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Structure of the Nucleon from Electromagnetic Form Factors

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Abstract. Recent experimental data on the ratio of electric to magnetic elastic form factors are reviewed in light of a model of the nucleon with an intrinsic (quark-like) structure and a meson cloud. The analysis points to the astonishing result that the proton *electric* form factor *vanishes* at $Q^2 \sim 8$ (GeV/c)^2 and becomes negative beyond that point. The intrinsic structure is estimated to have a r.m.s. radius of ~ 0.34 fm, much smaller than the proton r.m.s. radius ~ 0.87 fm. The calculations are in perfect agreement with the proton data, but deviate drastically from neutron data at $Q^2 > 1$ (GeV/c)^2. Relativistic invariance is a crucial ingredient responsible for the vanishing of G_{E_p}. Symmetry, rather than detailed dynamics, appears to be a determining factor in the structure of the nucleon. Scaling appears to occur at much larger values, $Q^2 \geq 30$ (GeV/c)^2, than previously thought.

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1 Introduction

Electromagnetic form factors have played a crucial role in understanding the structure of composite particles. A particularly important composite particle is the nucleon, which forms the basis upon which all matter is built. Studies of the structure of the nucleon with electromagnetic probes begun in the late 50's and early 60's when Hofstadter and collaborators demonstrated that the nucleon was not point-like with a (proton) root-mean square radius $\langle r_p^2 \rangle^{1/2} \sim 0.75$ fm. In the 1970's many experiments were performed, showing that the neutron was a complex particle with a negative r.m.s. radius and $dG_{E_n}/d(Q^2) \sim 0.50$ (GeV/c)^2. In 1973, it was suggested that the nucleon has a two component structure with an intrinsic part with form factor $g(Q^2)$ and a meson cloud parametrized in terms of vector mesons, (ρ, ω, φ). In the late 1970's the non-relativistic quark-model was used to describe the properties of hadrons. It was soon realized that this model cannot describe form factors in a consistent way. Also in the late 1970's, QCD emerged as the theory of strong interactions. In a perturbative approach, p-QCD, the asymptotic behavior of the form factors can be derived, yielding the large Q^2 behavior of the nucleon form factors to be $\propto \frac{1}{Q^4}$. Also in the 1980's, experimental groups noted that all form factors, except G_{E_n}, could be described by the empirical dipole form $G_D(Q^2) \propto 1/\left(1+\frac{Q^2}{0.71}\right)^2$. These observations culminated in the SLAC experiment NE11 on the ratio $\mu_p G_{E_p}/G_{M_p}$ that appeared to be consistent with scaling up to 10 (GeV/c)^2 [1]. However, in 2000-2002 experiments performed at TJNAF [2], [3] using the recoil polarization method have shown the astounding result that the ratio of proton electric to proton magnetic form factor decreases dramatically with Q^2, inconsistent with scaling. In this article, the present situation on electromagnetic form factors of the nucleon will be reviewed.

2 Analysis of form factors

Two basic principles play a crucial role in the analysis of electromagnetic form factors of the nucleon. The first of these is relativistic invariance. This principle fixes the form of the nucleon current to be[4]

$$J^\mu = F_1(Q^2)\gamma^\mu + \frac{\kappa}{2M_N} F_2(Q^2) i\sigma^{\mu\nu} q_\nu \tag{1}$$

where $F_1(Q^2)$ and $F_2(Q^2)$ are the so-called Dirac and Pauli form factors and κ is the anomalous magnetic moment. This symmetry is expected to be exact. The second is isospin invariance. Although this symmetry is not exact, being of dynamical origin, it is expected to be only slightly broken in a realistic theory of strong interaction. Isospin invariance leads to the introduction of isoscalar, F_1^S and F_2^S, and isovector, F_1^V and F_2^V, form factors, and hence to relations among proton and neutron form factors. The observed Sachs form factors, G_E and G_M can be obtained by the relations

