An Historical Review of Lepton Proton Scattering^{*}

Richard Taylor

Stanford Linear Accelerator Center Stanford University, Stanford, CA 94309

In this talk I will try to review some of the early experiments in the field of electron-proton scattering, concentrating mostly on the inelastic scattering experiments at SLAC. Ordinarily, those experiments would be covered in the first five or ten minutes of the talks by Professors Scuilli and Drell, but this is a special year, and I will feel free to reminisce about the early days in a somewhat personal way.

I was about three years old when Prof. Neville Mott calculated the scattering of electrons described by the Dirac equation from a massive point charge. Unlike many Nobel prize winners, I had not decided on a career in physics at that early age, and I didn't encounter this calculation until much later in my life, after I became a graduate student at Stanford.

The Mott cross section^[1] for the scattering of a relativistic electron can be written as

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \cos^2 \theta/2}{E^2 \sin^4 \theta/2} \quad . \tag{1}$$

This formula is very similar to the Rutherford cross section, with an additional factor of $\cos^2 \theta/2$ that expresses the electron's reluctance to change the direction of its spin when scattered. The Mott cross section is *not* a description of the scattering from a proton because the proton has a magnetic moment in addition to its charge. Furthermore, it was realized at an early date that the charge (and magnetic moment) of the proton might not be point-like, but could be distributed over a small region of space.^[2] The wave nature of the electron limits the "resolution" of electron scattering as a probe of nuclear structure, and in order to see dimensions ~ 10^{-13} cms (the range of the nuclear force) the electron momentum must be $\gtrsim 200$ Mev/c. As electron accelerators with such energies became practical, interest in the scattering process increased.

Rosenbluth^[3] calculated the cross section for elastic scattering from a finite sized proton with a magnetic moment in the late 1940s.

1

^{*} Work supported by Department of Energy contract DE-AC03-76SF00515.

An idealized experiment might look like this:



In such an experiment the electron loses energy to the proton in the collision, so the final electron energy is less than the initial energy:

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

The momentum transfer (squared) is

$$Q^2 = 4 E_0 E' \sin^2 \theta / 2 \quad . \tag{3}$$

The cross section can be written

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

where

$$\tau = Q^2/4 M^2$$
.

The form factors G_E and G_M describe the structure of the proton charge and magnetic moment. Both are functions of only the momentum transfer, Q^2 , and at $Q^2 = 0$,

$$G_E \mid_{Q^2=0} = 1$$
, $G_M \mid_{Q^2=0} = \mu_p$.

The cross section^[4] is the most general form for the scattering of (unpolarized) high energy electrons from protons in the one-photon approximation. The simplicity of this expression is matched by the simplicity of the experiments, as shown in the figure above. The experiments measure the fraction of the electrons in a beam that are deflected through an angle θ in their passage through the hydrogen target.

The first electron-proton scattering experiments of this kind were carried out at the High Energy Physics Laboratory on the Stanford campus in 1953. In that laboratory a travelling-wave linear accelerator powered by klystron amplifiers produced beams with an average current of about 1 microampere at energies of several hundred MeV. The early experiments were performed using a portion of the machine and a CH₂ target.^[4] A schematic view of the scattering apparatus is shown in Fig. 1. In the data from those experiments, the elastic scattering from



Figure 1. A schematic view of electron scattering experiment with a 180° magnetic spectrometer to measure the energy of the scattered electrons.



Figure 2. Number of scattered electrons (arbitrary units) versus magnetic current from a polyethelyne target.



가는 같아요.

Figure 3. Layout of electron scattering experiments in the HEPL Endstation.

the nuclei of hydrogen atoms occurs at a slightly different energy than that from the carbon nuclei, because of the difference in recoil energy in the two cases (see Fig. 2). The separation is not very clean using CH_2 , so a high-pressure gas target was built. Measurements with the gas target were already sufficiently precise to indicate a proton size of about 10^{-13} cms.

By 1955, the experimental areas at the end of the accelerator had been completed, and Hofstadter's group had installed a new large spectrometer in that area. A schematic of the beam transport and analysis system is shown in Fig. 3. The experimenters also commissioned a liquid hydrogen target with thin stainless steel walls, greatly improving the backgrounds under the elastic scattering peak (Fig. 4). The results of these measurements^[5] are shown in Fig. 5.

