TWO-MILE-LONG ELECTRON ACCELERATOR at the Stanford Linear Accelerator Center (SLAC) was used to obtain the experimental results reported in this article. The electron beam is raised to a maximum energy of 21 billion electron volts (GeV) as it travels down a vacuum pipe lined with klystron tubes and focusing magnets. Near the end of its trip the electron beam passes through a "beam switchyard" before reaching the target areas, which are located inside the two large buildings in the foreground.

The Structure of the Proton and the Neutron

The way ultrahigh-energy electrons are scattered by protons and neutrons suggests that these "elementary" nuclear particles have a complex internal structure consisting of pointlike entities

by Henry W. Kendall and Wolfgang K. H. Panofsky

Sixty-five years ago Ernest Rutherford observed how alpha particles are scattered by thin metal foils and concluded that the atom is not a homogeneous body but consists of negatively charged electrons surrounding a small, massive, positively charged nucleus. Since that time physicists in many laboratories have conducted scattering experiments with particles of ever increasing energy in an effort to probe the structure first of the atom, then of the nucleus and now of the basic constituents of the nucleus: the proton and the neutron. Are these "elementary" nuclear particles homogeneous? Recent investigations with electrons brought to an energy of 21 billion electron volts by the two-mile accelerator at the Stanford Linear Accelerator Center (SLAC) strongly suggest that history may be repeating itself on a scale 100,000 times smaller than that of the atom. It turns out that ultrahigh-energy electrons are scattered by protons and neutrons in ways that no one had predicted. The tentative conclusion is that the nuclear particles have a complex internal structure consisting of pointlike entities now called partons. And there is evidence that partons share some of the properties assigned earlier to those hypothetical particles named quarks.

Knowledge of the internal structures of the proton and the neutron may provide the key to understanding the "strong" force that holds the atomic nucleus together and endows the universe with its stability. The strong force makes its presence known in the nuclear reactions that fuel the stars and that, on a more modest scale, provide the energy for nuclear power and nuclear explosives. Although the exploitation of the strong force has become a commonplace in technology, the nature and origin of the force is still poorly understood.

In addition to exhibiting the strong force, protons and neutrons also respond to the electromagnetic force, which is some 100 times weaker. Both nuclear particles behave like tiny magnets and both comprise electric charges (although the neutron's net charge is zero). Whereas the strong force operates only when the interacting particles are very close together (a distance roughly equivalent to their own diameter: about 10^{-13} centimeter), the electromagnetic force has an infinite range, falling off in strength with the square of the separation. Since the neutron and the proton respond to the electromagnetic force, they scatter electrons aimed at them. It is the pattern of the scattering that provides clues to their structure.

Since the Stanford experiments are fundamentally the same as Rutherford's it will be useful to briefly review his techniques and results. He placed a natural emitter of alpha particles (particles with a charge of +2, later identified as helium nuclei) in an evacuated box equipped with a collimator so that a well-defined beam of particles would strike a target consisting of a metal foil [*see top illustration on page 63*]. The box was also provided with a zinc sulfide screen that would scintillate when it was struck by an alpha particle. The screen could be moved to intercept particles scattered at any angle, and the scintillations were counted one at a time with the aid of a low-power microscope. Two of Rutherford's collaborators, Hans Geiger and Ernest Marsden, soon noticed that alpha particles were being scattered at large angles far more often than one would have predicted on the basis of the then current ideas of atomic structure. The electric charge in atoms was believed to be diffusely distributed and hence should not have exhibited the concentrated electric fields needed to produce such large particle deflections.

Rutherford concluded that "the positive charge associated with an atom is concentrated into a minute center or nucleus, and that the compensating negative charge is distributed over a sphere of radius comparable with the radius of the atom." He also worked out the mathematical law describing how one point of electric charge would be scattered by another point charge [*see bottom illustration on page 63*]. The force between two charged particles was assumed to be given by Coulomb's law. Knowing the charge and mass of the interacting particles, Rutherford combined Coulomb's law with Newton's laws of motion to relate the probability of scattering through a given angle to the energy of the incident particle. The probability of scattering by a single target atom is the "scattering cross section," defined as the area of the incident beam within which the influence of the target atom gives rise to the process observed—in this case scattering. The cross section is not necessarily related to the "true" physical size of the target particle but rather represents a measure of the force exerted on the incident particle by the target particle.

The cross section is experimentally determined for different angles (measured from the axis of the incident beam), and the results can be compared with theoretical predictions. Rutherford's formula predicts the scattering cross section from the mass m and charge of the incident particle, the mass and charge of the target particle, the velocity v of the incident particle and the scattering angle θ. The formula depends directly on the particular combination of these variables that describes the vector difference, q, between the initial momentum and the final momentum of the scattered particle: $q = 2mv\,(\sin\theta/2)$. Another term for

q is "momentum transfer" [*see top illustration on page 64*]. The formula assumes that the interacting particles are mathematical points, having neither size nor shape. In general, however, a scattering cross section will depend not only on the details of the forces (for example exactly how their strength varies with distance) and on the laws of motion of the particles (which may involve non-Newtonian, or relativistic, considerations) but also on whatever internal structure the particles may have.

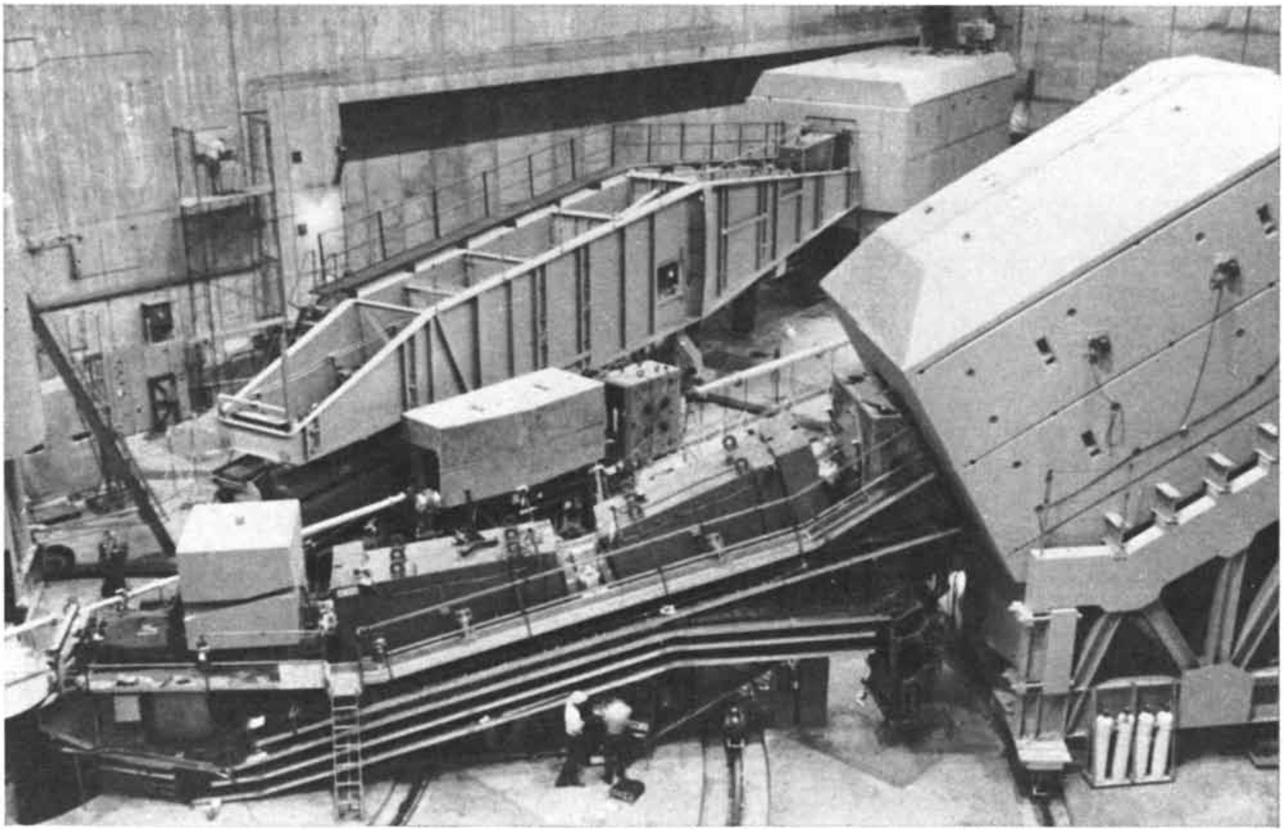
In scattering processes described by quantum mechanics the momentum transfer plays a central role, because it determines the scale of what is being studied. In quantum mechanics a particle that has a certain momentum p also has associated with it a certain wavelength λ. The formula that relates these properties is $\lambda = h/p$, where h is the extremely small number (6.6×10^{-27} erg-second) known as Planck's constant. The accuracy to which a particle can be located is limited by the associated wave; the probability of finding the particle at a given point is governed by the behavior of the "wave packet" describing the particle's motion. To locate one particle with another, the two have to interact (that is, the experimenter must scatter one from the other), and this involves a transfer of momentum between the two. Thus it is reasonable that the accuracy Δx to which the details of an unknown structure can be examined is governed by the momentum transfer q experienced in the collision; the resulting relation is $\Delta x = h/q$ [*see bottom illustration on page 64*]. This formula implies that our ability to distinguish fine detail in the target particle depends on making q as large as possible in order to make the wavelength λ as small as possible. (Momentum is the product of mass times velocity; at the energies of interest to physicists engaged in high-energy electron scattering the mass increases with increasing energy while the velocity remains essentially constant at the velocity of light.)

