momentum. When this result was compared with

$$\frac{1}{2}\int\left[F_2^{ep}(x) + F_2^{en}(x)\right]dx$$

they found that the ratio of neutrino and electron integrals was 3.4 $\pm$ 0.7 as compared to the value predicted for the quark model, 18/5 = 3.6. This was a striking success for the quark model.

Within the next few years additional neutrino results solidified these conclusions. The results presented[45] at the XVII International Conference on High Energy Physics held in London in 1974 demonstrated that the ratio 18/5 was valid both as a function of x and neutrino energy. Figure 10, taken

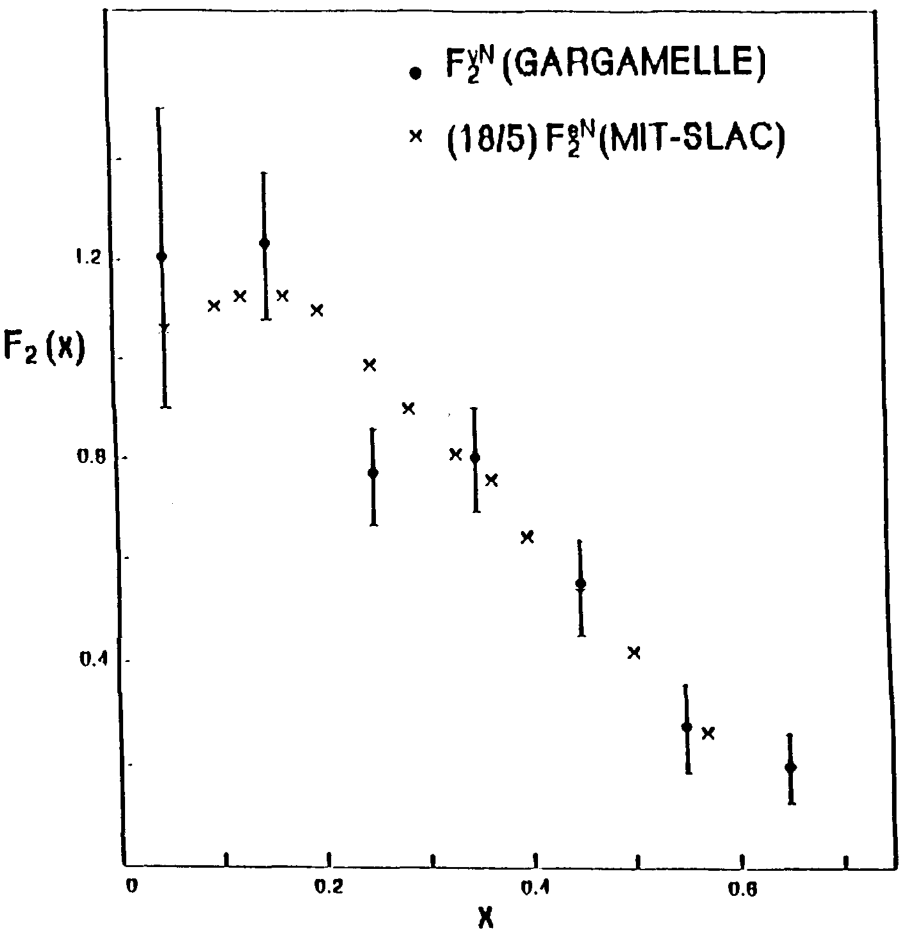

Fig. 10: Early Gargamelle measurements of $F_2^{\nu N}$ compared with $(18/5)F_2^{eN}$ calculated from the MIT-SLAC results.

from Gargamelle data, shows a comparison of $F^{\nu N}(x)$ and 18/5 F_2^{eN}, where $F_2^{\nu N}$ and F_2^{eN} each represents an average of proton and neutron structure functions, and Fig. 11 shows the ratio of the integrals of the two structure