The form factors, $F(Q^2)$, come from a slightly different form of the Rosenbluth cross section than that given in Eq. 4 above. In this energy region, F_1 and F_2 are within a few percent of G_E and G_M/μ respectively. The data indicated that F_1 and F_2 were not very different, and the analysis assumed that $F_1 = F_2$. (It was found later at higher Q^2 that $F_1 \neq F_2$, but that $G_E = G_M/\mu$, which is why those form factors became the standard ones.) The form factor falls rather rapidly with Q^2 (a point proton would have $F_1 = F_2 = 1$).

The finding that the proton had a size was a major discovery, and verified the prevailing opinion that the proton was a complicated object with a cloud of (virtual) pions around it. This was a new approach to the problem of the strongly interacting particles. It occurred at roughly the same time as the explosion in the number of new hadrons, many from the Radiation Laboratory across the bay



Figure 4. Counting rate versus energy from a liquid hydrogen target.



Figure 5. Proton form factor, F^2 ($F_1 = F_2$), measured at HEPL in 1955.

~ 5 g ·

in Berkeley, and it was immediately accepted as an important path for research. This research led rapidly to the proposal to build SLAC, in order to raise the available electron energy (and therefore Q^2) by more than an order of magnitude. In the early 1950s, electron physics was using only a few percent of the total resources going into high energy physics, so the construction of SLAC (and also CEA and DESY) represented a real shift in the allocation of resources within the field. The fraction of resources devoted to electron physics has continued to increase since that time, more recently driven by the success of electron positron colliders. That the future of high energy physics now seems to be based mostly on proton machines is probably evidence that something is wrong with our planning.

In the late 1950s, the climate was very good for high energy physics, and SLAC was formally approved around 1961. It was the largest project that had been seriously discussed in high energy physics up to that time. The machine was to be two miles in length and driven by 250 klystrons in the initial stage (plans were to increase to 1000 klystrons later). The klystrons were mounted in a long building at ground level, while the waveguide was buried in a tunnel some 25 feet below the surface in order to provide shielding in case of beam loss (Fig. 6).

I joined SLAC just as groundbreaking began, and went to work firming up the experimental area design. Designs for beam transport systems that would provide beams with defined energy and energy spread already existed (Fig. 7), and two such systems were arranged to supply beams to two separate experimental areas (see Fig. 8). One of the areas was intended for experiments with electron, positron, and γ -ray beams. In the other, the electron beam struck a target to produce secondary beams of πs , μs , K s, etc. The area to be used for electron scattering and photo-production experiments was 125 feet wide by 200 feet long, and had thick concrete walls to absorb neutrons produced by the beams. This greatly simplified the local shielding problems inside the so called "end station."

Inside this larger end station, we wanted to construct apparatus to measure both electron scattering and the photo-production of hadrons. Using magnetic spectrometers to look at single scattered electrons still seemed to be the simplest way to study electron scattering, and there were also many photo-production processes that could be studied in the same kind of setup. From Eq. 2, it is evident that the secondary energy is a strong function of angle -- beyond 20° the scattered electron energy from a 20 GeV primary will always be less than 10 GeV. The cross section varies steeply with angle (at least like $1/\sin^4\theta/2$), so large solid-angle spectrometers are needed at backward angles. A large, solid-angle spectrometer capable of analyzing electrons at the full energy of 20 GeV would be very expensive, so it was cost effective to build multiple spectrometers -- one with full energy capability but relatively small solid-angle for use in the forward direction, and others with larger solid angles but lower maximum energies for measurements at bigger angles. The momentum resolution of the spectrometers had to be much better than m_{π}/E_0 , so that processes in which an extra pion was produced could be distinguished.





Figure 7. Schematic of transport elements for a schematic beam transport system at SLAC.



Figure 8. Layout of energy-analyzed beams for SLAC.