In scattering experiments of the type performed at Stanford momentum is measured in units of GeV/c, where "GeV" stands for giga (10^9, or one billion) electron volts and c is the velocity of light. An electron of 20 GeV lacks only one part in three billion of traveling at the velocity of light. Under these conditions the particle energy expressed in GeV and its associated momentum expressed in GeV/c are essentially equal.

Two Kinds of Scattering

The scattering of electrons can be either "elastic" or "inelastic." In elastic scattering the target particle recoils much as if it were a billiard ball, remaining in the same internal state it was in before the collision. In inelastic scattering the target particle either disintegrates or is left in an excited state, a state different from its original condition. There is a trade-off between the two processes: one robs the other. Both processes tell a good deal about the structure of the target particle. We shall discuss elastic scattering first.

Rutherford's formula does not adequately describe the elastic scattering of high-energy electrons for two reasons. First, the velocities are so great that one must use relativistic quantum theory to describe the wave nature and behavior of the incident and target particles. Second, electrons have "spin," that is, they have a unique angular momentum, as if they rotated around an internal axis. The



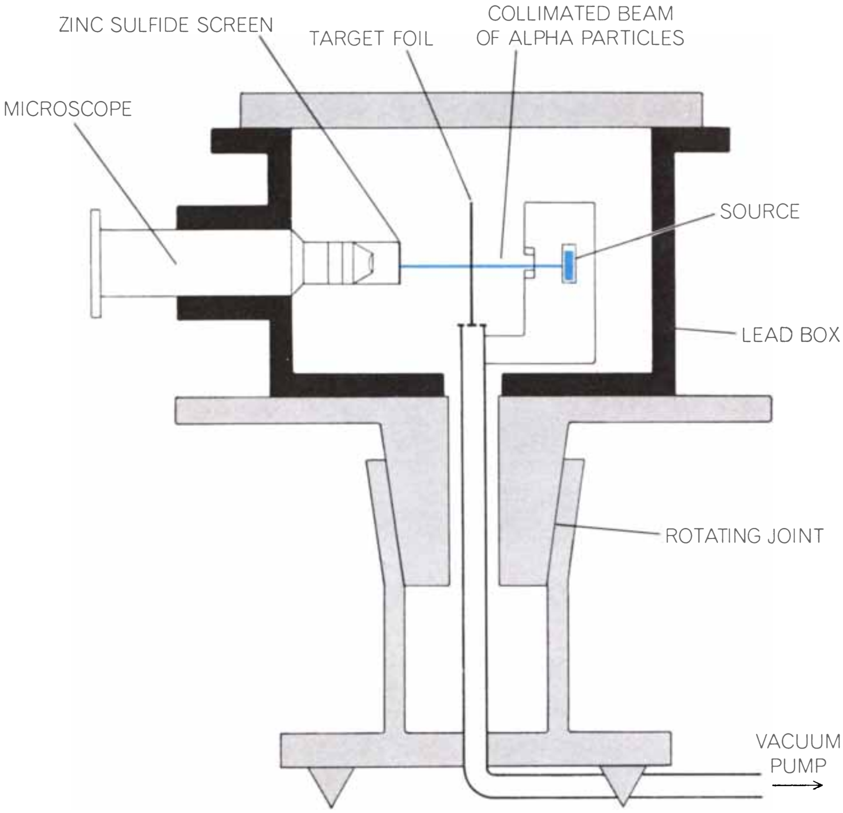
LARGE MAGNETIC SPECTROMETERS in one of the experimental areas at the SLAC site are used to separate and classify the scattered electrons emerging from the target and to funnel them into a system of detectors. Three spectrometers, each consisting of a complicated array of magnetic lenses and bending magnets, are installed around a common pivot point in this area; two are visible in this view. The scale of the instruments can be appreciated by noting the two men standing near the "middle-sized" device.

more precise formula that must be used is known as the Mott cross section. Except for the term that accounts for the spin of the electron, the Mott equation can be reduced directly to Rutherford's equation in those cases where the velocity of the incident particle is much smaller than the speed of light, as was true in Rutherford's experiments [*see top illustration on page 65*]. Since Rutherford did not know that quantum mechanics governed his scattering experiments, it is only a happy accident that his formula correctly describes low-energy scattering. We now know that Newton's "classical" laws of motion can be successfully applied only when scattering is attributable primarily to those forces whose strength varies inversely with the square of the distance, as the electrical Coulomb force does.

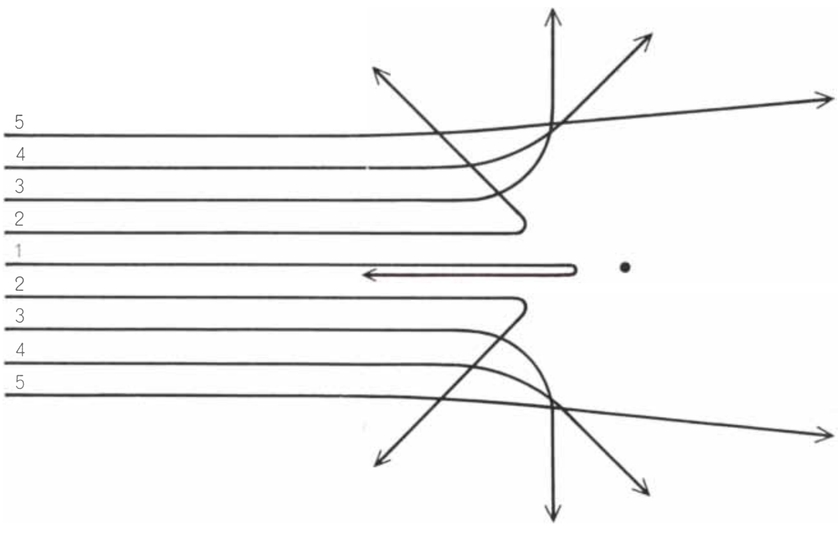
The Mott formula itself must be modified if the electron is scattered not by another point charge but rather by an object of finite dimensions [*see bottom illustration on page 65*]. In that case each segment of the electron wave front is diffracted separately by each subunit of charge within the target particle. The individual wavelets scattered by the subunits then recombine to form an outgoing wave that describes the scattered electron. As one might expect, some of the wavelets add constructively and some interfere, thereby canceling one another. The elastic-scattering cross section from a charged particle of finite size is therefore generally less than the cross section from a point charge. The factor by which the scattering is decreased below that from a point charge is given by the square of a number called a form factor, designated F.

The formula for the form factor is obtained by tracing the extra length each wavelet has to travel when it is scattered by charged subunits within the target particle. The formula depends solely on the momentum transfer, q, which is the vector difference in momentum between the ingoing and the outgoing electron. Given a sufficiently high value of q, the form factor will be sensitive to details of the target's structure; if q is too small, the experiment will reveal little.

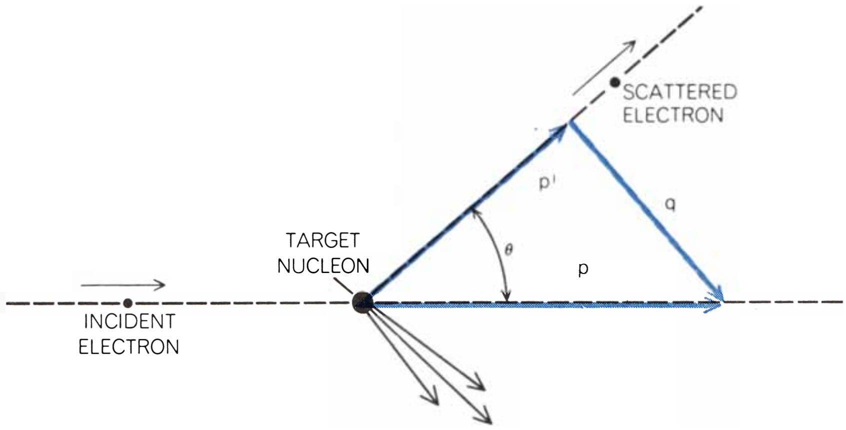
If the target particle is a nucleon (a proton or a neutron), one would like to study its structure at distances smaller than its own radius, which is known to be about .8 fermi (one fermi is 10^{-13} centimeter). To have a resolution of, say, .1 fermi would require a momentum transfer of 2 GeV/c. In the present experiments the practical limit is about 5 GeV/c and is therefore small enough to



ORIGINAL APPARATUS used by Ernest Rutherford and his co-workers to study how alpha particles are scattered by thin metal foils is shown in this illustration, which was adapted from a diagram published in *Philosophical Magazine* in 1913. A natural emitter of alpha particles was placed in an evacuated box equipped with a collimator so that a well-defined beam of particles would strike the target foil. A zinc sulfide screen that would scintillate when struck by an alpha particle was moved to intercept particles scattered at any angle and the scintillations were counted with the aid of a low-power microscope. It was on the basis of observations made with this device that Rutherford concluded that the atom consists of a massive, positively charged nucleus surrounded by negatively charged electrons. All later scattering experiments are essentially variations of this basic technique.



