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STRUCTURE OF HADRONS FROM ELECTROMAGNETIC FORM FACTORS

F. Iachello
Center for Theoretical Physics, Sloane Physics Laboratory,
Yale University, New Haven, CT 06520-8120, USA

Abstract

It is suggested that *all* hadronic electromagnetic form factors be described in terms of a two-component model, in which the photon couples to both an intrinsic structure, q^3 for baryons and $q\bar{q}$ for mesons, and a cloud of $q\bar{q}$ pairs. The time-like form factors of this model can be tested at meson factories, especially DAΦNE-2.

1 Review of nucleon space-like form factors

1.1 Space-like proton

The study of the structure of the nucleon with electromagnetic probes has been the subject of many investigations since the pioneering work of Hofstadter *et al.* in the early 1960's. By 1995 a comprehensive experiment performed at SLAC [1] using the Rosenbluth method to separate electric from magnetic form factors appeared to indicate that the large Q^2 behavior of both the electric and magnetic form factor of the proton was $\propto 1/Q^4$ and in fact given by the empirical scaling law $G_D(Q^2) = 1/(1+\frac{Q^2}{0.71})^2$. This result was consistent with perturbative QCD and dimensional scaling [2]. However, in a series of experiments performed at TJNAF in 2000-2002 [3, 4] using the recoil polarization method which measures the ratio G_E/G_M directly, without Rosenbluth separation, an astounding result was found, namely that the proton electric form factor decreases dramatically with Q^2. This result is inconsistent with scaling and p-QCD but in agreement with an old calculation, performed in 1973, in terms of a two-component model [5]. This has reopen the question of what is the actually structure of the nucleon.

1.2 Space-like neutron

In other SLAC experiments in the 1990's [6] it appeared that the magnetic form factor of the neutron was also following the empirical scaling law, consistent with p-QCD, and that the electric form factor was consistent with zero. However, again in experiments performed at TJNAF in 2003 using the recoil polarization method [7], it was found that the electric form factor of the neutron is definitely different from zero and in fact increases dramatically with Q^2. This result is inconsistent with the 1973 parametrization.

1.3 Models of the nucleon

The TJNAF results have spurred a considerable amount of theoretical papers. Leaving aside the question of why the SLAC results are inconsistent with TJNAF, perhaps due to two-photon contributions, there remains the basic question of what is the structure of the nucleon.

Form factors can in principle be calculated on the lattice. Unfortunately these calculations are still far from being realized. For this reason one must resort to models. Different models of the nucleon correspond to different assumptions for the Dirac and Pauli form factors that appear in the nucleon electromagnetic current

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

Many lines of thought have been recently followed. Three of these are: (1) Two-component model [8], where the two components are the intrinsic valence quark structure, q^3 for baryons, and the meson $q\bar{q}$ cloud. (2) Relativistic constituent quark model

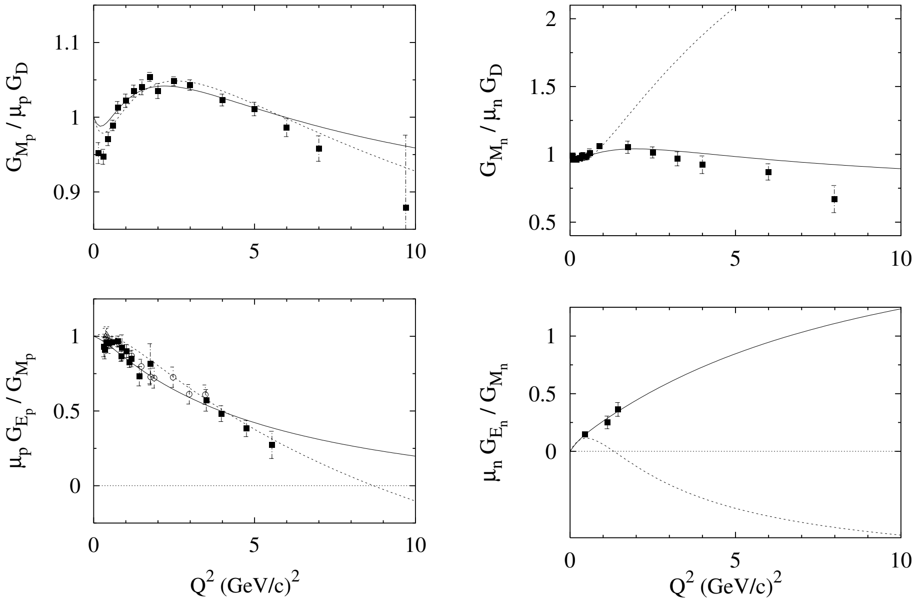

Figure 1: *(Left) Comparison between experimental and theoretical space-like proton form factors. Top panel: the magnetic form factor $G_{M_p}/\mu_p G_D$. Bottom panel: the ratio $\mu_p G_{E_p}/G_{M_p}$. The solid lines are from the 2004 parametrization [8], the dashed lines are from the 1973 parametrization [16]. (Right) Comparison between experimental and theoretical space-like neutron form factors. Top panel: the magnetic form factor $G_{M_n}/\mu_n G_D$. Bottom panel: the ratio $\mu_n G_{E_n}/G_{M_n}$. The solid lines are from the 2004 parametrization [8], the dashed lines are from the 1973 parametrization [16]. Adapted from [8].*