The design of the 8 GeV maximum-momentum spectrometer was straightforward (Fig. 9), consisting of two magnets bending in a vertical plane, with three quadrupoles to provide focussing. The magnets were all mounted on a platform that could be rotated to accept electrons leaving the target at different angles. Bending in the vertical simplified the design because it effectively separated the measurement of momentum from the determination of scattering angle. For focussing arranged as in Fig. 10, and for a given setting of the spectrometer in angle and (central) momentum, one coordinate of particle position at the focal plane(s) determined momentum while the other orthogonal coordinate determined the angle of scattering. The counter hodoscopes mounted in the focal plane(s)—the $p + \theta$ planes are slightly separated for obvious reasons—give $\Delta \theta$ and Δp directly. Behind the focal plane counters are more counters to determine the kind of particle passing through (to separate electrons from πs or μs).

The overall scale of the spectrometers is set by the maximum field in the bending magnets, the desired resolution (together with the minimum size of the hodoscope counters!), the solid angle, and the need for shielding from background particles. Our choices led to a spectrometer weighing several hundred tons. A 20 GeV spectrometer of similar design exceeded what we considered to be a reasonable height. This led to many discussions — bending down into a vast pit instead of up in the air (which I found clumsy and expensive) or bending in the horizontal plane (as had been done at DESY), but with twisted quadrupoles to preserve the orthogonality. That design was favored for a while, but eventually it was shown that it contained unacceptable aberrations that would compromise the momentum resolution. Finally, Richter and Brown realized that by arranging a momentum crossover in the middle of the spectrometer, one could reverse the direction of bend following the crossover and end up with a significant reduction in vertical size. Without sextupole corrections, this design would have given a momentum focal plane at only 3° to the horizontal (and the direction of the particles), so sextupoles were added to raise that angle to a convenient 45°. The new design was quickly adopted, and the group began the construction of the first two spectrometers. A third spectrometer was added to the facility by D. Ritson's group somewhat later. This had a maximum momentum of 1.6 GeV, and a solid angle five times larger than that of the 8 GeV spectrometer. The layout of the three spectrometers in the building is shown in Fig. 12.

The spectrometer facility was one of the first experimental facilities to have a powerful computer (for that time — it looks pretty weak nowadays) dedicated to online analysis and control of the experiment. The computer controlled the magnet settings in the spectrometer, collected data from the counters and monitors, and calculated cross sections as the data were collected. This allowed us to record much more data than would have been possible "by hand," and was also very useful in reducing errors in the set up.



.



Figure 9. Schematic of the 8 GeV spectrometer set up in End Station A.



Figure 10. Optics of the 8 GeV spectrometer.

•---

.



Figure 11. Counter system for the 8 GeV spectrometer.





By the spring of 1967, the spectrometers were ready (Fig. 13), and we began to measure elastic scattering cross sections with the 8 GeV spectrometer.

Electrons were easily distinguished from pions by the size of the signal from the shower counter (as shown in Fig. 14). In Fig. 15, one observes the pattern of simultaneous hits in the p and θ hodoscopes. The elastic peak is prominent, and demonstrates the dependence of scattered energy on the scattering angle very clearly. For each run, the computer calculated the "online" cross section, which was accurate enough to use for run planning.

The data tapes with records of each scattered electron were then reanalyzed in the laboratory's computer center. The signals were very clean. Figure 16 shows a typical elastic peak. Within a few months the elastic results were available — the Q^2 range was extended from around 5 GeV/c² to 25 Gev/c², but the data fell reasonably close to the dipole formula fitted by Hofstadter's group a decade earlier. This was a disappointment to the collaboration, who had hoped for more interesting behavior. A second experiment used the SLAC positron beam (almost as intense as the electron beams from synchrotrons) to check the "one-photon" approximation by comparing e^+ and e^- cross sections.

Our third experiment involved measurements of inelastic scattering. The first such experiment had been performed by Panofsky and collaborators at HEPL a decade earlier, but progress in this field had been much slower than in the case of elastic scattering. Excitation of the 1233 resonance was observed in 1958, but it was 1963 before the second resonance was observed in this way. Our original proposal to measure inelastic scattering was aimed principally at the detection and measurement of the Q^2 dependence of the resonant states.

The kinematics of inelastic scattering are almost as simple as those for elastic scattering:



The recoiling electron has less energy than that in elastic scattering:

$$E' = \frac{E - \left(\frac{W^2 - M^2}{M}\right)}{1 + \frac{2E}{M}\sin^2\theta/2} , \qquad (5)$$

where W is the mass of the recoiling hadronic system. The invariants Q^2 and ν have the same form as before:

 $Q^{2} = 4 EE' \sin^{2} \theta/2$ $\nu = E - E'$

(though E' will be different from the elastic case).