ACCORDING TO RUTHERFORD, the scattering of one point of electric charge by another point charge could be described by a mathematical law that combined Coulomb's law (for the force of attraction or repulsion between two charged particles) with Newton's laws of motion to relate the probability of scattering through a given angle to the energy of the incident particles. In this diagram of the Rutherford scattering process the amount of scattering can be seen to depend also on the position of the incident particle's trajectory.



MOMENTUM TRANSFER, an important concept in the theoretical treatment of the scattering process, is defined as the vector difference (q) between the initial momentum (p) and the final momentum (p') of the scattered particle. The formula that expresses this relation is $q = 2mv\ (sin\ \theta/2)$, where m is the mass of the incident particle, v is its velocity and θ is the scattering angle. In elastic scattering the target nucleon simply recoils; in inelastic scattering it either disintegrates to form other particles or it is left in an excited state.

provide substantial information about the proton. If the form factor were known for a wide range of values of the momentum transfer, the charge distribution in the target particle could be reconstructed.

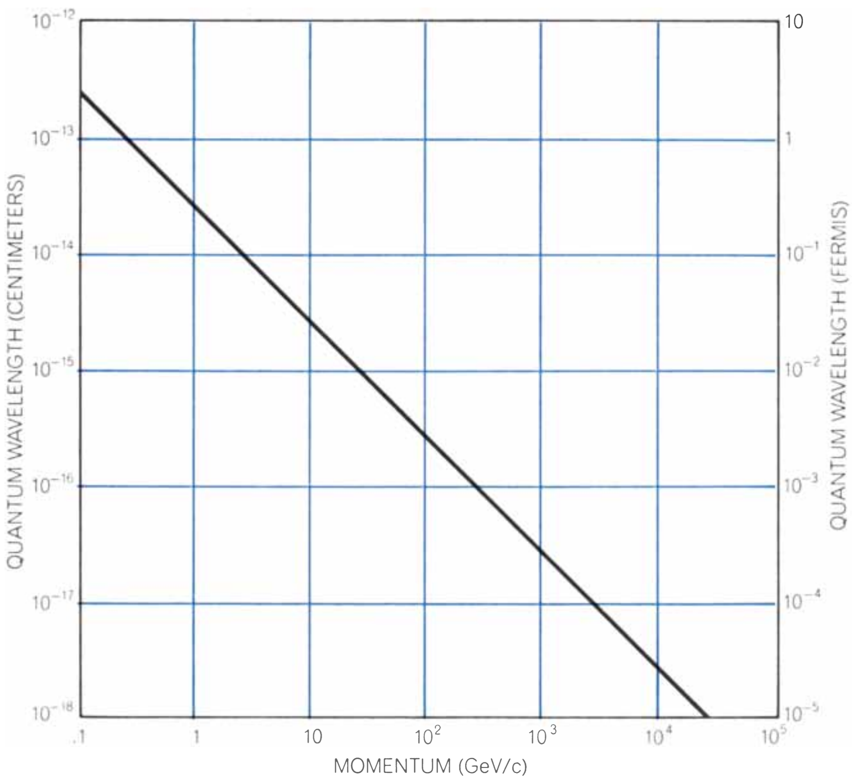
The task of computing the distribution of charge within a particle such as a proton from electron-scattering data closely resembles the task of reconstructing the structure of a crystal from the complex diffraction pattern produced when it is bombarded by X rays. The electron-scattering problem is much more difficult, however, particularly when the velocity of the recoiling proton approaches the velocity of light. The effects of relativity on the motion of the proton introduce ambiguities that complicate our attempts to reconstruct the spatial distribution of the charge.

A further complication is introduced by the proton's spin, which produces a magnetic moment. As a result the incident electron can interact with the proton's magnetization as well as with its electric charge. Since the magnetization can also have a finite distribution in space, it gives rise to a second form factor, designated F_m to distinguish it from the electric form factor F_e. The effect of these complications is to modify Rutherford's original formula to take account of the following facts: Both the incident and the target particle carry spin, the target particle is extended in space, the collision velocities are so high that relativistic effects are introduced, and the motion of both particles is described by wave mechanics rather than by classical mechanics [*see illustration on page 66*].

This somewhat elaborate discussion should not detract from the basic simplicity of the electron-scattering process. The process enables one to explore the unknown structure of subnuclear particles with the known forces of electromagnetism. This is in contrast to those experiments (interesting for other reasons) in which two particles of unknown structure collide, for example in proton-proton or pion-proton scattering. As far as is known to date, electrons behave like point charges and interact in scattering experiments only through the force of electromagnetism. (It is true, of course, that electrons also interact through the "weak" force, which plays a role in radioactive decay processes, but since the weak force is roughly 10^{10} times smaller than the electromagnetic force it can be ignored in electron-scattering experiments.) The laws of electricity and magnetism as they are now embodied in the equations of quantum electrodynamics represent the one and only area in physics where a single quantitative description has proved valid over the entire range of experiments for which it has been tested, from cosmic dimensions down to 10^{-15} centimeter. Thus the assumption that these particular forces are understood seems well justified.

The Two-Mile Accelerator

Before discussing the results of elastic- and inelastic-scattering experiments obtained with the Stanford electron accelerator, we shall briefly describe the facility and the techniques involved. The



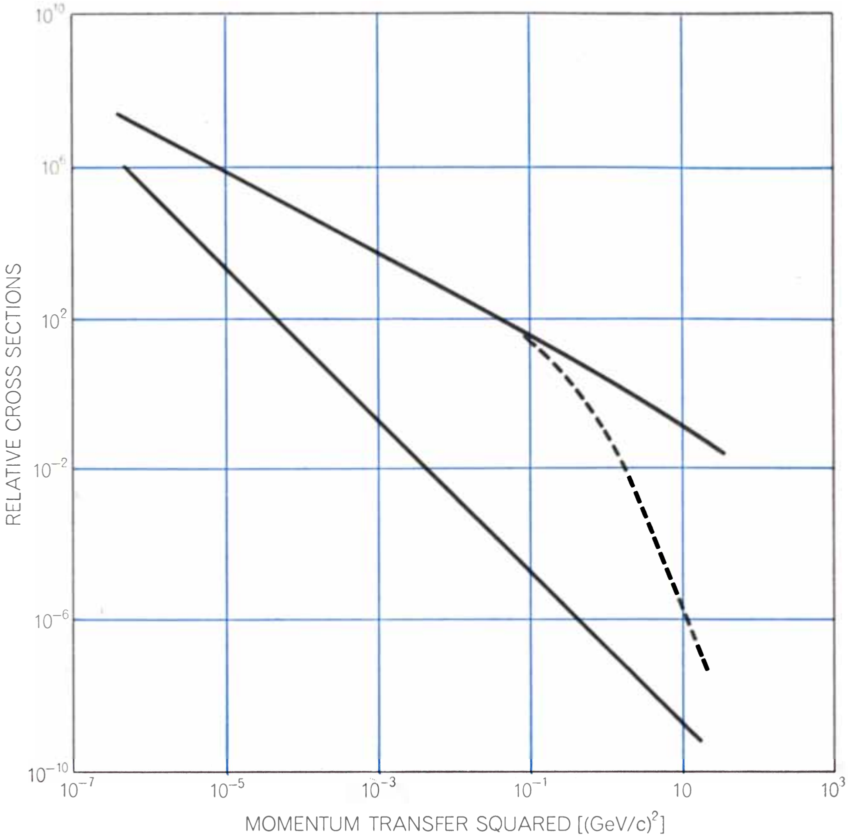
POSSIBILITY OF LOCATING A PARTICLE of momentum p is governed by its associated wavelength λ according to the relation $\lambda = h/p$, where h is Planck's constant (6.6×10^{-27} erg-second). In this graph of the relation momentum is measured in units of GeV/c, where "GeV" stands for giga (10^9) electron volts and c is the velocity of light. The quantum wavelength of the incident particle is given in both centimeters (*left*) and fermis (*right*).

electron beam is raised to a maximum energy of 21 GeV as it travels down a two-mile evacuated pipe lined with 245 klystron tubes that pour electromagnetic energy into the beam. During its two-mile trip the beam is kept tightly focused by magnetic "lenses" spaced every 100 meters. At the end of its trip the beam passes through a final "purgatory" of magnets and slits that closely define the width and energy range of the electron beam that reaches the target. A typical scattering experiment requires a target containing hydrogen or deuterium and a means for selecting and identifying electrons scattered at different angles and measuring their momenta in the presence of many other particles produced by the collisions of electrons and nuclei.

