

Reanalysis of the nucleon spacelike and timelike electromagnetic form factors in a two-component model

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Recent experimental data on spacelike and timelike form factors of the nucleon are analyzed in terms of a two-component model with a quarklike intrinsic q^3 structure and $q\bar{q}$ pairs.

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Recent experiments on the electromagnetic form factors of the proton [1,2] and the neutron [3] using the recoil polarization technique have shown a dramatically different picture of the nucleon as compared with a previously accepted picture [4,5]. Leaving aside the question of whether or not the experimental results are in disagreement with each other [6], which is the subject of many theoretical investigations related to the role of two-photon contributions [7], the new experiments for the proton [1,2] are in excellent agreement with a model of the nucleon put forward in 1973 [8] wherein the external photon couples both to an intrinsic structure and to a meson cloud through the intermediate vector mesons (ρ, ω, φ). On the contrary, the new experiments for the neutron [3] are in agreement with the 1973 model up to $Q^2 \sim 1$ (GeV/c)², but not so for higher values of Q^2 [9]. It is of great current interest to understand whether a modification of the 1973 parametrization can bring the calculation in agreement with both proton and neutron data.

We use the formalism of [8] and introduce Dirac, $F_1(Q^2)$, and Pauli, $F_2(Q^2)$, form factors. The observed Sachs form factors G_E and G_M can be obtained from F_1 and F_2 by the relations

$$\begin{aligned} G_{M_p} &= (F_1^S + F_1^V) + (F_2^S + F_2^V), \\ G_{E_p} &= (F_1^S + F_1^V) - \tau(F_2^S + F_2^V), \\ G_{M_n} &= (F_1^S - F_1^V) + (F_2^S - F_2^V), \\ G_{E_n} &= (F_1^S - F_1^V) - \tau(F_2^S - F_2^V), \end{aligned} \quad (1)$$

where we have introduced the isoscalar, F^S , and isovector, F^V , form factors and used $\tau = Q^2/4M_N^2$.

In 1973, the Dirac form factor was attributed to both the intrinsic structure and the meson cloud, while the Pauli form factor was attributed entirely to the meson cloud. Since this model was previous to the development of QCD, no explicit reference was made to the nature of the intrinsic structure. In this article, we identify the intrinsic structure with a three-valence-quark structure and reanalyze the situation. In particular, we study the question of whether or not there is a coupling to the intrinsic structure also in the Pauli form factor F_2 . Relativistic constituent quark models in the light-front approach [10,11] point to the occurrence of such a coupling.

In the meantime, the development of perturbative QCD (PQCD) [12] has put some constraints on the asymptotic behavior of the form factors—namely, that the non-spin-flip form factor $F_1 \rightarrow 1/Q^4$ and the spin-flip form factor $F_2 \rightarrow 1/Q^6$. This behavior has been very recently confirmed in a perturbative QCD reanalysis [13]. The 1973 parametrization, even if it was introduced before the development of PQCD, had this behavior. In modifying it, we insist on maintaining the asymptotic behavior of PQCD and introduce in F_2^V a term of the type $g(Q^2)/(1+\gamma Q^2)$. The parametrization we use is therefore

$$\begin{aligned} F_1^S(Q^2) &= \frac{1}{2}g(Q^2) \left[1 - \beta_\omega - \beta_\varphi + \beta_\omega \frac{m_\omega^2}{m_\omega^2 + Q^2} + \beta_\varphi \frac{m_\varphi^2}{m_\varphi^2 + Q^2} \right], \\ F_1^V(Q^2) &= \frac{1}{2}g(Q^2) \left[1 - \beta_\rho + \beta_\rho \frac{m_\rho^2}{m_\rho^2 + Q^2} \right], \\ F_2^S(Q^2) &= \frac{1}{2}g(Q^2) \left[(\mu_p + \mu_n - 1 - \alpha_\varphi) \frac{m_\omega^2}{m_\omega^2 + Q^2} \right. \\ &\quad \left. + \alpha_\varphi \frac{m_\varphi^2}{m_\varphi^2 + Q^2} \right], \\ F_2^V(Q^2) &= \frac{1}{2}g(Q^2) \left[\frac{(\mu_p - \mu_n - 1 - \alpha_\rho)}{1 + \gamma Q^2} + \alpha_\rho \frac{m_\rho^2}{m_\rho^2 + Q^2} \right], \end{aligned} \quad (2)$$