-7-



Figure 13. Photo of the spectrometers in End Station A.

-8-



Figure 14. Online computer-generated graph showing the spectra of pulse height in the shower counter for a run on the elastic peak.







Figure 16. Same data as in Fig. 15, plotted against missing mass. The peak is displaced from the missing mass of the proton at 938 GeV by a slight mismatch in energy calibrations between the switchyard and the spectrometer.

 W^2 is also an invariant:

$$W^2 = M^2 + 2M\tau - Q^2 . (6)$$

Excitation of a resonance is easily recognized by the occurrence of a peak at the appropriate value of W.

Drell and Walecka^[6] had calculated the general form of the cross section for inelastic scattering, and their version looks very much like the Rosenbluth cross section:

$$\frac{d^2\sigma}{d\Omega \, dE} = \frac{\alpha^2}{4 \, E_0 \, \sin^2\theta/2} \, \cos^2\theta/2 \, \{ W_2 \, (Q^2, \, \nu) \, + \, W_1 (Q^2, \, \nu) \, 2 \tan^2\theta/2 \} \, . \tag{7}$$

Note that W_1 and W_2 (no connection with W, the mass of the hadronic state) are functions of both Q^2 and ν (or Q^2 and W^2). In general, each value of W can have its own Q^2 dependence, and it was through the Q^2 dependence of the resonances that we hoped to learn more about those states.

Another equivalent description of the cross section was given by Hand^[7] in his first paper on inelastic scattering (where he attributes the formula to Berkelman):

$$\frac{d\sigma}{d\Omega \ dE} = \frac{\alpha}{4\pi^2} \frac{(W^2 - M^2) E'}{M \ Q^2 E_o \left(1 - \epsilon\right)} \left(\sigma_T + \epsilon \sigma_L\right), \tag{8}$$

10 Z

where

$$\epsilon = \frac{1}{\left[1 + 2 \tan^2 \theta / 2 \left(1 + \nu^2 / Q^2\right)\right]} \quad \text{(polarization parameter)} , \qquad (9)$$

and σ_T and σ_L are each functions of Q^2 , ν , that correspond to the absorption of transverse and longitudinal virtual photons. In the limit as $Q^2 \rightarrow 0$, σ_T approaches the photo cross section for photons of energy, ν . The early experiments on inelastic scattering were carried out with the 20 GeV spectrometer at an angle of 6° to the incident beam. A typical spectrum of scattered electrons is shown in Fig. 17.

For 6° scattering and 10 GeV incident energy, the elastic peak is still the most prominent feature of the data; three resonant states are clearly visible followed by a gradual fall off in the scattering cross section as the scattered electron energy is decreased (W is increased). It was well known that radiative tails from the elastic peak and the inelastic scattering would contribute to the cross sections at higher missing masses — a calculation of the elastic tail is shown in the figure. That calculation involves the elastic form factor for all values of Q^2 below the value of Q^2 for the elastic peak. In order to interpret the cross sections at higher values of the missing mass, it was necessary to make corrections for radiation in the *inelastic* processes, but the necessary form factors were not known. It turns out that to a very good approximation, knowledge of the cross sections for different initial and final electron energies at just one angle is sufficient to correct the inelastic data for that angle.

For this and other reasons, a set of inelastic spectra at a given angle were taken at each of several settings of the primary energy. Independent estimates of the radiative corrections were then made at SLAC and at MIT, and agreed well. The uncorrected 10 GeV spectrum is shown in Fig. 18a, and the corrected spectrum in Fig. 18b. In Fig. 18c, the ratio of corrected to uncorrected is shown — note that the corrections are quite substantial in some places — justifying our initial concern that the large uncorrected cross sections at high W might have been due to radiative processes.

Figure 19 shows a set of radiatively-corrected inelastic cross sections measured at 10°, which shows clearly the general features of the measurements.

