

THE ELASTIC FORM FACTORS OF NUCLEONS

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ABSTRACT

The current state of research on elastic electromagnetic form factors of the proton and neutron at large momentum transfers is presented. Some preliminary conclusions are reached on n/p for $Q^2 > 2 \text{ (GeV/c)}^2$ from a recent SLAC experiment on electron-deuteron quasielastic scattering. Recent theoretical activity in QCD in the study of elastic form factors of hadrons which has been vigorous is documented. Finally, possible future experimental work at larger Q^2 for the pion, proton, and neutron is discussed.

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1. INTRODUCTION

The nucleon is more than just a pole in the complex energy plane with quantum number $J = \frac{1}{2}^+$, $S = 0$, and $B = 1$ ¹⁾. While it has been clear for some time that the nucleon has a rich internal structure and is therefore not elementary, nevertheless the proton and neutron do have a special status -- their existence. This stability has been used with weakly interacting probes to "establish" the quark-parton substructure in deep inelastic scattering investigations, which has in turn led to a standard model of the strong interaction -- quantum chromodynamics (QCD). Furthermore, this remarkable longevity ($> 10^{30}$ years for the proton and 15.3 minutes for the slightly more energetic neutron) is a question that is of great moment in present searches for evidence of proton decay and of the massive W^+ and Z^0 gauge bosons. After this little preamble, let us turn to the subject of this paper.

The elastic form factors of nucleons provide crucial information about the internal structure of matter. One has great confidence in extracting this information, particularly with electromagnetic interactions, as experiments at PETRA have shown the lepton (e, μ) probe to be structureless up to $s = -Q^2 = 1000 \text{ GeV}^2$. We can look forward to enlarging this statement to include the electroweak form factors of hadrons if the $SU(2) \times U(1)$ model passes its tests in the coming years. The requirement that the nucleon remains bound after absorbing a massive virtual photon, $Q^2 \gg M^2$, places severe constraints on our detailed understanding of structure in a dynamic environment of large Q^2 . For the proton these limits have reached $Q^2 = 33 (\text{GeV}/c)^2$ and $-4.5 (\text{GeV}/c)^2$ for the space-like and time-like regions, respectively.

The external electromagnetic interaction is depicted in Fig. 1, where the charge-current density J_μ is described in terms of two scalar form factors, F_1 and F_2 or G_E and G_M for the spin- $\frac{1}{2}$ nucleon. The asymptotic nucleon states N and N' satisfy the Dirac equation for a free particle, and J_μ is constructed according to relativistic covariance and gauge invariance. For the time-like interaction $N\bar{N} \rightleftharpoons e\bar{e}$, the N' arrow would be reversed and the virtual photon γ_v would originate in the annihilation channel. The nucleon form factors are real functions of Q^2 for $Q^2 > 0$, and complex functions for $Q^2 < 0$ beyond $\pi\pi$ threshold.

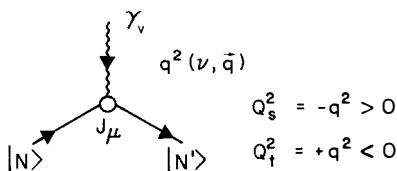


Fig. 1 Diagram for virtual photon-nucleon elastic scattering

With the coming of age of QCD as the standard model of the strong interactions, research into the elastic form factors of hadrons, and of nucleons in particular, should once again be an important frontier area. This standard model must be subject to a variety of experimental constraints.

It was suggested that I present an overview of this field at Moriond. Accordingly, the organization will be a review of previous results in Section 2, presentation of our quasielastic electron-deuteron measurement with elastic n/p results in Section 3, and a brief outline of future plans and possibilities for work in the $Q^2 > 0$ and $Q^2 < 0$ momentum transfer regions in Section 4. Attention is drawn to important possible future work in determining the charged pion form factor at large Q^2 . The resurgence of theoretical activity in the last two years will be documented but only a few specific predictions will be mentioned in Sections 3 and 4.