in the light-front approach with quark form factors [9, 10]. (3) Soliton model [11]. The results of the most recent analysis in terms of the two-component model are shown in Fig. 1. The conclusions drawn from the analysis of space-like form factors are: (i) The nucleon appears to be rather complex ($q\bar{q}$ pairs, or quark form factors, needed). (ii) p-QCD does not set in until large Q^2 (conservative estimate ≥ 10 (GeV/c)^2; more likely ≥ 30 (GeV/c)^2). (iii) None of the present models is fully consistent with all data (other components, gluons?, needed).

2 Nucleon time-like form factors

The first successful measurement of $e^+e^- \to p\overline{p}$ was performed in 1973 by Castellano *et al.* at Frascati [12]. In the 1970's many experiments were performed. In 1993 Armstrong *et al.* [13] performed the first successful measurement of $p\overline{p} \to e^+e^-$. Finally, Antonelli *et al.* [14] performed at Frascati in 1998 the only available measurement of $e^+e^- \to n\overline{n}$.

The analysis of time-like form factors makes use of the fact that time-like and space-like form factors are related by analytic continuation $q^2 = -Q^2$. For time-like form factors of the nucleon, the physical region is $q^2 \geq 4M_N^2$. Time-like form factors are usually analyzed by means of dispersion relations [15]. However, by an appropriate analytic continuation, they can also be analyzed in terms of models. Very recently, an analytic continuation of the two-component model has been suggested [16, 8]. Analytic continuation of the relativistic constituent quark model with quark form factors [10] can also be done, although it has not been implemented yet. The results for the two-component model are shown in Fig. 2. Conclusions drawn from presently available data are: (i) $\mid G_{M_n} \mid$ time-like is inconsistent with $\mid G_{M_n} \mid$ space-like. (ii) $\mid G_{M_p} \mid$ time-like is in good agreement with the two-component model. (iii) No information is available on the electric form factors $\mid G_{E_n} \mid$ and $\mid G_{E_p} \mid$.

In view of this situation, it appears that remeasurements of time-like form factors are of crucial importance for understanding the structure of the nucleon. An upgrade of DAΦNE provides an unique opportunity to solve one of the most important questions in Physics, namely what is the structure of the nucleon. In this respect, it is important to note that polarization measurements could be used to distinguish between different models as pointed out recently by Brodsky *et al.* [17].

Another important aspect that could be investigated with the DAΦNE upgrade is the question of whether or not there are subthreshold resonances in the $p\bar{p}$ and $n\bar{n}$ channel. From both proton and neutron data there are indications of subthreshold resonances. Adding [16] a subthreshold isoscalar resonance at $m_X \simeq 1870$ MeV [14] and negligible width to the two-component parametrization of F_2^S

$$\begin{aligned} F_2^S(q^2) &= \frac{1}{2}g(q^2)[(-0.120 - \alpha_\varphi - \alpha_X)\frac{m_\omega^2}{m_\omega^2 - q^2} \\ &\quad + \alpha_\varphi \frac{m_\varphi^2}{m_\varphi^2 - q^2} + \alpha_X \frac{m_X^2}{m_X^2 - q^2}] \end{aligned} \tag{2}$$

produces good agreement with experiment, Fig. 3. The resonance is weakly coupled,