At 4.88 GeV (measured at DESY) the resonant peaks are very prominent, but as E_0 increases (i.e., at higher Q^2), the peaks fade out and the so-called "deep" inelastic continuum dominates. These large cross sections were unexpected by most of us. When the cross sections at a given value of W (divided by the Mott cross section) were plotted against Q^2 (Fig. 20), the behavior was very different from the Q^2 behavior of the elastic cross section. In fact, the inelastic cross sections hardly vary with Q^2 , while the corresponding elastic ratio falls by nearly two orders of magnitude. This result implies scattering from charge centers much smaller than the proton size.





Figure 18. Radiative corrections at 10 GeV and 6°.



Figure 19. Radiatively-corrected cross sections for various incident energies and a scattering angle of 10°.

, ---



Figure 20. Behavior of the inelastic cross section at W = 2 GeV and W = 3 GeV as Q^2 changes.

Even before the data were taken, Bjorken^[8] had explored the inelastic scattering process with the tools of "current algebra," which previously had been applied mostly to weak current interactions. He wanted to make predictions about W_1 and W_2 before the data was obtained. In his lectures at a summer school in Varenna in 1967, he suggested that in the limit of ν and Q^2 approaching infinity, the form factors would depend on the ratio of ν/Q^2 , rather than ν and Q^2 independently — a phenomena that was dubbed "scaling" of the cross section. This means that the form factors in the equation

$$\frac{d^2\sigma}{d\Omega \, dE'} = \sigma_{\text{Mott}} \{ W_2 + 2 W_1 \, \tan^2 \theta/2 \}$$
(10)

can be expressed as

1.34

$$F_1(\nu/Q^2) = 2M W_1(Q^2, \nu)$$

$$F_2(\nu/Q^2) = \nu W_2(Q^2, \nu) ,$$
(11)

as ν and $Q^2 \to \infty$. (Bjorken used the variable $\omega = 2M\nu/Q^2$, but the inverse, $1/\omega = x = Q^2/2M\nu$, is more commonly used today.)

Bjorken also found an inequality for inelastic electron scattering when W_2 is summed over all values of ν :

$$\int_{\frac{Q^2}{2M}}^{\infty} d\nu [W_2^p(\nu, Q^2) + W_2^n(\nu, Q^2)] > \frac{1}{2}, \qquad (12)$$

where W^p and W^n are the form factors for the proton and neutron respectively. (This was one of a number of "sum rules," several of which were proposed^[9,10,11] for inelastic lepton scattering, and some of which have been tested.) The formula^[12] implies point-like cross sections in the high Q^2 limit. We would soon find these point-like cross sections at rather low values of Q^2 . Bjorken was then anxious to know if the "scaling" postulate was obeyed, as well.

Scaling is a very strong constraint on the cross sections, connecting what appear to be very different kinematic regions together. Henry Kendall first made a plot of W_2 versus ν (assuming $2M W_1 \tan^2 \theta/2 \ll W_2$ at the forward angles where the early data was taken). The values of W_2 tend to $\frac{1}{4}$ nest" above $\nu = 4$, $(W_2 \cong \text{constant}/\nu)$ and so W_2 could be a function of ν/Q^2 above the region ν where the resonances occur (see Fig. 21).

With the early small angle data, we were unable to separate W_1 and W_2 . W_1 and W_2 are not independent of each other. This can be seen by writing the W_3 in terms of the photon absorption form factors.

$$W_1 = \frac{K}{M^2} \frac{\sigma_T}{\sigma_0} \qquad W_2 = \frac{K}{M^2} \frac{Q^2}{Q^2 + \nu^2} \quad \left(\frac{\sigma_T + \sigma_L}{\sigma_0}\right) \tag{13}$$



where

$$\sigma_0 = \frac{4\pi^2 \alpha}{M} = 127 \,\mu \mathrm{b} \,, \qquad K = \frac{W^2 - M^2}{2M} \,. \tag{14}$$

With $R = \sigma_L / \sigma_T$, νW_2 can be written as

$$\nu W_2 = F(\omega) = \frac{\left(\frac{d^2\sigma}{d\Omega dE'}\right)_{\text{meas}}}{\left(\frac{d\sigma}{d\Omega}\right)_{\text{MOTT}}} \left\{ 1 + 2 \left(\frac{1}{1+R}\right) \left(1 + \frac{\nu^2}{Q^2}\right) \tan^2\theta/2 \right\}^{-1}$$
(15)

where R can take on any positive real value.