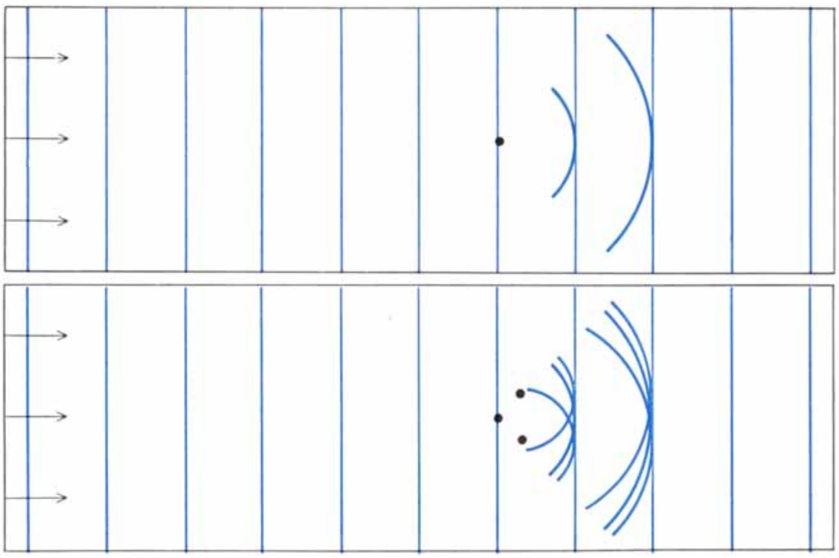
A vessel containing liquid hydrogen provides the target protons; the nucleus of ordinary hydrogen consists of a single proton. Using liquid deuterium, or heavy hydrogen, is the next best thing to having a target of free neutrons; the deuterium nucleus consists of a proton and a neutron. To a good approximation the scattering from deuterium nuclei is simply the sum of the scattering from neutrons and protons. Because the beam striking these liquefied gases is very intense they must be cooled continuously by means of a heat exchanger, not simply to prevent boiling but to minimize changes in density that would throw off the results.

To separate and classify the electrons emerging from the target the Stanford installation is equipped with three magnetic spectrometers, which funnel the electrons into a system of detectors. They were designed and constructed as a collaborative effort by physicists from the California Institute of Technology, the Massachusetts Institute of Technology and the group at SLAC. Very high resolution in both energy and angle is required, since we must be able to distinguish between elastically and inelastically scattered electrons and to resolve the detailed structure in the spectra of electron energies produced by inelastic scattering.

In the inelastic scattering one or more pions can be produced in the scattering collision. Since the energy required to create a pion is 139 MeV (million electron volts) the resolution needed must be considerably better than the ratio of 139 MeV to the incident energy, which can exceed 20 GeV. A resolution of better than .7 percent in energy is therefore needed. A similar analysis of the collision kinematics indicates that the resolution in angle should be a fraction of a milliradian, which is about three minutes



SCATTERING CROSS SECTION, defined as the area of the incident beam within which the influence of a target atom gives rise to a certain kind of interaction, is given here for the scattering of an electron by a target nucleon according to the Rutherford formula (*bottom line*) and according to the Mott formula (*top line*). Except for the term that accounts for the spin of the electron, the Mott formula reduces directly to Rutherford's as the energy and the velocity of the incident electron become small. The broken curve shows Mott scattering from a finite proton. The curves are drawn for a scattering angle of 20 degrees.



MODIFICATION of the scattering formula is required if the electron is assumed to scatter not from another point charge (*top*) but rather from an object of finite dimensions (*bottom*), represented here as composed of three point constituents. In the latter case each segment of the electron wave front is diffracted separately by each subunit of charge. The individual wavelets scattered by subunits then recombine to form an outgoing wave that represents the scattered electron. The amount by which the scattering cross section from a charged particle of finite size is reduced below that from a point charge is called the form factor (F).

of arc. What counts is the precision in *relative* angle and in *relative* energy between the incident and the scattered electrons; therefore these requirements for the resolution of both angle and energy apply equally to the incident beam and to the spectrometers analyzing the scattered beam.

The spectrometers are large and complicated machines [*see illustration on page 62*]. They consist of magnetic lenses and bending magnets that deflect the scattered electrons vertically and then bring them to a focus. The amount of vertical deflection is a measure of the electron's momentum; the horizontal position is a measure of the scattering angle. Hundreds of counters, the equivalent of the zinc sulfide scintillation screen used in Rutherford's experiments, identify the momentum and angle of each electron. The counters are narrow bars of specially prepared transparent plastic that scintillate briefly when they are struck by a high-energy particle. Each bar is viewed by a photomultiplier tube that signals each tiny light flash.

The signals from the counters and other particle-identification devices are processed and passed on to a large computer. The computer is run "on line," storing data for later detailed analysis at the same time it is performing a simplified partial analysis. In addition to displaying such results the computer provides status information on the equipment and performs many routine "housekeeping" chores, such as adjusting currents in the spectrometer magnets and logging beam currents and other quantities of interest.

Nucleon Form Factors

The elastic-scattering experiments carried out by Cal Tech, M.I.T. and SLAC physicists have yielded measurements of the four elastic form factors that describe the structure of the proton and the neutron. The quality and quantity of these data, however, are quite variable. The most accurate measurements are those that give the magnetic form factor of the proton [*see illustration on page 72*]. The magnetic form factor of the neutron, obtained by subtracting from the deuterium scattering the scattering attributable to the proton, looks similar to the proton curve except that the errors are larger. The electric form factor of the proton resembles its magnetic form factor, but the electric curve has been determined for only a much smaller range of variables. The electric form factor of the neutron is known to be practically zero; the errors in the existing measurements, however, are large.

One might ask: Why are electrons scattered by the neutron at all, since the neutron has no electric charge? The answer has two parts. First, the neutron's spin produces a magnetic moment; this alone would show up in the scattering described by the magnetic form factor. Second, the electric current that gives rise to the neutron's magnetism can produce localized accumulations of charge within the particle even though the particle's net charge is zero. Such accumulations give rise to electric scattering whenever the values of momentum transfer exceed zero. Thus elastic electron scattering not only responds to the overall charge and magnetic moment of the neutron but also reveals what is going on inside.

The experiments indicate that the magnetic structures of the neutron and the proton are almost identical but that the magnitude of the scattering from each is proportional to the magnetic properties of each particle as found from static experiments. In other words, the magnetic form-factor curves of the two particles are identical in shape as far as we can tell from experiment. It is probably also significant that over the limited range accessible to experiment the electric scattering of the proton is proportional to the magnetic scattering. This suggests that the distribution of electric charge within the proton is directly related to the magnetic structure.

The scattered wavelets create a diffraction pattern similar to the shadow pattern formed when parallel rays of light strike the edge of an object. If the object has a sharp edge, the pattern will consist of alternate dark and light bands. Similarly, if the proton were an object with a sharply defined surface, one would see much more structure in the form-factor curve than is in fact seen. Evidently, therefore, the proton has a fuzzy boundary. Details of the curve give the proton's average radius: about .8 fermi, or $.8 \times 10^{-13}$ centimeter.

RUTHERFORD CROSS SECTION $\sigma_R = \frac{(2e^2\ m)^2}{q^4}$	e=ELECTRON m=MASS OF ELECTRON $q=2\sqrt{pp'}\ \sin\theta/2$ p=INITIAL MOMENTUM OF ELECTRON p′=FINAL MOMENTUM OF ELECTRON
MOTT CROSS SECTION $\sigma_M = \frac{(2e^2\ E'/c^2)^2}{q^4} \cdot \frac{E'}{E}\left(\cos^2\frac{\theta}{2}\right)$	θ=SCATTERING ANGLE OF ELECTRONS E=INITIAL ENERGY OF ELECTRON E′=FINAL ENERGY OF ELECTRON c=VELOCITY OF LIGHT
ROSENBLUTH CROSS SECTION $\sigma=\sigma_M\left(\frac{F_e^2+\tau F_m^2}{1+\tau}+2\tau F_m^2\tan^2\frac{\theta}{2}\right)$	F_e= ELECTRIC FORM FACTOR F_m=MAGNETIC FORM FACTOR $\tau=q^2/4M^2c^2$ M=MASS OF NUCLEON

INCREASING COMPLEXITY is introduced to the scattering equation as one proceeds from the Rutherford formula to the Mott formula to the Rosenbluth formula (*left*). The final equation takes into account the following facts: both the incident and the target particle carry spin, the target particle is extended in space, the collision velocities are so high that relativistic effects are introduced, and the motion of both particles is described by wave mechanics rather than by classical mechanics. Symbols are defined in key at right.