$$\begin{aligned} G_{M_p} &= \left(F_1^S + F_1^V\right) + \left(F_2^S + F_2^V\right) \\ G_{E_p} &= \left(F_1^S + F_1^V\right) - \tau\left(F_2^S + F_2^V\right) \\ G_{M_n} &= \left(F_1^S - F_1^V\right) + \left(F_2^S - F_2^V\right) \\ G_{E_n} &= \left(F_1^S - F_1^V\right) - \tau\left(F_2^S - F_2^V\right) \end{aligned} \tag{2}$$

with $\tau = Q^2/4M_N^2$. These relations also satisfy another constraint, namely the kinematical constraint $G_E(-4M_N^2) = G_M(-4M_N^2)$. This constraint is of crucial importance in the time-like region, while playing a minor role in the space-like region.

Different models of the nucleon correspond to different assumptions for the Dirac and Pauli form factors. In 1973 [5] a model of the nucleon in which the external photon couples to both an intrinsic structure, described by the form factor $g(Q^2)$, and a meson cloud, treated within the framework of vector meson (ρ, ω and φ) dominance, was suggested. In this model the Dirac and Pauli form factors are parametrized as

$$\begin{aligned} F_1^S(Q^2) = \frac{1}{2}g(Q^2)[&(1-\beta_\omega-\beta_\varphi) \\ &+\beta_\omega\frac{m_\omega^2}{m_\omega^2+Q^2}+\beta_\varphi\frac{m_\varphi^2}{m_\varphi^2+Q^2}] \end{aligned} \tag{3}$$

$$\begin{aligned} F_1^V(Q^2) &= \frac{1}{2}g(Q^2)[(1-\beta_\rho)+\beta_\rho\frac{m_\rho^2}{m_\rho^2+Q^2}] \\ F_2^S(Q^2) &= \frac{1}{2}g(Q^2)[(-0.120-\alpha_\varphi)\frac{m_\omega^2}{m_\omega^2+Q^2} \\ &\quad +\alpha_\varphi\frac{m_\varphi^2}{m_\varphi^2+Q^2}] \end{aligned} \tag{4}$$

$$F_2^V(Q^2) = \frac{1}{2}g(Q^2)[3.706\frac{m_\rho^2}{m_\rho^2+Q^2}] \tag{5}$$

In [5] three forms of the intrinsic form factor $g(Q^2)$ were used. The best fit was obtained for $g(Q^2) = (1+\gamma Q^2)^{-2}$. This form will be used in the remaining part of this talk. Before comparing with the data, an additional modification is needed. In view of the fact that the ρ meson has a non-negligible width, one needs to replace

$$\frac{m_\rho^2}{m_\rho^2+Q^2} \rightarrow \frac{m_\rho^2+8\Gamma_\rho m_\pi/\pi}{m_\rho^2+Q^2+(4m_\pi^2+Q^2)\,\Gamma_\rho\alpha(Q^2)/m_\pi} \tag{6}$$

where

$$\alpha\left(Q^2\right) = \frac{2}{\pi}\left[\frac{4m_\pi^2+Q^2}{Q^2}\right]^{1/2}\ln\left(\frac{\sqrt{4m_\pi^2+Q^2}+\sqrt{Q^2}}{2m_\pi}\right). \tag{7}$$

This replacement is important for small Q^2, although, because of the logarithm dependence of the $\pi\pi$ cut expressed by the function $\alpha(Q^2)$, its effect is felt even at moderate and large Q^2.