2. PREVIOUS RESULTS

Elastic electron scattering from the proton and neutron was one of the dominant areas of high-energy research during almost two decades, starting in the early 1950's¹⁾ The principal results were the mapping of the nucleon charge and current distributions for $Q^2 \lesssim 1 \text{ (GeV/c)}^2$, the prediction of vector mesons, and the testing of baryon symmetry models, particularly SU(6). Beyond $Q^2 \approx M^2$ progress was slow, and the semi-empirical scaling laws for the proton and neutron were known to be, at best, approximate and inconsistent²⁾. They are

$$G_M^p = \mu_p / (1 + Q^2/0.71)^2 \quad (1a)$$

$$G_E^p = G_M^p / \mu_p \quad (1b)$$

$$G_M^n = G_M^p \mu_n / \mu_p \quad (1c)$$

$$G_E^n = 0, \quad (1d)$$

with normalizations at the static limit $Q^2 = 0$ of the magnetic moment $G_M(0) = \mu$ and charge $G_E(0) = Z$. In the time-like region, study of the reaction $\bar{p}p \rightarrow e^+e^-$ for $4M^2 < |Q^2| < 4.5 \text{ GeV}^2$ has yielded a form factor well above the dipole fit. However, past limitations of low intensity and competing backgrounds have not made this data of comparable quality to space-like e, e' measurements; no separation of G_E from G_M has been attempted³⁾. The experimental situation is summarized in Figs. 2 and 3. In Fig. 2a, G_M^p is extracted from the data for $Q^2 > 3.5 \text{ (GeV/c)}^2$ assuming the validity of Eq. (1b); at $Q^2 \sim 20 \text{ (GeV/c)}^2$ the data are $\sim 20\%$ smaller than the dipole fit, i.e. Eq. (1a)⁴⁾. In Fig. 2b, G_E^p "scales" for $Q^2 < 1$, whereas beyond 1.5 (GeV/c)^2 Eq. (1b) may be violated by 50% ⁵⁾. For the neutron data,

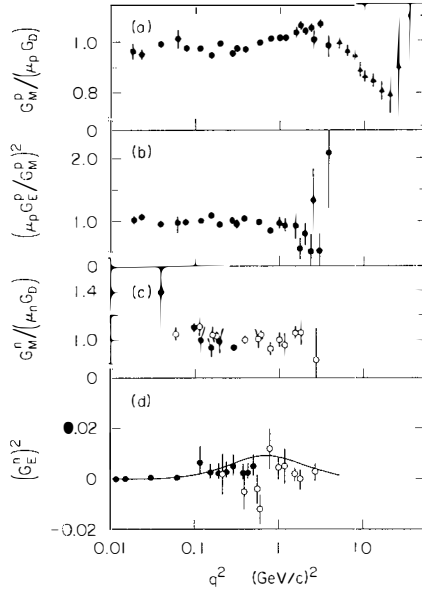


Fig. 2 Existing data for the elastic nucleon form factors. G_D is the dipole form $1/(1 + Q^2/0.71)^2$. a) $G_M^p/(\mu_p G_D)$; b) $(\mu_p G_E^p/G_M^p)^2$; c) $G_M^n/(\mu_n G_D)$; d) $(G_E^n)^2$.

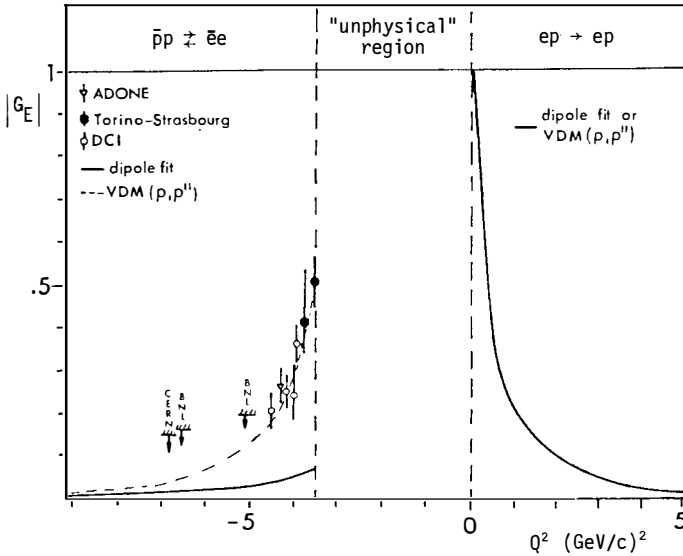


Fig. 3 Proton's form factor G_E for $-10 < Q^2 < 5$ (GeV/c)², from Ref. 3

G_M^n follows Eq. (1c) to $Q^2 \sim 2.7 \text{ (GeV/c)}^2$, whereas $(G_E^n)^2$ is consistent with 0 or slightly positive over the range $0 < Q^2 < 2.7 \text{ (GeV/c)}^2$ ^{5,6)}. At very low Q^2 , 0 to $\sim 0.4 \text{ (GeV/c)}^2$, $G_E^n \neq 0$ and is positive⁷⁾.