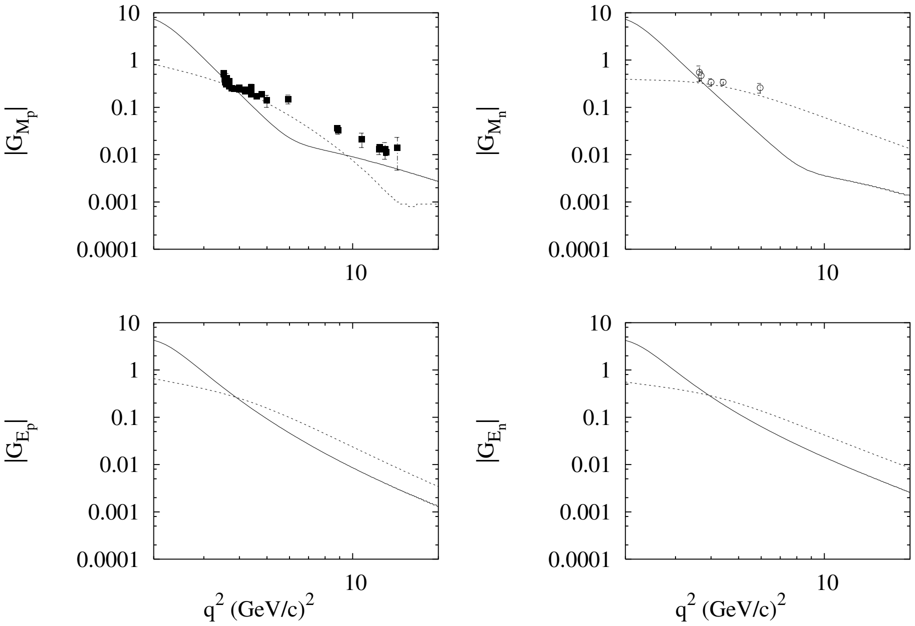

Figure 2: *(Left) Comparison between experimental and theoretical time-like proton form factors. Top panel: the magnetic form factor* $\mid G_{M_p} \mid$. *Bottom panel: the electric form factor* $\mid G_{E_p} \mid$. *The solid lines are from the 2004 parametrization [8] and the dashed lines are the analytic continuation of the 1973 parametrization [16]. (Right) Comparison between experimental and theoretical time-like neutron form factors. Top panel: the magnetic form factor* $\mid G_{M_n} \mid$. *Bottom panel: the electric form factor* $\mid G_{E_n} \mid$. *The solid lines are from the 2004 parametrization [8] and the dashed lines are the analytic continuation of the 1973 parametrization [16]. Adapted from [8].*

$\alpha_X = 0.001$. An isovector resonance would produce similar results except for the interchange of peaks in the neutron form factors. A careful remeasurement of G_{M_n} close to threshold at DAΦNE-2 can determine whether the resonance is isoscalar or isovector.

3 Other hadronic form factors

3.1 Form factors of baryons

Model calculations provide predictions for all hadronic form factors. The two-component model complemented with $SU_f(3)$ flavor symmetry, provides predictions for the form

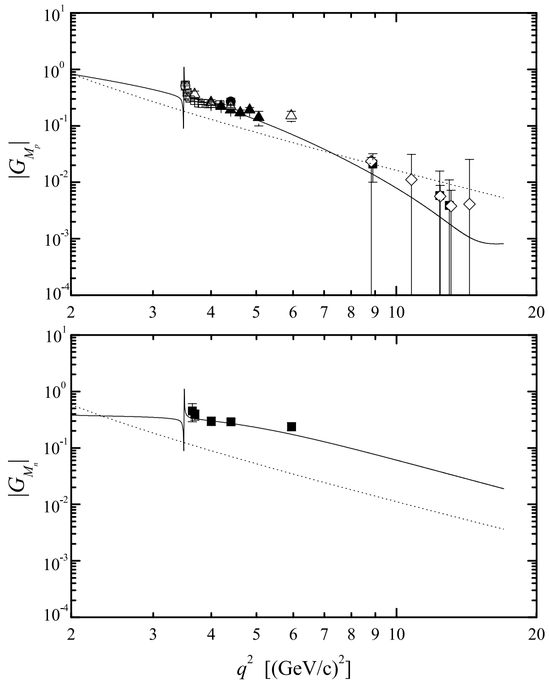

Figure 3: *Effects of an isoscalar subthreshold resonance on the time-like form factors* $\mid G_{M_p} \mid$ *(top panel) and* $\mid G_{M_n} \mid$ *(bottom panel). The dotted lines are the dipole form factors* $\mu_p G_D$ *and* $\mu_n G_D$*. From [16].*

factors of baryon belonging to the $\underline{8}$ and $\underline{10}$ representations of $SU_f(3)$, in particular for the time-like form factors in $e^+e^- \to \Sigma^+\Sigma^-$. These could be measured at DAΦNE-2.

3.2 Form factors of pseudoscalar mesons

It has been assumed for some time that form factors of pseudoscalar mesons in the time-like region were well described by the large Q^2 behavior predicted by p-QCD, $\propto 1/Q^2$. Recent measurements at TJNAF [18)] in the space-like region have shown that p-QCD fails to describe the observed behavior. On the other side, a two-component model appears to describe the data well [19)]. In this model, the pion form factor is parametrized as

$$F_\pi(Q^2) = g_{PS}(Q^2)\left[(1-\beta_\rho)+\beta_\rho \frac{m_\rho^2}{m_\rho^2+Q^2}\right]$$
$$g_{PS}(Q^2) = \frac{1}{(1+\gamma_{PS}Q^2)}. \tag{3}$$

An analytic continuation, similar to that for the nucleon, gives the pion form factor in the time-like region. The pion form factor in the time-like region could be measured at DAΦNE-2 by $e^+e^- \to \pi^+\pi^-$. A calculation of the pion form factor both in the space-like and time-like region is in the process of being completed and will be presented soon [20].