with $\mu_p = 2.793$ and $\mu_n = -1.913$. This parametrization ensures that the three-quark contribution to the anomalous moment is purely isovector, as given by SU(6). For the intrinsic form factor we use $g(Q^2) = (1 + \gamma Q^2)^{-2}$. This form is consistent with PQCD and in addition is the form used in our approach to the intrinsic three-quark structure by means of algebraic methods [14]. The values of the masses here are the standard ones: $m_\rho = 0.776$ GeV, $m_\omega = 0.783$ GeV, $m_\varphi = 1.019$ GeV. The five coefficients $\beta_\rho, \beta_\omega, \beta_\varphi, \alpha_\rho, \alpha_\varphi$ and the value of γ are fitted to the data. Before comparing to the data, two modifications are needed in Eq. (2). The first modification is crucial for the small Q^2 behavior and arises from the large width of the ρ meson. This is taken into account as in [8] by the replacement [15]

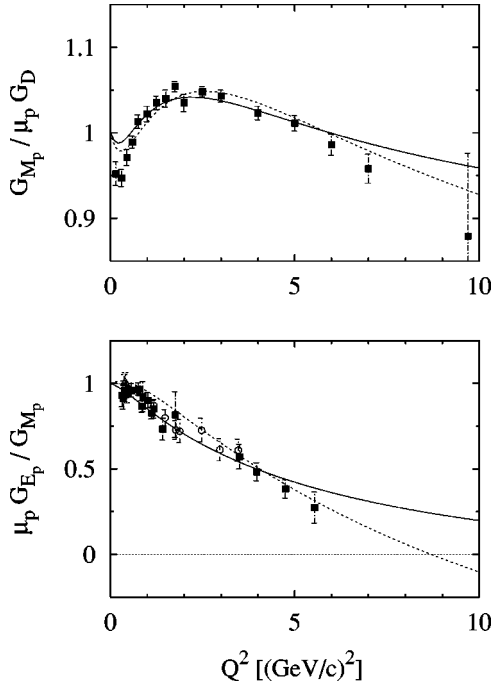


FIG. 1. Comparison between experimental and theoretical spacelike nucleon form factors. Top panel: the proton magnetic form factor $G_{M_p}/\mu_p G_D$. The experimental values are taken from [4]. Bottom panel: the ratio $\mu_p G_{E_p}/G_{M_p}$. The experimental data included in the fit are taken from [2] (solid squares). Additional data, not included in the fit, are taken from [1] (open circles) and [17] (open triangles). The solid lines are from the present analysis and the dashed lines from [8].

$$\frac{m_\rho^2}{m_\rho^2 + Q^2} \rightarrow \frac{m_\rho^2 + 8\Gamma_\rho m_\pi/\pi}{m_\rho^2 + Q^2 + (4m_\pi^2 + Q^2)\Gamma_\rho \alpha(Q^2)/m_\pi}, \quad (3)$$

with

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

Since our intent is to compare with [8], we use the same value of the effective width $\Gamma_\rho = 0.112$ GeV.

The second (not important for the present range of Q^2 measurements) is the logarithmic dependence of perturbative QCD. This can be taken into account by the replacement

$$Q^2 \rightarrow Q^2 \frac{\ln[(\Lambda^2 + Q^2)/\Lambda_{\text{QCD}}^2]}{\ln[\Lambda^2/\Lambda_{\text{QCD}}^2]}, \quad (5)$$

with $\Lambda = 2.27$ GeV and $\Lambda_{\text{QCD}} = 0.29$ GeV [16]. Since this change gives rise to small corrections below $Q^2 = 10$ (GeV/c) 2 , we neglect it in the present paper.

We have determined the five coefficients $\beta_\rho, \beta_\omega, \beta_\phi$ and α_ρ, α_ϕ and the parameter γ by a fit to recent data on electromagnetic form factors. Because of the inconsistencies between different data sets, most notably between those obtained from recoil polarization and Rosenbluth separation, the choice of the data to which to fit plays an important role in the final outcome. We have used recoil polarization JLab