Particles Real and Virtual

One of the most surprising findings to physicists is the fact that the curve representing the magnetic form factor of the proton, shown on page 72, is smooth over an enormous range of experimental variables. The observed scattering cross section, which varies as the square of the form factor multiplied by the Mott formula for point scattering, falls off by 10^{12} over the range of variables for which measurements have been made. The cross sections associated with the lowest part of the curve are extremely small: the smallest cross section measured was about 2×10^{-39} square centimeter per steradian, which under the conditions of the experiment means that only one out of every 10^{18} electrons was scattered into the detector. The scattering decreases as the fourth power of the momentum transfer. This rapid falling off is one of the current puzzles in high-energy physics. To understand how the

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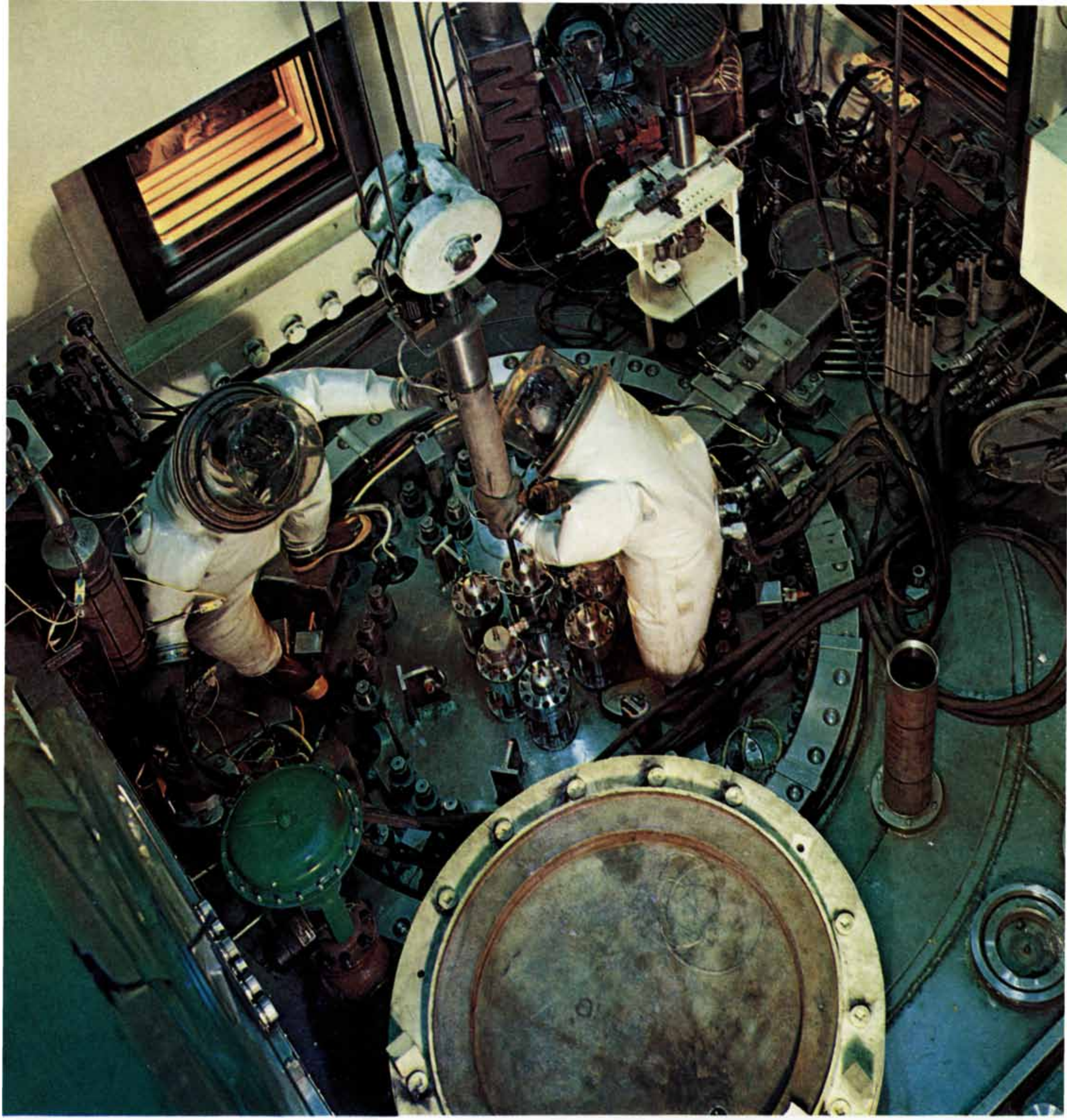

Technicians charging a fast breeder reactor

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puzzle arises and how it may be explained it is necessary to dwell briefly on the concept of "virtual particles."

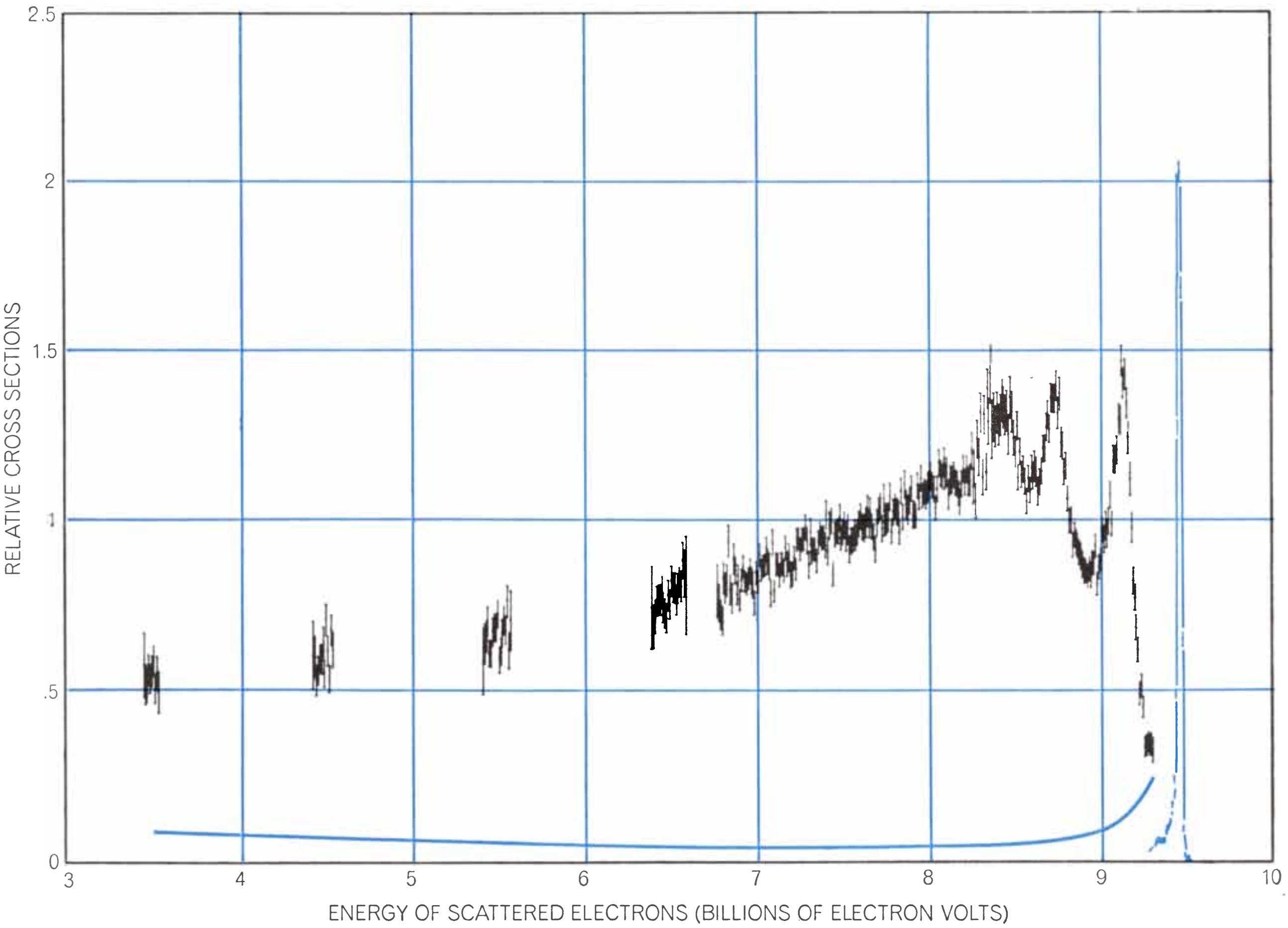
The concept of virtual particles is related to the uncertainty principle enunciated by Werner Heisenberg more than 40 years ago. In the wave description of matter it is impossible to determine simultaneously a particle's wavelength and its momentum. Heisenberg's principle relates the uncertainty in the measurement of the particle's wavelength, Δx, with the uncertainty in the particle's momentum, Δp. The product of the two uncertainties is proportional to Planck's constant h ($\Delta p \cdot \Delta x \simeq h$). Equivalently one can relate the uncertainty in the particle's measured energy, ΔE, to the uncertainty in the time, Δt, within which the measurement was made, in which case $\Delta E \cdot \Delta t \simeq h$.

Now, in relativity theory mass and energy are equivalent, as expressed by Einstein's relation $E = mc^2$. One can imagine, therefore, that for a very short time Δt any given amount of energy ΔE can be converted into a mass m equivalent to the rest mass of some particle, provided that the product of ΔE and Δt does not exceed h. In other words, without violating the uncertainty principle one or more particles can appear in a system and exist for immeasurably brief periods. In a sense their existence is "hidden" by an irreducible uncertainty in our knowledge of the system. Particles that appear in this way are called virtual particles; they cannot be observed directly as real particles can.

Most models that describe the interaction between the electron and the proton visualize the photon (the quantum of light) as the carrier of the electromagnetic force. It too can be real or virtual. Real photons are the packets of waves that carry energy from a radiating source (such as a star) to an absorber (such as the pigments in the eye). In quantum electrodynamics the electromagnetic forces that act between two (or more) moving charges are attributed to the emission and absorption of virtual photons. Hence in electron scattering a virtual photon emitted by the electron interacts with, and is absorbed by, the electric charge and magnetism within the proton. Virtual photons can carry energy and momentum in any proportion, unlike real photons, whose energy and momentum are uniquely related.

Although it may seem that virtual particles violate fundamental conservation laws, the violation is closely delimited to those areas where the uncertainty principle applies. It does not apply, for example, to the conservation of electric charge. Thus it is not possible for a single virtual electron to appear in a vacuum; it must always be accompanied by a particle of opposite charge, the positron.