3. QUASIELASTIC e-d SCATTERING

3.1 Motivation

An experiment to measure $e + d \rightarrow e' + X$ in the quasielastic region in the interval $2.5 \leq Q^2 \leq 10 \text{ (GeV/c)}^2$ was performed at SLAC by the American University Group in 1979. Preliminary results have been presented⁸⁾. Our motivation was to provide new information on e-n elastic scattering to extend the Q^2 range for the neutron in Fig. 2. Various theoretical and phenomenological predictions indicated that the ratio of elastic neutron to proton cross-sections (hereafter labelled σ_n/σ_p or n/p) might increase with Q^2 , remain constant, or even diminish as $(Q^2)^{-1}$.

It is useful to cast the predictions in terms of two sets of form factors, G_E and G_M of Eq. (1) or the Dirac- F_1 and Pauli- F_2 form factors with the connections

$$G_E = F_1 - \tau F_2, \quad (2a)$$

$$G_M = F_1 + F_2. \quad (2b)$$

where for the neutron, $F_1(0) = 0$ and $F_2(0) = u_n$, for the proton $F_1(0) = 1$ and $F_2(0) = u_p - 1$, and the dimensionless parameter $\tau = Q^2/M^2$. These original form factors are pertinent when discussing the neutron since, for a particle which is everywhere neutral⁹⁾,

$$F_1(Q^2) = 0, \quad (3)$$

and in addition, predictions have been made for F_{1n}/F_{1p} for $Q^2 \gg M^2$. The curve in Fig. 2d satisfies Eq. (3), $G_E^n = -\tau G_M^n$, i.e. $F_{1n} = 0$.

For the conditions of the SLAC experiment, $\theta_e = 10^\circ$, so that the cross-section ratio, to excellent approximation, is

$$\left. \frac{\sigma_n}{\sigma_p} \right|_d = \frac{\left(\frac{G_E^n}{G_E^p} \right)^2 + \tau \left(\frac{G_M^n}{G_M^p} \right)^2}{\left(\frac{G_E^p}{G_E^p} \right)^2 + \tau \left(\frac{G_M^p}{G_M^p} \right)^2} = \frac{F_{1n}^2 + \tau F_{2n}^2}{F_{1p}^2 + \tau F_{2p}^2}. \quad (4)$$

Predictions for this ratio as $Q^2 \rightarrow \infty$ are:

a) Combining Eqs. (1b), (1c), and (1d),

$$\frac{\sigma_n}{\sigma_p} \rightarrow \frac{\mu_n^2}{\mu_p^2} = 0.47; \quad (5)$$

b) Combining Eqs. (1b), (1c), and (3) ($F_{1n} = 0$),

$$\frac{\sigma_n}{\sigma_p} \rightarrow \frac{\mu_n^2}{\mu_p^2} (1 + \tau); \quad (6)$$

c) assuming the asymptotic limits of the dimensional-scaling quark model (DSQM)¹⁰, $Q^4 F_1 \rightarrow C_1$ and $Q^6 F_2 \rightarrow C_2$, where C_1 and C_2 are normalization constants, yields

$$\frac{\sigma_n}{\sigma_p} \rightarrow \left(\frac{C_{1n}}{C_{1p}} \right)^2; \quad (7)$$

d) assuming (c) with models for the quark wave functions with dominance of the same spin or flavour, which fit the inelastic structure functions $\nu W_{2n}/\nu W_{2p}$ as $x \rightarrow 1$, gives $F_{1n}/F_{1p} = -1/3$ ¹¹) and

$$\frac{\sigma_n}{\sigma_p} \rightarrow \frac{1}{9}, \quad (8)$$

or $F_{1n}/F_{1p} = -\frac{1}{2}$ ¹²) and

$$\frac{\sigma_n}{\sigma_p} \rightarrow \frac{1}{4}; \quad (9)$$

e) combining (c) with $F_{1n} = 0$

$$\frac{\sigma_n}{\sigma_p} \rightarrow \frac{(C_{2n}/C_{2p})^2}{\tau}; \quad (10)$$

f) assuming a VDM model¹³), which fits in both the space-like and the time-like region and also satisfies crossing, yields $F_{1n}/F_{1p} = -0.37$, which is between Eqs. (8) and (9).