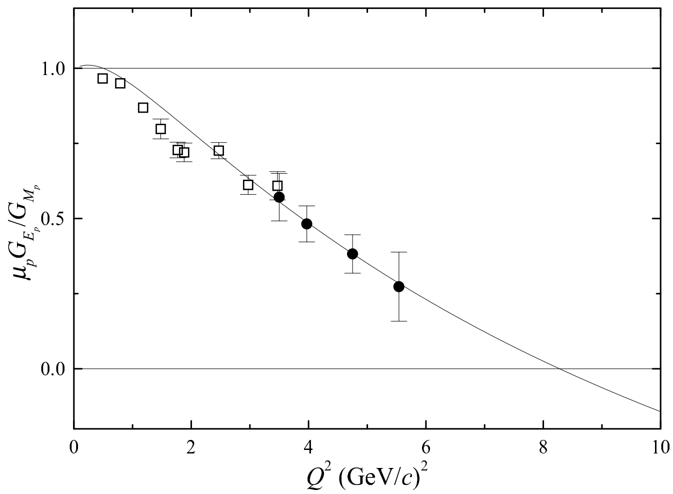


Fig. 1. The measured ratio $\mu_p G_{E_p}/G_{M_p}$ compared with the 1973 prediction. Ref. [2]: open square. Ref. [3]: filled circle.

2.1 The ratio of electric to magnetic form factors of the proton

By using the coupling constants given in Table 1 of [5] $\beta_\rho = 0.672, \beta_\omega = 1.102, \beta_\varphi = 0.112, \alpha_\varphi = -0.052$, an intrinsic form factor with $\gamma = 0.25$ (GeV/c)$^{-2}$, standard values of the masses ($m_\rho = 0.765$ GeV, $m_\omega = 0.784$ GeV, $m_\varphi = 1.019$ GeV), and a ρ width $\Gamma_\rho = 0.112$ GeV, one can calculate the ratio $\mu_p G_{E_p}/G_{M_p}$. The result is shown against the new data [2], [3] in Fig.1. The agreement is astonishing. Fig. 1 also shows the remarkable result that the *electric* form factor of the proton crosses zero at $Q^2 \sim 8$ (GeV/c)^2. It would be ot utmost importance to measure the ratio $\mu_p G_{E_p}/G_{M_p}$ at $Q^2 \geq 6$ (GeV/c)^2. A measurement of the zero of the electric form factor, adding to the already measured sharp drop from 1 at $Q^2 = 0$ to ~ 0.27 at $Q^2 = 5.6$ (GeV/c)^2, would unequivocably establish the complex nature of the nucleon. In the model put forward in 1973, the nucleon has both an intrinsic structure (presumably three valence quarks) and additional contributions (presumably $q\bar{q}$ pairs). (The complex nature of the nucleon resulting from electromagnetic form factors is in accord with results obtained by the EMC collaboration [6], where the additional, non q^3, components were attributed to gluons.) An estimate of the spatial extent of the intrinsic region (where the fundamental quarks sit) can be obtained from the value of γ in the intrinsic form factor. The r.m.s. of this distribution is ~ 0.34 fm, much smaller that the proton r.m.s. radius ~ 0.87 fm. The zero in the *electric* form factor is a consequence of the two term structure of Eq.(2), in particular of the fact that the second term is multiplied by $-Q^2/4M_N^2$. Any model with a two term structure will produce results in qualitative agreement with data. Indeed three of the descriptions considered in [3], a soliton model [7], and two relativistic constituent quark models [8], [9] have this structure and produce results in qualitative agreement with experiment. Also the introduction of relativity in non-relativistic quark models goes in the direction of reducing the ratio [10]. To

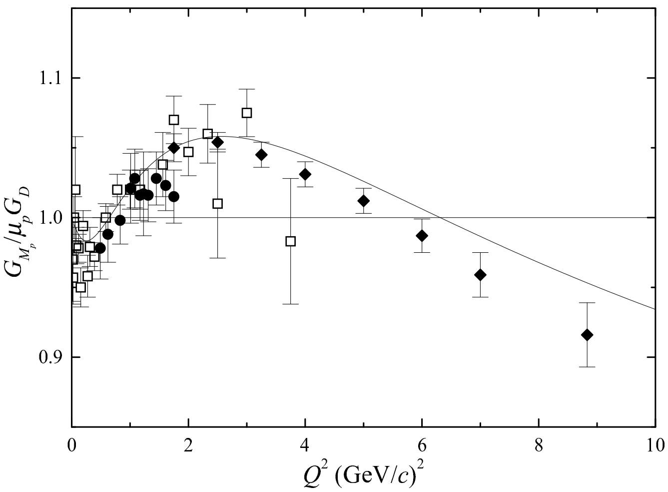


Fig. 2. Experimental values $G_{M_p}/\mu_p G_D$ compared with calculation. Ref.[11]: open square. Ref. [12]: filled circle. Ref. [1]: filled diamond.