There is a class of unstable particles,



TYPICAL SCATTERING SPECTRUM produced by an electron beam with an energy of 10 GeV colliding with stationary protons includes both elastic events (*color*) and inelastic events (*black*). The elastic peak at right has been reduced in height by a factor of five; the asymmetry of its tail arises because the electrons can emit "soft" X rays that "rob" various amounts of energy and thus blur out the elastic peak on the low-energy side. The smaller peaks or bumps in the inelastic spectrum correspond to excited states of the proton; they are called resonance excitations, or simply resonances. To the left of these bumps is a smoother continuous spectrum called the continuum. As one goes to higher incident energies the resonances tend to disappear but the continuum remains.

the neutral vector mesons, whose members resemble photons in many ways, with two important exceptions: they have mass and they exhibit the strong force. The most prominent is the rho meson, which has a mass equivalent to about 750 MeV. (The mass of the proton is equivalent to 939 MeV.) Rho mesons can be created as real particles in the laboratory, and their decay products can be detected. Neutral vector mesons can also be created as single virtual particles by photons propagating in a vacuum—and the photons that create them can be either real or virtual. In a sense the photon is a vector meson a tiny fraction of the time.

Because vector mesons are massive they become a significant factor in modifying photon processes only in experiments at very high energies, such as those we are describing. In addition, as carriers of the strong force, the vector mesons play an important role when real photons of very high energy interact with nucleons.

Before the recent scattering experiments were conducted theorists thought they could predict how the vector mesons would participate in both elastic and inelastic scattering at high energies. In particular they predicted that if elastic scattering is dominated by vector mesons, the form-factor curve should fall off as the inverse square of the momentum transfer. Instead the curve decreases as the inverse fourth power. Clearly the simple model does not work.

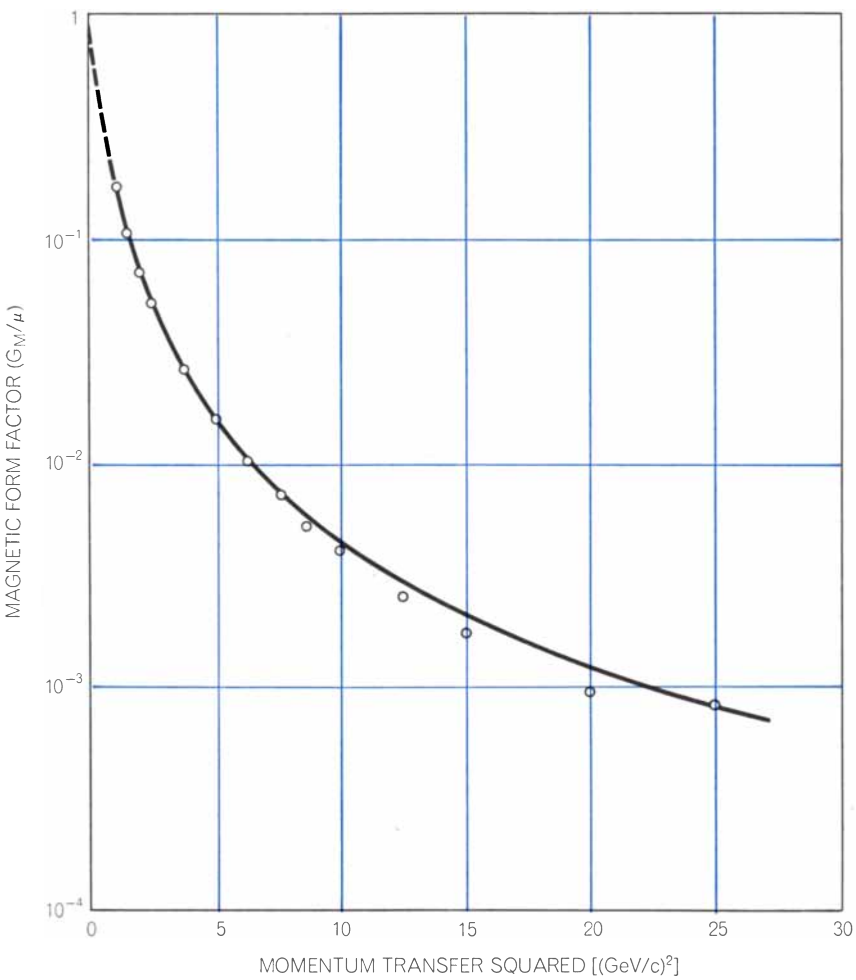
Inelastic v. Elastic Scattering

In a collaborative program of measurements carried out by workers at M.I.T. and SLAC very large cross sections were discovered for the inelastic-scattering processes. When one looks at a typical scattering spectrum produced by electrons of 10 GeV colliding with protons, one sees first of all a broad peak with an asymmetric tail [*see illustration on preceding page*]. The peak represents elastic scattering; the asymmetry of the tail results from the fact that the electrons can emit "soft" photons (X rays) that steal various amounts of energy and so blur the elastic peak on the low-energy side.

In addition, the scattered-electron spectrum contains two features produced by inelastic processes. First one sees a number of bumps that correspond to excited states of the proton. They are often called resonance excitations, or simply resonances. The position of the bumps corresponds to now well known excited states of the proton, identified in many high-energy experiments. Four specific resonances have been identified in inelastic electron scattering; the size of the associated bumps depends strongly on the magnitude of the momentum transfer to the proton. The bumps shrink rapidly in size as the momentum transfer increases. The shrinkage occurs just about as fast as the shrinkage of the elastic-scattering peak itself. From this we conclude that the radial dimensions of the excited states represented by the bumps are comparable to the dimensions of the proton itself in its unexcited condition. This implies that in some way most of the nucleon structure is involved when it is in a resonance, or excited, state.

The second feature of the scattered-electron spectrum produced by inelastic processes is called the continuum: the smooth distribution in the energies of those scattered electrons that do not fall in the resonance peaks. Physicists regard the continuum as perhaps the most exciting and puzzling part of all the recent Stanford results. As we go to larger scattering angles or to higher incident energies the resonances tend to disappear but the continuum remains.

When the inelastic-scattering program was formulated, theorists had believed that the continuum cross sections would decrease nearly as rapidly as the elastic cross sections when the momentum transfer was raised. Instead the results show that for incident electron energies ranging from 4.5 to 19 GeV the inelastic-scattering cross sections more closely resemble those that would be produced by point targets [*see illustration on page 75*]. In one comparison the best predictions available before the experiments turned out to be low by as much as a factor of 40 [*see top illustration on opposite page*]. The factor of error is even



MAGNETIC FORM FACTOR OF PROTON was found by the Cal Tech–M.I.T.–SLAC group to be unexpectedly smooth over an enormous range of experimental variables. (The square of the magnetic form factor is the amount by which the scattering cross section attributable to the magnetization of a charged particle of finite size is less than that of a point charge.) The fact that the form factor decreases as fourth power of the momentum transfer, which is faster than theorists had predicted, is a current puzzle of high-energy physics.

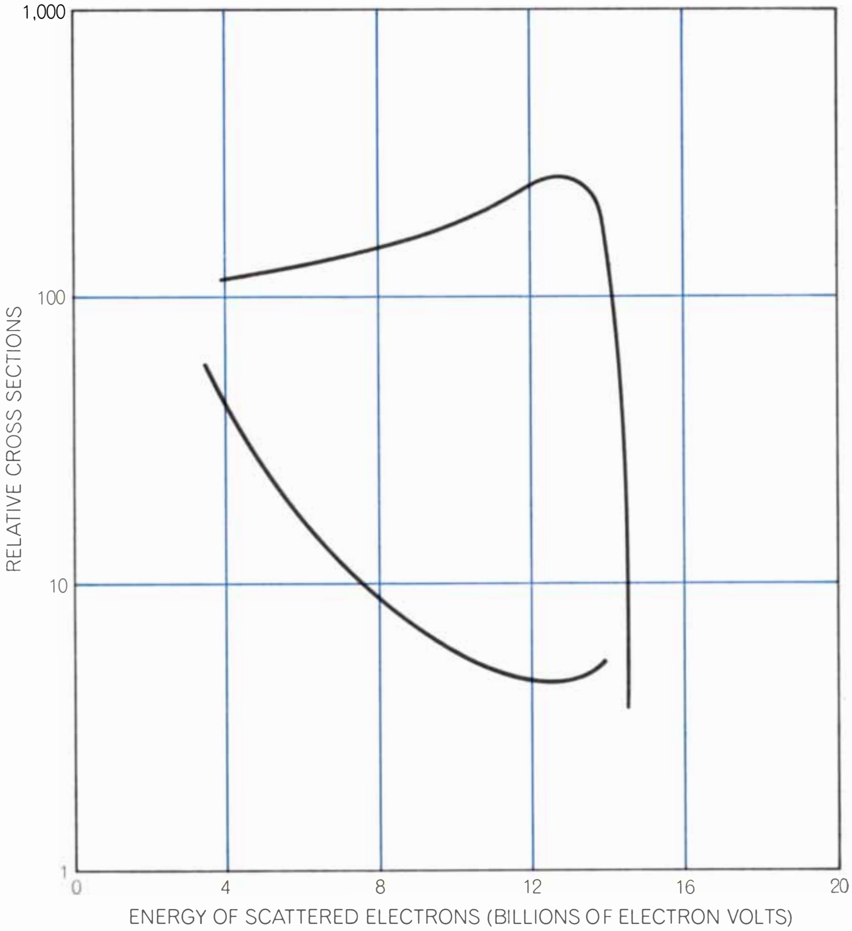
higher in other spectra. The tentative conclusion is that the internal structures from which inelastic scattering takes place are much smaller than the nucleons either in their ground state or in their excited state.