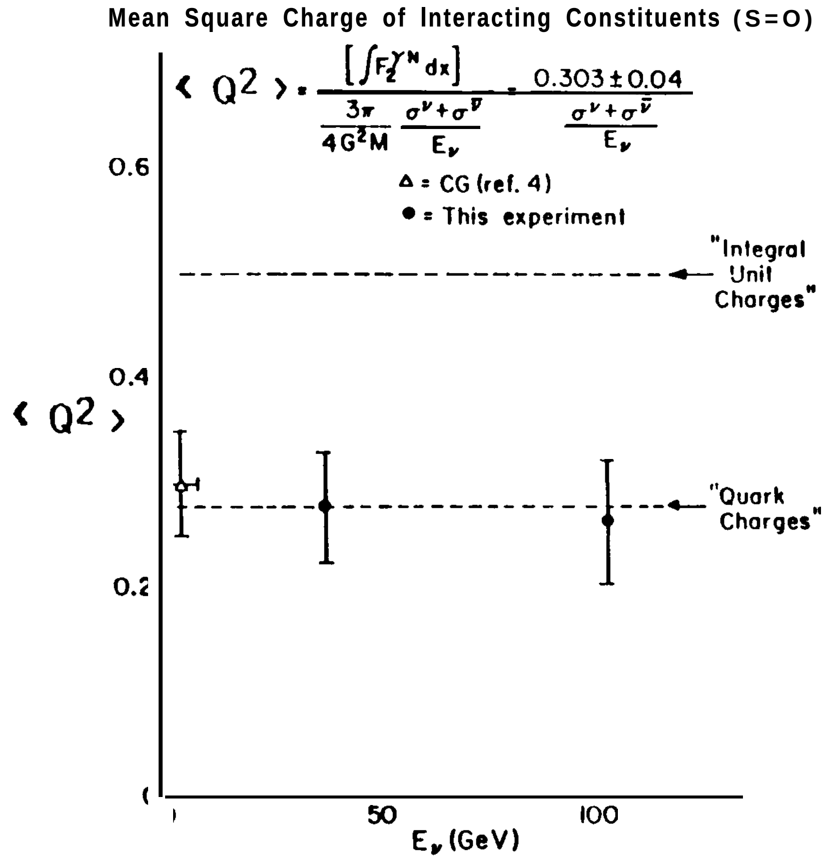

Fig. 11: Comparison of the ratio of integrated electron-nucleon and neutrino-nucleon structure functions to the value 5/ 18 expected from quark charges. The open triangle data point is from Gargamelle and the tilled-in circles are from the CIT-NAL Group. From Ref. [45]. The quantity Q^2) is the mean square charge of the quarks in a target consisting of an equal number of protons and neutrons.

functions as a function of neutrino energy calculated from Gargamelle and CIT-NAL data. In addition, the Gargamelle group evaluated the Gross-Llewellyn Smith sum rule[46] for the F^3 structure function, which uniquely occurs in the general expressions for the inelastic neutrino and antineutrino nucleon cross sections as a consequence of parity non-conservation in the weak interaction. This sum rule states that

$$\int F_3^{\nu N}(x)\, dx = (\text{number of quarks}) - (\text{number of antiquarks})$$

which equals 3 for a nucleon in the quark model. Obtaining values of $F_3^{\nu N}(x)$ from the differences of the neutrino and anti-neutrino cross sections, the

Gargamelle group found the sum to be 3.2 ± 0.6, another significant success for the quark model.

GENERAL ACCEPTANCE OF QUARKS AS CONSTITUENTS

After the London Conference in 1974, with its strong confirmation of the constituent quark model, a general change of view developed with regard to the structure of hadrons. The bootstrap approach and the concept of nuclear democracy were in decline, and by the end of the 1970's, the quark structure of hadrons became the dominant view for developing theory and planning experiments. A crucial element in this change was the general acceptance of QCD,[47,48] which eliminated the last paradox, namely, why are there no free quarks? The infra-red slavery mechanism of QCD provided a reason to accept quarks as physical constituents without demanding the existence of free quarks. The asymptotic freedom property of QCD also readily provided an explanation of scaling, but logarithmic deviations from scaling were inescapable in this theory. These deviations were later confirmed in higher energy muon and neutrino scattering experiments at FNAL and CERN. There were a number of other important experimental results reported in 1974 and the latter half of the decade which provided further strong confirmations of the quark model. Among these were the discovery of Charmonium[49,50] and its excited states,[51] investigations of the total cross section for $e^+e^- \rightarrow$ hadrons,[52] and the discoveries of quark jets[53] and gluon jets.[54] The constituent quark model, with quark interactions described by QCD, became the accepted view of the structure of hadrons. This picture which is one of the foundations of the Standard Model has not been contradicted by any experimental evidence in the intervening years.

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REFERENCES

1. D. H. Coward et al., Phys. *Rev. Lett. 20, 292* (1968).
2. W. K. H. Panofsky, in *Proceedings of 14th International* Conference *on High Energy Physics* Vienna (1968) 23. The experimental report, presented by the author, is not published in the Conference Proceedings. It was, however, produced as a SLAC preprint.
3. E. D. Bloom *et* al. *Phys. Rev. Lett.* 23, 930 (1969); M. Breidenbach *et al. Phys. Rev. Lett. 23, 935* (1969).
4. The Mott cross-section $\sigma_{\text{Mott}} = \dfrac{e^4}{4E^2}\dfrac{\cos^2\theta/2}{\sin^4\theta/2}$
5. R. W. McAllister and R. Hofstadter, *Phys. Rev.* 102, 851 (1956).
6. J. D. Bjorken, *Phys. Rev.* 179, 1547 (1969); In a private communication, Bjorken told the MIT-SLAC group about scaling in 1968.
7. S. D. Drell and J. D. Walecka, *Ann. Phys. (NY) 28,* 18 (1964).