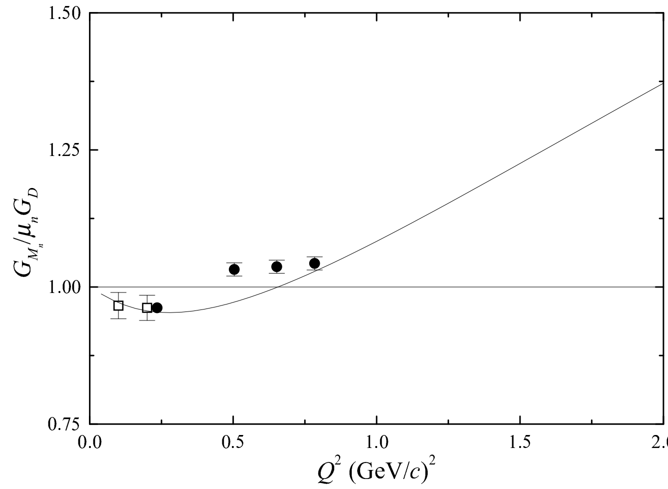


Fig. 3. Recent experimental values for $G_{M_n}/\mu_n G_D$ compared with calculation. Ref. [13]: open square. Ref.[14]: filled circle.

discriminate between various models it is necessary to find precisely at which value the zero occurs.

2.2 The magnetic form factor of the proton

The agreement between theory and data for the proton form factors is not limited to the ratio $\mu_p G_{E_p}/G_{M_p}$. Consider the magnetic form factor, G_{M_p}. For convenience of display, normalize it to the so-called dipole form factor, $G_D = (1 + \frac{Q^2}{0.71})^{-2}$. The data [11], [12], [1] in the interval $0 \leq Q^2 \leq 10$ (GeV/c)^2 are plotted in Fig.2. They show an ondulation, crossing the value one at $Q^2 \sim 0.6$ (GeV/c)^2 and again at ~ 6 (GeV/c)^2. The calculation is in excellent agreement with the data, with crossing points at precisely the same values ~ 0.6 and 6 (GeV/c)^2. The observed ondulation is proof that vector meson (with masses $\mu^2 \sim 0.5 - 1.0$ (GeV/c)^2) components are important. Without ρ meson component, the form factor should behave smoothly (see Fig. 3 of [5]).

2.3 The magnetic form factor of the neutron

Having established the structure of the proton, I now come to that of the neutron. This is dictated by isospin invariance. Measurements of the neutron form factors are obscured by the knowledge of the wave functions of deuterons or He^3. Older measurements are either in disagreement (for $Q^2 > 1$ (GeV/c)^2) or in marginal agreement ($Q^2 < 1$ (GeV/c)^2) with the 1973 model. However, the situation here appears to be similar to the situation for the proton form factors previous to the experiments of Jones et al [2] and Gayou et al [3]. I consider first the region $Q^2 \leq 1$ (GeV/c)^2. An analysis (2001) of recent experiments by J. Golak et al [13] and by H. Anklin et al [14] shows that the new data for G_{M_n}/G_D points to an ondulation with crossing point at ~ 0.6 (GeV/c)^2 as predicted by isospin invariance, and Eq.(2). This ondulation was absent in the old data. A comparison between the new data and the calculation is shown in Fig.3. For $Q^2 \geq 1$ (GeV/c)^2 the calculation is in disagreement with the old data. While the data remain close to 1, the calculation keeps increasing. New (unpublished) data at TJNAF appear to indicate that G_{M_n}/G_D does not increase as Q^2 increases. If these data are confirmed, one must conclude that either isospin invariance is broken above 1 (GeV/c)^2 or that there are additional components in the neutron that are not present in the proton.