The Parton Model

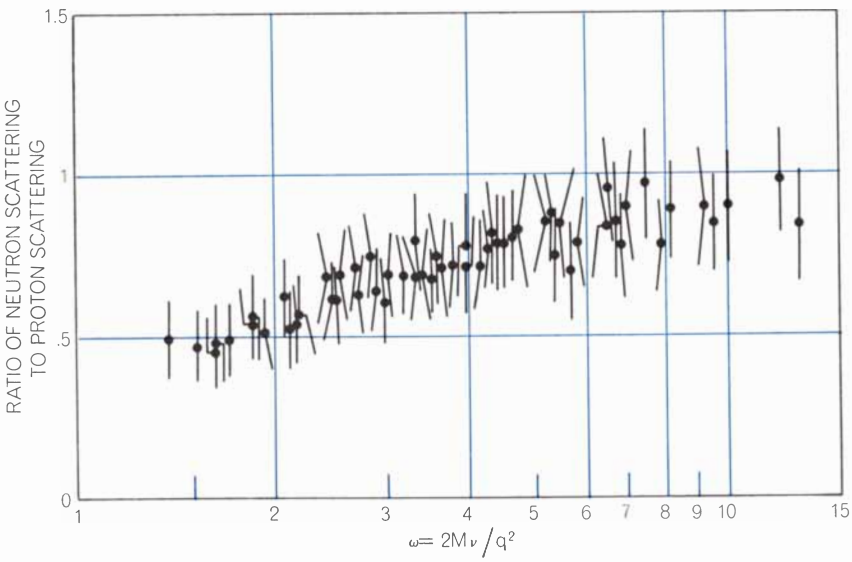
Richard P. Feynman of Cal Tech has been developing a theoretical model of the nucleon that may explain the inelastic-scattering results. He has given the name "parton" to the unknown constituents of the proton and the neutron that inelastically scatter high-energy electrons. Feynman assumes that partons are point particles. He and others have examined the possibility that partons may be one or another of the great array of previously identified subnuclear particles. The mesons that contribute to the "clouds" of nucleonic charge are obvious candidates, but there is strong experimental evidence that partons, if they exist at all, do not exhibit the known properties of mesons.

It has also been suggested that partons may be identical with the hypothetical entities known as quarks, the curious particles proposed independently in 1964 by Murray Gell-Mann and George Zweig of Cal Tech. Quarks are unlike all known particles in having a fractional electric charge: either $+2/3$ or $-1/3$ ($-2/3$ or $+1/3$ for antiquarks). Gell-Mann and Zweig suggested that mesons could be assembled from a quark and an antiquark. Nucleons and other particles with similar properties (that is, the baryons) would have to be assembled from three quarks. No real particles with fractional charge have yet been observed, in spite of long and continuing searches. Nevertheless, a fairly detailed picture of the nucleon's properties, as exhibited in inelastic scattering, can be constructed mathematically by arbitrarily assuming that the hypothetical partons have the properties formerly assigned to the equally hypothetical quarks.

Conceptual models such as the parton model represent the theorist's effort to describe the nucleon's internal structure in accordance with the most advanced information provided by high-energy experiments. The theorist tries to solve the mathematical problems that arise when the model is used to "predict" the properties observed in experiments that have already been completed; he also suggests further measurements to test the validity of the model. Models fail either because the mathematical difficulties cannot be overcome or because their



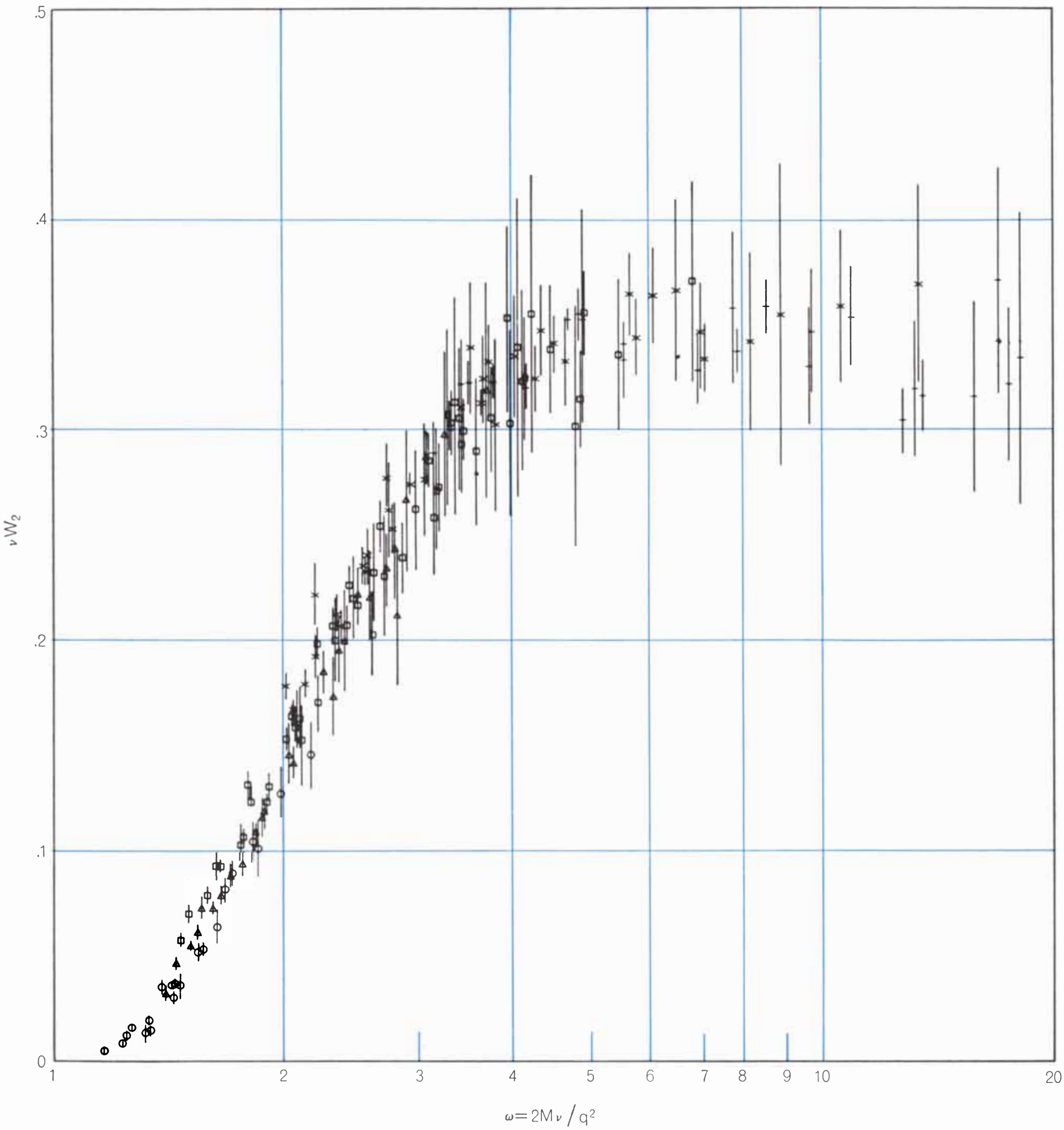
EVIDENCE that the internal structures of the proton and the neutron from which inelastic scattering takes place are much smaller than the nucleons either in their ground state or in their excited state is summarized in this graph, which covers a portion of the spectrum recorded by the M.I.T.-SLAC group in which the predicted scattering cross section (*bottom curve*) is lower by a factor of 40 than the observed cross section (*top curve*). The data were obtained at a scattering angle of six degrees; the energy of the incident electrons was 16 GeV.



ANOTHER UNEXPECTED RESULT of the scattering experiments is that inelastic scattering from the proton is distinctly different from inelastic scattering from the neutron. In this graph the ratio of the inelastic-scattering cross sections of the two types of nucleon is plotted as a function of a new variable, ω, which is defined as the ratio of the square of the momentum transfer (q) to the difference in energy of the electron before and after scattering.

predictions do not agree with experiment. The verification of a model, such as occurred with Rutherford's nuclear atom, can greatly extend the range and scope of the physicist's understanding. It is through the interplay of observation, prediction and comparison that the laws of nature are slowly clarified.