 $F(\omega)$ versus ω was plotted for the extreme R values of 0 and ∞ as shown in Fig. 22. It can be seen that the data "scaled" quite well, even for the maximum value of R. Figure 23 shows νW_2 at $\omega = 4$ plotted against Q^2 from a later stage of the experiment.

This was impressive confirmation of Bjorken's predictions. Bjorken was aware that scattering from a proton composed of point-like objects would exhibit scaling behavior (as well as give point-like cross sections), but it was Feynman's "parton" model^[12] which popularized the view that we were seeing quasi-elastic scattering from constituents of the proton. In his model, electrons were assumed to scatter from bound constituents (partons). The recoiling partons interact internally, producing known particles — π s, Ks, etc. If the scattering is assumed to be quasi-free from point-like particles, then F_1 and F_2 will scale in $x = Q^2/2M\nu$. The process is shown schematically in Fig. 24.

Applying conservation of momentum to the elementary scattering process where the struck parton carries the fraction x of the proton momentum:



If the proton is moving fast enough in the center-of-mass frame, transverse momenta can be neglected, and

$$2x\mathbf{p}\cdot\mathbf{q} + Q^2 = 0(M^2)$$



Figure 22. Values of $F_2 = \nu W_2$ plotted against ν/q^2 for the early 6° data from SLAC. Each point is plotted twice, once for R = 0 (min) and once for $R = \infty$ (max).



Figure 23. Values of $\nu W_2|_{\omega=4}$ plotted against Q^2 from the SLAC data in 1970.



Figure 24. Parton model in which the electron strikes one of the partons in the nucleon, and subsequently that parton interacts with other partons.

If the energy is large enough so that the masses are neglible, then

$$x = \frac{-Q^2}{2(\mathbf{p} \cdot \mathbf{q})}$$

 $x=\frac{Q^2}{2m\nu}\;.$

or

The scaling variable x, is seen to correspond to the fractional momentum of the struck parton. The form factors $F_{1,2}(x)$ are then seen to be directly related to the momentum distribution of the point-like partons in the proton.

This simple physical picture became the model that was used to understand our data. The most obvious candidates for the partons were the quarks that had been suggested three years earlier by Gell-Mann and Zweig as constituents of the hadrons. At that time there were just three quarks—each with spin-1/2, and with fractional charges—the "up" quark with charge 2/3 that of the positron, and the "down" and "strange" quarks, each with 1/3 of the positron charge.

The proton was built of quarks, two "up", and one "down". The observed scattering corresponded well with what was called the "naive quark model" where the electron scattered independently from each of the quarks. Nevertheless, there was considerable reluctance to accept the scattering data as evidence for the existence of quarks. There had been many unsuccessful searches for free quarks



Figure 25. Separation of σ_T and σ_L .

in different kinds of experiments, fractional charges were an unpopular concept, and it was difficult to reconcile the proposed "quasi-free" scattering with the strong binding needed to keep the quarks inside the proton.

Our experiments were continuing, using the 8 GeV spectrometer to measure the scattering at larger angles. Our principal goal now was the separation of the two structure functions. To find σ_L and σ_T (or W_1 and W_2), we needed measurements of $d^2\sigma/d\Omega dE'$ at different values of the scattering angle, θ , but at the same values of Q^2 and ν .

From Eq. 9 we can write

$$\sigma_T + \epsilon \sigma_L = \frac{1}{\Gamma} \frac{d^2 \sigma}{d\Omega \, dE'}$$

where

$$\hat{\Gamma} = \frac{\alpha}{4\pi^2} \frac{(W^2 - M^2)E'}{MQ^2(1-\epsilon)E_0} \; .$$

With measurements at several angles, we can plot $1/\Gamma \left[\frac{d^2\sigma}{d\Omega} \frac{d\Omega}{dE'} \right]$ against ϵ .