2.4 The electric form factor of the neutron

A similar situation occurs for new (1999) data for the electric form factor G_{E_n} by Herberg et al [15], Passchier et al [16], Ostrick et al [17], Rohe et al [18], Zhu et al [19]. These are in fair agreement with the calculation as shown in Fig. 4. For $Q^2 \geq 1$ (GeV/c)^2 the calculation is in disagreement with new unpublished data. While the data remain close to 0.05, the calculation keeps decreasing and crosses zero at ~ 1.4 (GeV/c)^2. It would be of the utmost importance to measure G_{M_n} and G_{E_n} at $Q^2 \geq 1 GeV^2$ in a as much as possible model independent way. A measurement of the ratio $\mu_n G_{E_n}/G_{M_n}$ similar to that done for the proton, perhaps using the reaction $d(\overrightarrow{e}, e'\overrightarrow{n})p$ [20], will be of great value. Similar observations can be made for G_{E_n}. In present analyses this form factor is even more sensitive to models than G_{M_n}.

3 Scaling laws

Another important question is the extent to which the new data support scaling laws [21]. The parametrization of Eq.(3) is consistent with scaling laws expected from perturbative QCD, $F_1 \sim 1/Q^4$, $F_2 \sim 1/Q^6$ except for F_2^V whose asymptotic behavior ($Q^2 \to \infty$) is

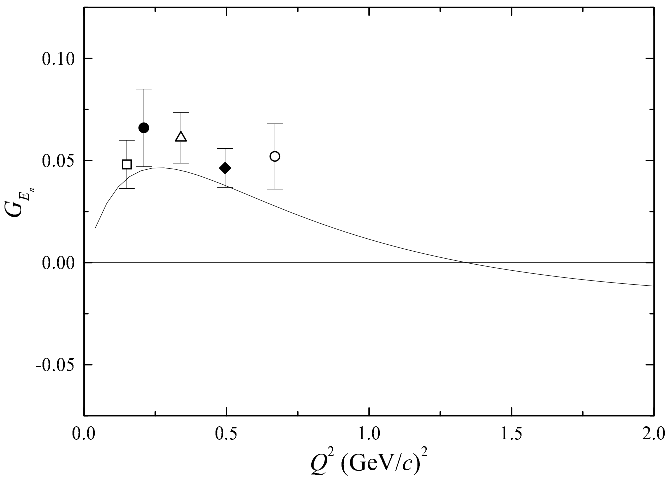


Fig. 4. Recent experimental values for G_{E_n} compared with calculation. Ref. [15]: open square. Ref.[16]: filled circle. Ref.[17]: filled diamond. Ref.[18]:open up triangle. Ref.[19]: open circle.

$$F_2^V(Q^2) \rightarrow \frac{3.706}{2\gamma^2 Q^6} \frac{m_\rho^2 + 8\Gamma_\rho m_\pi/\pi}{1 + \frac{\Gamma_\rho}{m_\pi}\frac{2}{\pi}\ln 2\sqrt{\frac{Q^2}{4m_\pi^2}}}, \qquad (8)$$