8. M. Gell-Mann, Phys. Lett. 8, 214 (1964).
9. G. Zweig, CERN preprint 8182/TH 401 (1964); CERN preprint 8419/TH 412.
10. M. Gell-Mann, Caltech Synchrotron Laboratory Report CTSL-20 (1961); Y. Neeman, Nucl. Phys. 26, 222 (1961).
11. R. E. Taylor, Deep Inelastic Scattering: The Early Years. Les Prix *Nobel 1990.*
12. H. W. Kendall, Deep Inelastic Scattering: Experiments on the Proton and the Observation of Scaling. *Les Prix Nobel 1990.*
13. H. D. Abarbanel, M. L. Goldberger and S. B. Treiman, *Phys. Rev. Lett. 22, 500* (1969).
14. H. Harari, *Phys. Rev. Lett. 22,* 1078 (1969); *Phys. Rev. Lett. 24, 286* (1970).
15. T. Akiba, *Lett. Nuovo Cimento 4,* 1281 (1970).
16. H. Pagels, *Phys. Rev.* D3, 1217 (1971).
17. J. W. Moffat and V. G. Snell, *Phys. Rev.* D30, 2848 (1971).
18. P. V. Landshoff and J. C. Polkinghorne, DAMPT 70/36 (1970).
19. G. Domokos, S. Kovesi-Domokos and E. Shonberg, *Phys. Rev.* D3, 1184 (1971); *Phys. Rev.* D3, 1191 (1971).
20. J. J. Sakurai, *Phys. Rev. Lett.* **31B, 22 (1970);** J. Chou and J. J. Sakurai, *Phys. Lett.* **31B, 22 (1970).**
21. For a review of the Vector Dominance and Generalized Vector Dominance Models, see T. H. Bauer, R. E. Spital, D. R. Yennie and F. M. Pipkin, *Rev. Mod. Phys. 50,* 261 (1978).
22. J. D. Bjorken, *Proceedings of the International School of Physics "Enrico Fermi", Course XLI: Selected Topics in Particle Physics,* J. Steinberger, ed. (Academic Press, New York, 1968).
23. M. Cell-Mann, *Phys. Rev.* 125, 1062 (1962); For a review of current algebra see: J. D. Bjorken and M. Nauenberg, *Ann. Rev. Nucl. Sci.* **18, 229** (1968).
24. S. L. Adler, *Phys. Rev.* **143, 1144** (1966).
25. J. D. Bjorken, *Phys. Rev. Lett.* **16, 408** (1966).
26. J. D. Bjorken, *Phys. Rev.* **163, 1767 (1967).**
27. R. P. Feynman, *Phys. Rev. Lett. 23,* 1415 (1969); *Proceedings of the III International Conference on High Energy Collisions,* organized by C. N. Yang *et al.* (Gordon and Breach, New York, 1969).
28. S. Drell, D. J. Levy and T. M. Yan, *Phys. Rev.* **187, 2159 (1969);** *Phys. Rev.* **Dl,** 1035, 1617 (1970).
29. N. Cabbibo, G. Parisi, M. Testa and A. Verganelakis, *Lett. Nuovo Cimento 4, 569 (1970).*
30. T. D. Lee and S. D. Drell, *Phys. Rev.* **D5,** 1738 (1972).
31. J. D. Bjorken and E. A. Paschos, *Phys. Rev.* **185, 1975 (1969).**
32. J. Kuti and V. F. Weisskopf, *Phys. Rev.* **D4, 3418** (1971).
33. P. V. Landshoff and J. C. Polkinghorne, Nucl. *Phys.* B28, 240 (1971).
34. G. Miller *et al., Phys. Rev.* D5, 528 (1972).
35. J. S. Poucher *et al., Phys. Rev. Lett. 32,* 118 (1974).
36. A. Bodek et *al., Phys. Rev. Lett. 30,* 1087 (1973); *Phys. Lett.* **51B, 417 (1974);** *Phys. Rev.* D20, 1471 (1979).
37. E. M. Riordan *et al., Phys. Rev. Lett. 33,* 561 (1974); *Phys. Lett.* 52B, 249 (1974).
38. W. B. Atwood *et al., Phys. Lett.* **64B, 479** (1976).
39. W. B. Atwood and C. B. West, *Phys. Rev.* **D7, 773 (1973).**
40. A Bodek, *Phys. Rev.* D8, 2331 (1973).
4 1. C. G. Callan and D. J. Cross, *Phys. Rev. Lett.* **21, 311 (I 968).**
42. K. Gottfried, *Phys. Rev. Lett.* **18, 1174** (1967).
43. C. G. Callan and D. J. Cross, *Phys. Rev. Lett. 22, 156* (1969).
44. D. H. Perkins, in *Proceedings of the XVI International Conference on High Energy Physics,* Chicago and NAL, Vol. 4, 189 (1972).
45. *Proceedings of the XVII International Conference on High Energy Physics,* London, (1974). M. Haguenauer, p. IV-95; F. Sciulli, p.IV-105; D. C. Cundy, p. IV-131.

DEEP INELASTIC SCATTERING

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REFERENCES

1. R. E. Taylor, Deep Inelastic Scattering: The Early Years. H. W. Kendall, Deep Inelastic Scattering: Experiments on the Proton and the Observation of Scaling, and J. I. Friedman, Deep Inelastic Scattering: Comparisons with the Quark Model. *Les Prix Nobel 1990.*