Recently, perturbative QCD calculations of the elastic form factors of mesons and baryons have been made. (More details will be given in Section 4.) These results appear to confirm the DSQM bounds of item (c) above, and are quite sensitive to the shape of the quark distribution amplitude¹⁴). In terms of two helicity form factors parallel and antiparallel to the nucleons helicity,

$$\frac{G_M^n}{G_M^p} = -\frac{1}{3} \left[1 - \frac{G_{||}^{\pi}}{G_{||}} \right]. \quad (11)$$

If the endpoint region $x \rightarrow 1$ dominates, where one valence quark carries essentially all of the momentum¹¹) rather than the dominant hard-scattering contribution of perturbative QCD, then the prediction is $-1/3$ for Eq. (11), which is the same result for σ_n/σ_p as in Eq. (8).

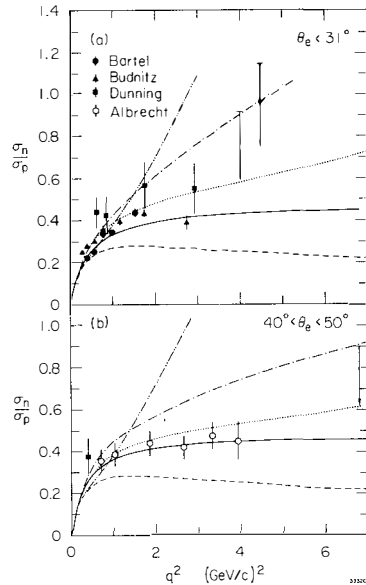


Fig. 4 Existing data and some models for the ratio of elastic neutron and proton cross-sections $\sigma_n^{\text{el}}/\sigma_p^{\text{el}}$. a) $\theta < 31^\circ$, i.e. $\tan^2 \theta/2 \ll 1$; b) $40^\circ \leq \theta \leq 50^\circ$. The curves are: $\frac{\sigma_n}{\sigma_p}$ Eq. (5), —·—·— Eq. (6), ——— VDM model of Blatnik and Zovko (Ref. 13), —····— Veneziano-type model of Felst (Ref. 13).

Taken together, these predictions in Eqs. (5)-(11), most of which are in reasonable agreement with the data in Fig. 2, yield very different behaviour for σ_n/σ_p at larger Q^2 . Some of these predictions are shown in Fig. 4 together with previous small-angle data [Eq. (4)] and for larger-angle data.

3.2 Experiment and preliminary results

A brief report of the experiment together with preliminary results has been given elsewhere⁸⁾. The radiatively corrected quasielastic e-d spectra are presented in Fig. 5. An example of the deuteron to proton ratio is given in Fig. 6, where our measured e-p elastic and inelastic spectra have been smeared with Fermi motion to simulate scattering from a nucleon bound in the deuteron. The ratio of σ_d/σ_p^d is independent of W^2 in the peak region. Further detailed analysis is in progress. As reported, the n/p cross-section is approximately *constant* in the range $2.5 < Q^2 < 8$ $(\text{GeV}/c)^2$, averaging