4 Inelastic form factors

4.1 The N-Δ(1232) form factors

These are the most extensively studied inelastic form factors. The first measurement was performed by Bartel *et al.* [21] at DESY in 1968. Many experiments were performed in the 1970's. In the 1990's it was found that the magnetic form factor drops faster than empirical scaling law, in disagreement with p-QCD that predict a fall-off as $1/Q^4$. Finally, in 2002 measurements at TJNAF have shown non-zero electric and longitudinal components.

The analysis of N-Δ form factors is by far more complex than that of the elastic form factors. I begin here with a brief reminder of some basic formulas. There are three form factors. These form factors can be written in terms of helicity amplitudes, as

A. Magnetic form factor

$$G_M^{Ash} = K\left[A_{1/2}+\sqrt{3}A_{3/2}\right], \tag{4}$$

where K is a kinematical factor.

B. Electric form factor. It is customary to quote the ratio of electric to magnetic form factor

$$R_{EM} = \frac{A_{1/2}-\frac{1}{\sqrt{3}}A_{3/2}}{A_{1/2}+\sqrt{3}A_{3/2}}. \tag{5}$$

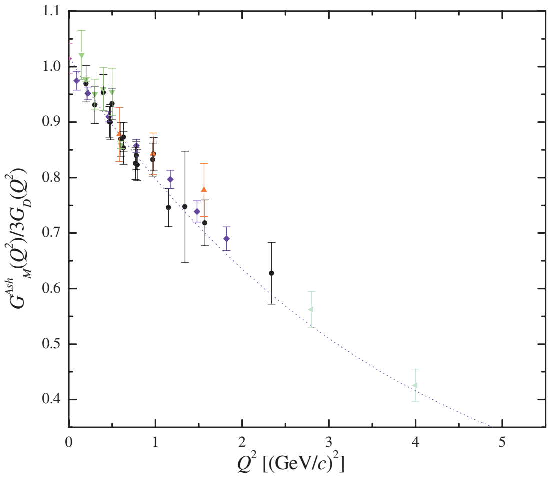

Figure 4: *The N-$\Delta(1232)$ magnetic form factor $G_M^{Ash}/3G_D$. The dashed line is the two-component calculation. From [20].*

C. Longitudinal form factor. It is customary to quote the ratio of longitudinal to magnetic form factor

$$R_{SM} = \frac{S_{1/2}}{A_{1/2}+\sqrt{3}A_{3/2}}. \tag{6}$$

Here $A_{1/2}, A_{3/2}$ are the transverse helicity amplitudes and $S_{1/2}$ is the longitudinal amplitude.

Inelastic form factors can be analyzed in terms of models. Two have been used: a two-component model [20] and a relativistic quark model [10]. Fig. 4 shows the comparison of the measured form factor with the calculation in the two-component model. Results of the analysis are: (i) N-Δ form factors appear to be dominated by coupling to ρ. (ii) p-QCD does not set in until large $Q^2 \geq 4$ (GeV/c)^2. (iii) R_{EM} and R_{SM} are very sensitive to models. The measured ratio R_{EM} favors the two-component model.

5 Conclusions

(i) In 1960 Hofstadter demonstrated that the nucleon is not point-like. In 2000-2002 experiments at JLab have shown that the nucleon has a complex structure.

(ii) A two-component model with an intrinsic (valence quarks) plus meson cloud ($q\bar{q}$ pairs) appears to describe all hadronic data well. The Fock state representation for baryons is

$$\mid N\rangle = a_0 \mid q^3\rangle + a_1 \mid q^3 q\bar{q}\rangle + ... \tag{7}$$

and for mesons

$$\mid \pi\rangle = b_0 \mid q\bar{q}\rangle + b_1 \mid q\bar{q}q\bar{q}\rangle + ... \tag{8}$$

(iii) The size of the intrinsic structure appears to be r.m.s.$\sim 0.34-0.49$ fm while the size of the cloud appears to be r.m.s. ~ 0.86 fm.

(iv) p-QCD is not reached at 10 (GeV/c)^2. Physics up to this scale is dominated by a mixture of hadronic and quark components.

The DAΦNE upgrade could contribute considerably to our understanding of the structure of hadrons, and hence of QCD in the non-perturbative regime. Possible projects are: $e^+e^- \to n\bar{n}$ (unique to DAΦNE); $e^+e^- \to p\bar{p}$; $e^+e^- \to \Sigma^+\Sigma^-$; $e^+e^- \to \pi^+\pi^-$.

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