Separation can only be made over the portions of the Q^2 , W^2 plane that are kinetically accessible. In the actual running, measurements of spectra were made at various energies and angles, and interpolation and extrapolation were used to make plots like Fig. 25. The first attempts at separation were made at DESY, combining large angle data taken at that accelerator (with $E_0 \leq 6$ GeV) and small angle data from SLAC (Fig. 26). A direct comparison of cross sections at the two labs showed excellent agreement and reduced the probability of normalization difficulties in using mixed data. SLAC's large angle data was available soon thereafter, and both analyses (Fig. 27 and Fig. 28) showed that σ_L was smaller than σ_T . These results were presented at the Daresbury ElectronPhoton Conference in 1969.

The small values of $R = \sigma_L/\sigma_T$ were an important boost for the quark hypothesis, since spin-1/2 objects would lead to $\sigma_L \ll \sigma_T$, whereas competing models based on vector dominance could only fit the point-like cross sections by assuming $\sigma_L \gg \sigma_T$. The data also agreed within errors with the "Callan-Gross" relationship

$$F_2 = x F_1 \tag{16}$$

for spin-1/2 particles.

In 1970, a new set of experiments was underway as the group began to make measurements on deuterium in order to study scattering from the neutron. The deuteron scattering is assumed to be approximately equal to the sum of scattering from a free neutron and a free proton with some small corrections,

$$\sigma_D = \sigma_p + \sigma_n \quad (+\text{corrections}) \tag{17}$$

and

$$\frac{\sigma_n}{\sigma_p} = \frac{\sigma_D}{\sigma_p} - 1 \quad (-\text{corrections}) \ (18)$$

The corrections are quite small, except near x = 1, where the motion of the neutron and proton in the deuteron can cause significant changes in the scattering cross sections at a given value of x. In the quark model, the charge differences in the quark make-up of the proton and the neutron should lead to less scattering from the latter. If the scattering were dominated by diffraction processes, as in the vector dominance model, the neutron and proton would act similarly and the neutron scattering should be the same as proton scattering. The ratio of σ_n/σ_p was not cleanly predicted by other models. Parton models usually contained a "sea" of parton-antiparton pairs that would be the same in both protons and neutrons at low values of x.



Figure 26. Comparison of SLAC measurements with DESY, showing the excellent agreement between the two experiments.



Figure 27. Separation of σ_L and σ_T carried out at DESY using mixed SLAC-DESY data.

١.

à





In the quark model, the sum of the squares of the quark charges in the proton and in the neutron were different:

$$\Sigma Q_p^2 = \left(\frac{1}{3}\right)^2 + \left(\frac{2}{3}\right)^2 + \left(\frac{2}{3}\right)^2 = 1$$
$$\Sigma Q_n^2 = \left(\frac{1}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{2}{3}\right)^2 = \frac{2}{3},$$

but the momentum spectrum of the various quarks inside the nucleons was not known. One clear prediction from the "quasi-elastic" quark model was a lower limit for σ_n/σ_p (the ratio of σ_n/σ_p should never fall below 1/4), the ratio for scattering from a down quark to that from an up quark,

 $\left(1/3/2/3\right)^2 = \frac{1}{4}$.

The measured spectrum for the set of measurements taken through 1974 is shown in Fig. 29. Earlier versions of the graph jumped around a bit as we

SEPARATION OF OS AND OT USING PRELIMINARY 18° & 26° DATA

14 1 1 1 1



Figure 28. Separation of σ_L and σ_T , using preliminary 18° and 26° data with SLAC 6° and 10° data.

studied the corrections. This spectrum shows the effects of the "sea" of particle and antiparticles near x = 0, but also a very clear difference in the scattering from the neutron.

By late 1971, the experiments had demonstrated:

- Large cross sections for the inelastic scattering with approximately pointlike behavior.
- Scale invariant behavior over a fair range in Q^2 .
- Dominance of transversely polarized virtual photon absorption at high Q^2 , with $R = \sigma_L/\sigma_T < 1$.
- Significant differences between the form factors of the neutron and the proton.

All of these experimental results were compatible with the quark model (if about one-half the momentum of the proton was carried by the quarks). Many theorists had accepted the quark interpretation of our results, but by no means all. There was no explanation of the paradoxical behavior of the quarks—light and quasifree in the scattering experiments, massive and heavily bound in the nucleon.