$$\frac{\sigma_n}{\sigma_p} = 0.3 \pm 0.05. \quad (12)$$

PRELIMINARY

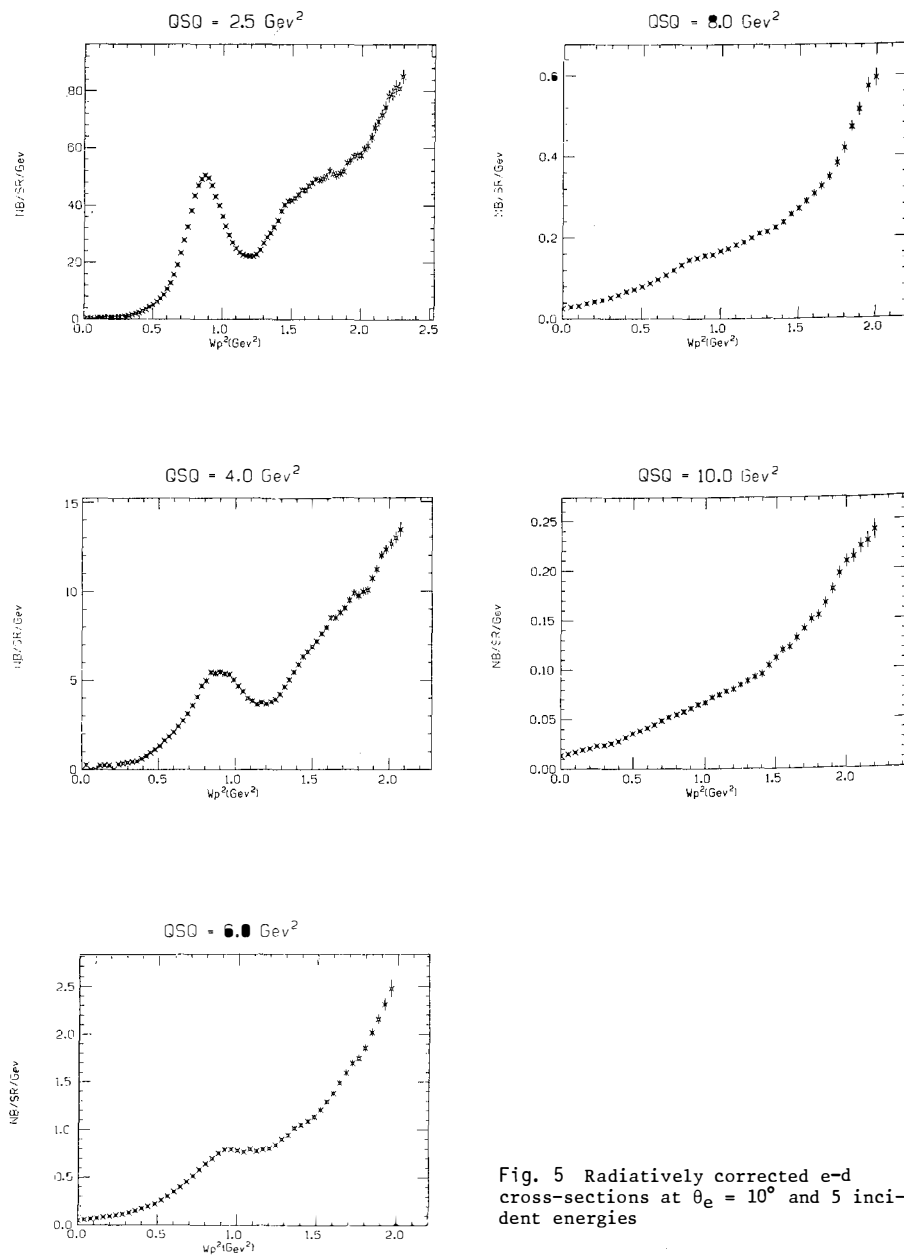


Fig. 5 Radiatively corrected e-d cross-sections at $\theta_e = 10^\circ$ and 5 incident energies

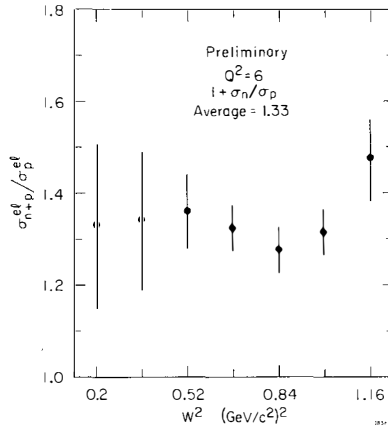


Fig. 6 The ratio of e-d to smeared e-p cross-section at $Q^2 = 6 \text{ (GeV/c)}^2$ near $W^2 = M^2$

Inspection of the e-d spectra in Fig. 5 shows the difficulty in extracting an elastic e-n signal for $Q^2 > 6 \text{ (GeV/c)}^2$. (See Section 4.4 for further remarks.)