Another unexpected result is that inelastic scattering from the proton is distinctly different from inelastic scattering from the neutron [*see bottom illustration on preceding page*]. It turns out, however, that the electron-scattering results can be greatly simplified if one introduces a variable representing the ratio of the square of the momentum transfer to the difference in energy of the electron before and after scattering. If the various observations are plotted as a function of this simple ratio, the data recorded over a large range of scattering angles and initial and final energies coalesce into a single curve for the proton and a single curve for the neutron [*see illustration below*]. This unexpected coalescence has a simple explanation if one assumes that



"UNIVERSAL CURVE" results when the inelastic-scattering data taken over a large range of scattering angles and initial and final energies are plotted as a function of the new variable ω introduced in the bottom illustration on the preceding page. This coalescence into a single curve (one for the proton and one for the neutron) is consistent with the idea that the scattering of the high-energy electrons actually takes place from pointlike objects within the individual nucleons. The physical nature of these objects, which have been called "partons," remains uncertain. The coalescence illustrated by the curve has been given the name "scaling." This kind of relation, involving the square of the momentum transfer, occurs naturally in the kinematics of scattering from pointlike particles.

What did we learn from building the moon camera?

We learned what a good camera we already had on earth.

Because the moon Hasselblad is basically our electrically-driven Hasselblad 500 EL.

We also learned that NASA's photographic needs were much the same as the needs of serious photographers anywhere.

NASA needed to bring back high-resolution photographs. (Don't *you?*) The Hasselblad 500 EL offered the superb optics of Carl Zeiss lenses, plus the large 2¼" square format.

NASA needed great shooting capacity. (Haven't *you* been in spots where you wish you'd had more film in your camera? Or could switch from black and white to color in mid-roll?) The 500 EL, with its interchangeable backs, offered a large capacity magazine. Which meant that no film would have to be loaded by the astronauts during the entire moon walk. A fresh, pre-loaded back could be snapped on as needed. In a matter of seconds.

NASA needed simplicity of operation. (Aren't there times when you, too, want to concentrate on your subject, not your equipment?) The 500 EL offered electrically-driven automatic film advance and cocking of shutter.

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There are, of course, some differences between the moon and earth Hasselblads.

For one thing, the moon Hasselblad has wings on the diaphragm and shutter speed rings so they can be operated with bulky gloves on.

It has an oversized shutter release button for the same reason.

And a longer handle on the magazine slide for the same reason again.

And a safety lock to prevent the film back from floating off into space during weightlessness.

The earth Hasselblad doesn't have any of these things because it doesn't need them.

On the other hand the earth Hasselblad has things the moon Hasselblad doesn't have. Or need. Like interchangeable film transport mechanisms, three focusing screens and viewers.

In its own way, the earth Hasselblad, with its reflex viewing system, is just as sophisticated as the moon Hasselblad. So rather than stand in awe of the astronauts' Hasselblad, it would be equally appropriate for the astronauts to stand in awe of *your* Hasselblad.

If you don't require an electrically-driven film advance, there are other Hasselblad bodies. All part of the Hasselblad system which includes three basic cameras, ten interchangeable Carl Zeiss lenses ranging from 40 to 500mm, five interchangeable magazines from 12 to 70 exposures, interchangeable viewfinders plus a large number of specialized accessories.

We didn't have to push technology to fantastic new limits to come up with the moon camera. We had such a product all along.

Which only goes to show that when you constantly shoot for the moon, you stand a good chance of making it.

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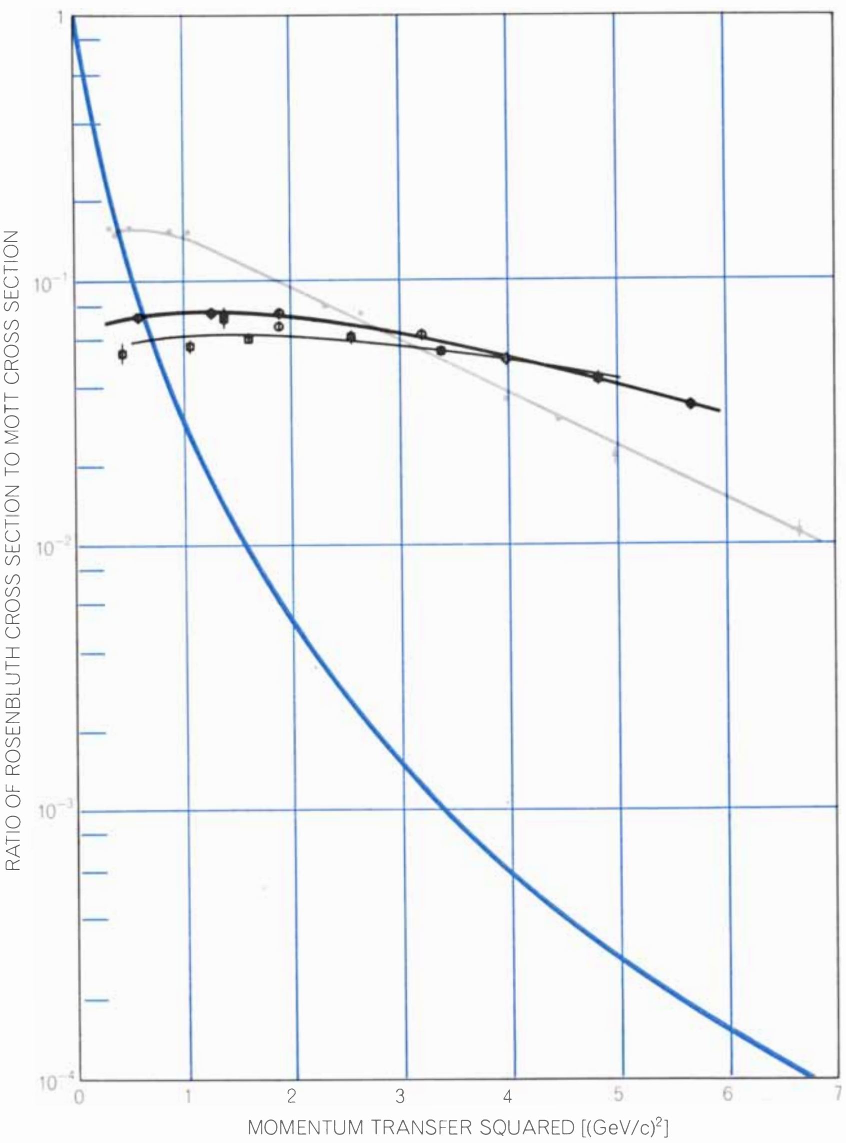
the scattering is produced by individual partons, since a "scaling" relation involving the square of the momentum transfer arises naturally in the kinematics of scattering from point particles. In addition the difference between neutron scattering and proton scattering can be accounted for qualitatively by the different configurations of the three quarks needed to produce protons and neutrons.

Because the partons, whatever they may be, are so intertwined with one another their individual properties are difficult to determine. Paradoxically the problem becomes simpler if one conceives of a cloud of partons moving in a frame of reference at nearly the velocity of light, so that the entire nucleon is relativistically contracted into a flat disk. Here the virtual photon that carries the electromagnetic force exerted by the scattered electron interacts with only one of the partons; the parton (owing to the relativistic dilation of time) exists as a free object long enough for it to retain its individual character. Therefore the theoretical analysis of events in the rapidly moving frame can be made with some degree of confidence and transformed back to the laboratory frame. In this way theory can be compared with experiment. Although the parton model is qualitatively quite successful in explaining the scattering results, its quanti-



FURTHER EVIDENCE that the observed inelastic-scattering cross sections may be produced by point targets is presented in this graph, in which the ratio of Rosenbluth scattering to Mott scattering is given for elastic electron scattering (*colored curve*) and for three different portions of the inelastic-scattering spectrum (*black curves*). Before these results were obtained it had been assumed that the inelastic-continuum cross sections would decrease as rapidly as the elastic cross sections when the momentum transfer was raised.

tative predictions are not uniformly reliable. There is evidently a need both for more experimental information and for more theoretical studies.

Even though the parton model is incomplete, it has already been used to interpret experimental results from other particle reactions, and it has supplied the motivation for several experiments now in the planning stage. At the Italian nuclear research center in Frascati an intense beam of high-energy electrons circulating in a storage ring has been made to cross a counterflowing beam of positrons. A certain fraction of the positrons and electrons interact and annihilate each other, frequently giving rise to two or more pions. The cross sections for annihilation and pion production turn out to be much larger than was expected. Electron-positron annihilation and the "deep" inelastic scattering of electrons observed at Stanford are directly related phenomena; in a fundamental way they can be regarded as inverse reactions of each other. Hence the large cross sections at Frascati support and confirm the large scattering cross sections at Stanford. A further related result is that neutrino beams from the huge accelerator at CERN (the European Organization for Nuclear Research) have initiated inelastic reactions whose cross sections too are unexpectedly large. Again the parton model provides the best available explanation for the observations.

Several related experiments are now being planned. One calls for a comparison of neutrino and antineutrino scattering (which one expects to have equal cross sections). Another involves a search for positron-electron annihilation at high energies to yield a proton and an antiproton in addition to pions (a reaction that may also exhibit a pointlike cross section). A third experiment is being designed to measure the highly inelastic scattering of real photons (which one expects to show large cross sections similar to those observed in electron scattering).

The unpredicted electron-scattering results obtained with the two-mile linear accelerator at Stanford have stimulated a fresh wave of theoretical speculation and experimental study. It is still too early to say whether the parton model will lead to an understanding of the nucleon's structure or whether entirely new ideas may be required. Whatever the case, it seems likely that a full explanation of the electron-scattering studies will clarify not only the nature of the nucleon's constituents but also the nature of the strong interaction and the families of particles that are governed by it.