that is with a weak logarithm dependence due to the effective ρ mass induced by the ρ width. The scaling properties of F_1 and F_2 are determined by the only length scale in the problem, namely the size of the intrinsic quark structure, $1/\gamma$. In order to have a quantitative estimate of the value of Q^2 at which scaling is reached, I shall use the following definition: a function $f(z)$ is said to be x% scaled when its value is x% of the asymptotic value $f_{as}(z)$. The value at which this condition is met is the solution of the equation $\mid f(z) \mid = x \mid f_{as}(z) \mid$. For the form factors F_1^S, F_1^V, F_2^S and with minor modifications also for F_2^V, scaling properties are determined by the function $g(Q^2)$. Using the value $\gamma = 0.25$ (GeV/c)$^{-2}$, one obtains an estimate of scaling properties. The function $g(Q^2)$ is 80% scaled at $Q^2 \geq 34$ (GeV/c)^2. This value is much larger than conventionally believed, $Q^2 \sim 4$ (GeV/c)^2. (The dipole form $G_D(Q^2)$ is 80% scaled at $Q^2 \sim 6$ (GeV/c)^2.) The situation for the scaling properties of the form factors G_E and G_M is more complex. The parametrization of Eq.(3) is consistent, apart from a weak logarithm dependence, with the scaling laws of perturbative QCD, $G_E \sim G_M \sim 1/Q^4$. However, relativity introduces here another scale, $4M_N^2 = 3.52$ (GeV/c)^2, and, independently from the actual value of the size scale γ, relativistic invariance requires that scaling is not reached unless Q^2 is greater than a few times $4M_N^2$. (This is particularly so for the *electric* form factors). To check scaling properties it would be of utmost importance to measure the ratio $\mu_p G_{E_p}/G_{M_p}$ with the recoil polarization method beyond 10 (GeV/c)^2.

Another prediction from perturbative QCD is that the ratio G_{M_p}/G_{M_n} approaches zero from the negative side for large Q^2,

$$\frac{G_{M_p}}{G_{M_n}} \rightarrow 0^- \qquad (9)$$

as a power of $\ln(Q^2/\Lambda^2)$ [22]. The predictions of the model discussed here are $G_{Ep} \rightarrow -4.08/Q^4, G_{M_p} \rightarrow 0.9120/Q^4$, and $G_{E_n} \rightarrow -10.86/Q^4, G_{M_n} \rightarrow -4.33/Q^4$ from which one can obtain

$$\frac{G_{M_p}}{G_{M_n}} \rightarrow -0.21. \qquad (10)$$

The electric values have been obtained by estimating the logarithm dependence at $Q^2 = 100$ (GeV/c)^2. Checking this prediction requires the measurement of G_{M_n} at large Q^2. Both the p-QCD result and the 1973 result are in disagreement with the $SU(6)$ value $-3/2$ often used in experimental analyses.

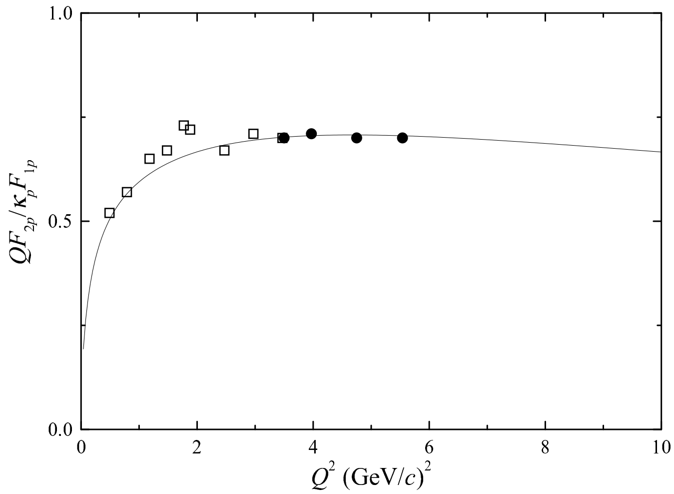
The extent to which dimensional scaling is valid has been in recent years the subject of many investigations [23]. It has been suggested that the appropriate scaling variable is $QF_{2p}(Q^2)/F_{1p}(Q^2)$ instead of $Q^2F_{2p}(Q^2)/F_{1p}(Q^2)$. Using Eq.(3) one can easily calculate $QF_{2p}(Q^2)/F_{1p}(Q^2)$. From this calculation one can see that the quantity $QF_{2p}(Q^2)/F_{1p}(Q^2)$ remains flat in the interval $2 \leq Q^2 \leq 10$ (GeV/c)^2 and drops from there on, especially after dimensional scaling is reached at $Q^2 \geq 34$ (GeV/c)^2, Fig.5. The scaling with Q is thus accidental and appropriate only to the intermediate region.