These spectra are a beautiful illustration of duality, first noted in e-p inclusive measurements¹⁵⁾, where in the present case the elastic peak and smeared (3,3) resonance rapidly and smoothly disappear with increasing Q^2 . Demonstration that this region can be represented by a smooth average of $\sqrt{s}W_{2d}$ continued from the deep inelastic scattering region ($W > 2 \text{ GeV}$) should be informative¹⁶⁾.

The results of this measurement in Eq. (12) would appear to rule out predictions contained in Eqs. (5), (6), and (8), and most of the predictions shown in Fig. 4. They point to a finite contribution of F_{1n} at least for $Q^2 > M^2$ ¹⁷⁾. [Recall Eq. (3) and earlier work.] The results show the first evidence of dimensional scaling for the elastic neutron form factor $F_n \equiv (\sigma_n/\sigma_{\text{Mott}})^{1/2}$, i.e.

$$Q^4 F_n \rightarrow \text{const}, \quad (13)$$

with a shape similar to the proton's in the preasymptotic region, $1 < Q^2 < 4 \text{ (GeV/c)}^2$ as displayed in Fig. 7¹²⁾. In our Q^2 range, the prediction in Eq. (9), $\sigma_n/\sigma_p \rightarrow 1/4$, is clearly preferred to that in Eq. (8). It is conceivable that the leading-order QCD Born term, where each valence quark carries momentum $(p+q)/3$, is subject to strong suppression by the quark distribution amplitudes. Nevertheless, it is certainly premature to argue that σ_n/σ_p has reached an asymptotic value. The VDM prediction of Blatnik and Zovko in Fig. 4 approximately describes the data.

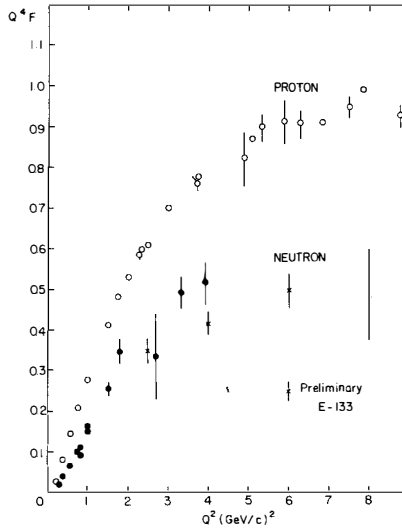


Fig. 7 The approach to the dimensional scaling limit for p and n from data of Refs. 12 and 8

4. FUTURE WORK

4.1 Pions

It may be possible to increase the present Q^2 boundary¹⁸⁾ of 4 (GeV/c)^2 for the π^+ elastic form factor by means of, for example, the EMC Forward Spectrometer at CERN using muon-induced scattering from H_2 and D_2 targets. Improvements in small-angle discrimination and in missing-mass resolution would be necessary. In view of the theoretical activity in calculating this form factor within QCD¹⁹⁾, a measurement of F_π to $Q^2 \gtrsim 10 \text{ (GeV/c)}^2$ could be highly significant.

4.2 Protons (space-like)

There is a proposal²⁰⁾ by our group at SLAC to measure the proton form factor with good statistical precision in the range $10\text{--}40 \text{ (GeV/c)}^2$. Possible experimental results are displayed in Fig. 8. The highest Q^2 region is now accessible to precise determination with the new high-intensity 30 GeV SLED beam. Coincidence measurements of the e-p final state by the SLAC 8 and 10 GeV/c spectrometers should yield unambiguous results even at the $10^{-39} \text{ cm}^2/\text{sr}$ cross-section level. Perturbative QCD calculations of G_M of the nucleon have been made¹⁴⁾ and offer the possibility of obtaining important information about the strong coupling constant $\alpha_s(Q^2)$ and the scaling behaviour of the quark-quark interactions. In contrast to inelastic lepton-nucleon scattering, the magnetic form factor is a