With the more accurate inelastic data, there were growing indications of small but definite departures from scaling. Scaling was still very good at x around .25, but there were problems at high and low values of x. Some of the nonscaling could be eliminated by restricting the minimum value of Q^2 and/or W^2 in the data, but this obviously weakened the evidence for scaling somewhat. Our data seemed to scale more accurately if the "scaling variable" was taken as W^2/Q^2 (which differs from $2M\nu/Q^2$ only by terms in M^2/Q^2 , and so is the "same" as $2M\nu/Q^2$ in the limit as Q^2 and $\nu \to \infty$). There were many other suggestions for new scaling variables, and this direction was followed for a while, until the rediscovery of gauge theories and the subsequent elucidation of "asymptotic freedom" in some forms of the theory. The theories with asymptotic freedom actually suggested that scale breaking should occur, and there was no further need to solve the problem of "broken scaling."

Theoretical progress was rather rapid after that, and in 1972 one particular gauge theory called "Quantum Chromodynamics" (QCD) was introduced, based on quarks and colored gluons in which there were firm predictions of logarithmic scale breaking. $F_2(x)$ was expected to "evolve" with increasing Q^2 , somewhat as indicated in Fig. 30, where scaling holds near x = 1/3, but is broken at other values of x with terms that vary as log Q^2 . Scale breaking was first detected unambiguously in the muon experiments at Fermilab in 1973. With the higher energy available there, those experiments could cover a larger range of Q^2 than the SLAC



Figure 30. Evolution of $F_2(x) = \nu W_2$ with increasing Q^2 , as suggested in QCD.

electron experiments. At low values of x, the muon scale breaking could not be transformed away by simple changes in the scaling variable. (Sometime later, as the accuracy and range of the electron data increased, similar conclusions could be drawn for both proton and neutron form factors derived from electron scattering.) This was a great triumph for QCD, and helped to make the quark model much more fashionable. When neutrino experiments — first from Garganmelle, and then from Fermilab and the SPS — also exhibited deep inelastic scattering from quarks with the expected weak couplings, few people were left unconvinced.

The "scaling" of our electron cross sections (Fig. 31) was powerful confirmation of the scaling hypothesis and the Callen-Gross relationship (scale breaking is small enough to be pretty much masked by the error bars) in this comprehensive plot. This experimental confirmation of the simple "quark-parton" picture contributed to impressive changes in the theoretical framework for elementary particles — hard collisions, partons, quarks, asymptotic freedom, QCD — all these new terms had some of their roots in the deep inelastic experiments.

Deep inelastic experiments with μ s and ν s continue to play a major role in particle physics, and in 1992 HERA will bring us *e-p* collisions, with values of Q^2 two to three orders of magnitude greater than the original SLAC experiments!



Figure 31. Form factors of the proton plotted as a function of x to demonstrate the effectiveness of the scaling hypothesis of Bjorken.

References

- ` . **`** . ` .

- 1. N. F. Mott, Proc. Royal Society (London), A124, 426 (1929); A135, 429 (1932).
- 2. L. I. Schiff, Summary of Possible Experiments with a High Energy Linear Accelerator, Stanford University, Microwave Laboratory SUML-102 (1949), unpublished.
- 3. M. N. Rosenbluth, Phys. Rev. 79, 1915 (1950).
- 4. C. Hofstadter, H. R. Fechter, and J. A. McIntyre, Phys. Rev. 91, 422 (1953).
- 5. C. Hofstadter and R. H. McAllister, Phys. Rev. 99, 1503 (1955).
- 6. S. D. Drell and J. D. Walecka, Amn. Phys. (N.Y.) 28, 18 (1964).
- 7. L. Hand, Phys. Rev. 129, 1584 (1963).
- 8. J. D. Bjorken, in Selected Topics in Particle Physics Proc. Int. School of Physics "Enrico Fermilab," Course XLI, J. Steinberg, ed., (Academics, New York, 1968).
- 9. J. D. Bjorken, Phys. Rev. 163, 1767 (1967).
- 10. J. D. Bjorken and E. A. Paschos, Phys. Rev. 163, 1975 (1968).
- 11. C. G. Callan and D. J. Gross, Phys. Rev. Lett. 21, 311 (1968).
- 12. R. P. Feynman, Phys. Rev. Lett. 23, 1415 (1969).

. .