4 Low-Q^2 behavior

The low-Q^2 behavior can also be analyzed in explicit form by using $\lim_{Q^2\rightarrow 0} \alpha(Q^2) = \frac{2}{\pi}(1 + \frac{1}{3}\frac{Q^2}{4m_\pi^2})$. From the slopes of the form factors at $Q^2 \rightarrow 0$, one can calculate the mean square radii, defined as $\langle r^2 \rangle = -6\frac{dG}{d(Q^2)}$. The resulting r.m.s. radii are: $\langle r^2 \rangle_{E_p}^{1/2} = 0.817$ fm, $\langle r^2 \rangle_{M_p}^{1/2} = 0.826$ fm and $\langle r^2 \rangle_{M_n}^{1/2} = 0.839$ fm. The neutron electric form factor has a slope at $Q^2 \rightarrow 0$ of $\frac{dG_{E_n}}{d(Q^2)} = 0.500$ (GeV/c)^2. These values are in agreement with old experimental data. Accurate proton values are of crucial importance for the interpretation of other experiments, such as muon $g-2$. The calculated proton electric r.m.s. radius is in disagreement with recent Lamb shift measurements in hydrogen. The origin of this discrepancy must be investigated.

5 Stability against perturbations

In conclusion, the new data clearly point out that the structure of the proton is rather complex and that it contains at least two components. The data appear to be in agreement in the entire measured range with a calculation in which the two component are an intrinsic structure, presumably q^3, and a meson cloud, $q^3q\bar{q}$, the latter being expressed through vector mesons (ρ, ω, φ). The situation for the neutron is different. The new data are in agreement



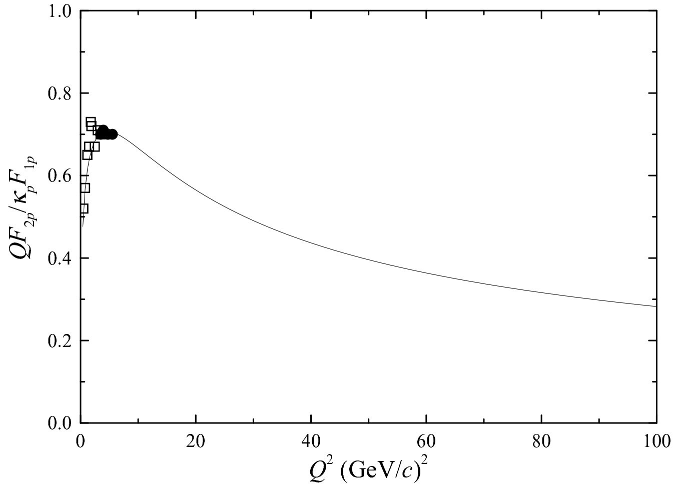


Fig. 5. The experimental ratio QF_{2_p}/F_{1_p} compared with calculation in the range $0 \leq Q^2 \leq 10$ (GeV/c)^2 (top) and $0 \leq Q^2 \leq 100$ (GeV/c)^2 (bottom). Ref.[2]: open square. Ref.[3]: filled circle.

with the 1973 calculation up to 1 (GeV/c)^2. From there on, they appear to be in disagreement with the new (unpublished) data [24]. One can inquire whether addition of other ingredients changes this conclusion. There are three contributions that can be analyzed easily.

(i) The role of additional vector mesons, $\rho(1450), \omega(1390), \varphi(1680)$ [25].