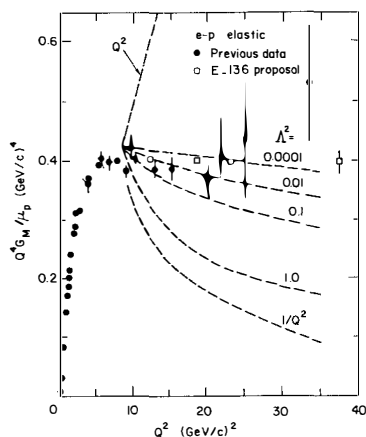


Fig. 8 Comparison from Ref. 14 (Le P and B) extended to $40 (\text{GeV}/c)^2$. The $\square$ are possible precision of a proposed experiment assuming a Q^2 -independent value of 0.4. Λ_{QCD} curves for 10 MeV to 1 GeV are shown.

leading-order QCD amplitude proportional to α_s^2 , and, in further contrast, higher-order twist terms are expected to be small. (The latter point may be controversial.) These proposed measurements go to larger Q^2 than do other exclusive reactions, in particular pp elastic scattering, and provide a large span in Q^2 from a single experiment.

As always in physics, surprise cannot be ruled out. A speculation on the appearance of structure in the form factor is displayed in Fig. 9 ²¹).

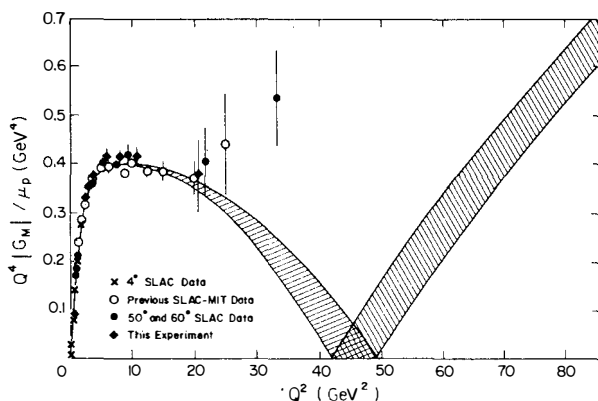


Fig. 9 Fit through existing e-p data of a speculation which allows for new structure inside the nucleon

4.3 Protons (time-like)

There is an approved experiment at LEAR to use the intensive low-energy $\bar{p}$ beam to study the reaction $\bar{p}p \rightarrow e^+e^-$ (22). In the range $0 < p_{\bar{p}} < 2$ GeV/c, this 2×10^6 $\bar{p}$ /s beam will permit measurement and possible separation of G_E and G_M for $-6 < Q^2 < -4M^2$. The experimental challenge is to separate electron pairs, with branching ratios of 3×10^{-7} to 4×10^{-9} , from the huge background produced by the hadrons coming from the dominant annihilation final states. The present situation is shown in Fig. 3 where VDM fits both regions, whereas Eqs. (1a) and (1b) fail completely for $Q^2 \leq -4M^2$. Hence the accurate determination of the proton form factors in the time-like region, which is dominated by poles of the vector mesons ρ , ω , ϕ , ρ' , ..., J/ψ , should yield significant constraints on hadronic structure.

4.4 Neutrons

The discussion, in Section 3, of the recent quasielastic electron-deuteron experimental results (Fig. 5), makes clear the requirement for deducing the neutron form factor at larger Q^2 -- the recoiling neutron must be measured in coincidence with the scattered electron. To convert a 10 GeV/c neutron in a hadron calorimeter and to time its arrival within a resolution of 500 ps in the environment of an intense electron beam is beyond the state of the art. However, present progress in detector development⁽²³⁾ may make such an e-n elastic scattering experiment possible in the range $8 < Q^2 \leq 18$ (GeV/c)².

Finally, it may be possible to separate the electric from the magnetic nucleon form factors G_E and G_M at moderate Q^2 , ~ 1 to 5 (GeV/c)², using polarization transfer techniques⁽²⁴⁾. The development of intensely polarized electron sources makes this possible⁽²⁵⁾.

5. CONCLUSIONS

Recent theoretical activity, particularly in QCD as the standard model of the strong interactions, has once again emphasized the importance and special role of elastic form factors in elucidating the hadron structure. However, the challenges to both experiment and theory are formidable but this is not a unique situation. The prospects look reasonable -- notwithstanding the prodigious activity in colliding-beam physics -- for maintaining the dialogue between experiment and theory in the fixed-target exploration of elastic form factors at ever-increasing Q^2 .

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