(ii) The addition of an intrinsic piece to the Pauli form factor F_2^V . This can be done by the replacement

$$3.706 \frac{m_\rho^2}{m_\rho^2 + Q^2} \rightarrow (3.706 - \alpha_\rho) \frac{1}{(1+\gamma Q^2)} + \alpha_\rho \frac{m_\rho^2}{m_\rho^2 + Q^2} \tag{11}$$

The additional piece must be of this type to insure the proper behavior of F_2^V for $Q^2 \rightarrow 0$ and $Q^2 \rightarrow \infty$.

(iii) The role of the widths of ω, φ as well as the effect of changing the width of the ρ meson from the value used in [5].

The *qualitative* features are not affected by these changes, although quantitatively one can make some improvements on the form factor of the neutron. However, because of isospin invariance, an improvement in the neutron form factors produces a deterioration in the description of the proton data. It does not appear that the problem of the neutron form factor at large Q^2 can be solved with these changes. To solve this problem one needs to introduce terms which act only on the neutron, that is terms with $F_S = -F_V$. Work in this direction is in progress.

One can also check whether the logarithm dependence of pertubative QCD

$$Q^2 \rightarrow Q^2 \frac{\ln\left[\left(\Lambda^2 + Q^2\right)/\Lambda^2_{QCD}\right]}{\ln\left[\Lambda^2/\Lambda^2_{QCD}\right]} \tag{12}$$

with $\Lambda = 2.27$ GeV/c and $\Lambda_{CQD} = 0.29$ GeV/c [26] produces major changes in the conclusions. This does not appear to be the case at least up to $Q^2 = 10$ (GeV/c)^2.

6 Consequences of the new experiment

Finally, the experimental results of Jones et al. [2] and Gayou et al. [3], confirming the model calculation of [5], has implications for all hadronic physics.

6.1 Time-like form factors

By an appropriate analytic continuation in the complex plane, the form factor of Eq.(3) can be used to analyze form factors in the time-like region. These can be and have been experimentally obtained in the reactions $p\bar{p} \rightarrow e^+e^-$ and $e^+e^- \rightarrow p\bar{p}$. A simple analytic continuation of the intrinsic form factor, $g(Q^2)$, into

$$g(Q^2) = \frac{1}{(1+\gamma e^{i\theta} Q^2)^2} \tag{13}$$

with $\theta = \pi/4$ appear to indicate that the form factors (3) are in agreement with the data [27].

6.2 Inelastic form factors

The two component structure of the nucleon will reflect itself also in the inelastic form factors. A calculation of the form factor factor $ep \rightarrow e\Delta(1232)$ is in progress.

6.3 Other hadronic form factors

A situation similar to that observed in the nucleon appears to occur also in other hadrons. A calculation of the pion form factor in the two component framework

$$F_\pi(Q^2) = g(Q^2)[(1-\beta_\rho) + \beta_\rho \frac{m_\rho^2}{m_\rho^2 + Q^2}] \tag{14}$$

with

$$g(Q) = \frac{1}{(1+\gamma Q^2)} \tag{15}$$

appears to be in excellent agreement with recent experiment [28].

7 Conclusions

The main conclusions that one can draw from the analysis of recent experimental data on electromagnetic form factors are:

(i) the proton appears to have a complex structure with at least two components, an intrinsic component (valence quarks) and a meson cloud ($q\bar{q}$ pairs). The size of the intrinsic structure is r.m.s. ~ 0.34 fm.

(ii) Perturbative QCD is not reached in the proton up to $Q^2 \sim 10$ (GeV/c)^2. Physics up to this scale is dominated by a mixture of hadronic and quark components.

(iii) Symmetry (in particular relativistic invariance), rather than detailed dynamics, appears to be the determining factor in the structure of the proton.

The situation appears to be different for the neutron. Here recent experimental data up to 1 (GeV/c)^2 are consistent with isospin invariance and the structure of the proton, while preliminary data at $Q^2 \geq 1$ (GeV/c)^2 appear to indicate that either isospin invariance is broken or that additional components play a role. It would be of the utmost importance to understand this discrepancy.

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