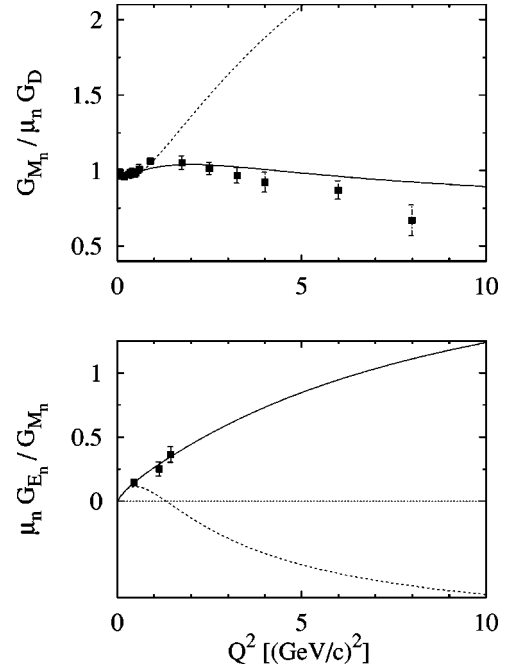


FIG. 2. Comparison between experimental and theoretical spacelike nucleon form factors. Top panel: the neutron magnetic form factor $G_{M_n}/\mu_n G_D$. The experimental data are taken from [21]. Bottom panel: the ratio $\mu_n G_{E_n}/G_{M_n}$. The experimental data are taken from [3]. The solid lines are from the present analysis and the dashed lines from [8].

data for the ratios $R_p = \mu_p G_{E_p}/G_{M_p}$ and $R_n = \mu_n G_{E_n}/G_{M_n}$ and Rosenbluth separation data, mostly from SLAC, for G_{M_p} and G_{M_n} , as well as some recent measurements of G_{E_n} . The data actually used in the fit are quoted in the captions to Figs. 1–3 and are indicated by solid squares in those figures. The values of the parameters that we extract are $\beta_\rho = 0.512$, $\beta_\omega = 1.129$, $\beta_\phi = -0.263$, $\alpha_\rho = 2.675$, $\alpha_\phi = -0.200$, and γ

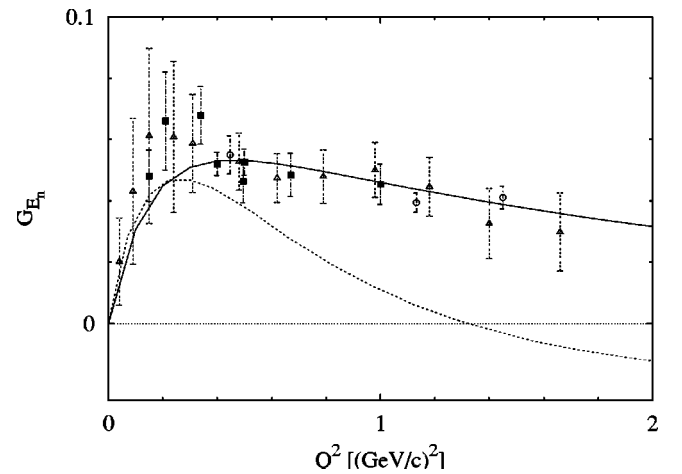


FIG. 3. Comparison between experimental and theoretical spacelike nucleon form factors: the neutron electric form factor G_{E_n} . The experimental data included in the fit are taken from [22] (solid squares). Additional data, not included in the fit, are taken from [3] (open circles) and [23] (open triangles). The solid lines are from the present analysis and the dashed lines from [8].

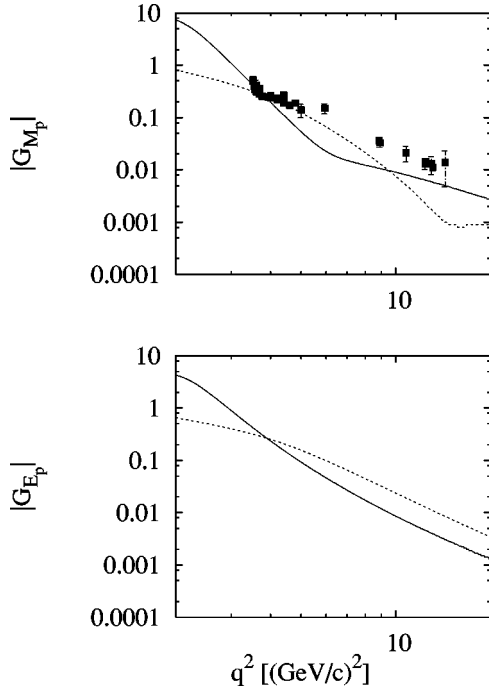


FIG. 4. Comparison between experimental and theoretical time-like nucleon form factors. Top panel: the proton magnetic form factor $|G_{M_p}|$. The experimental values are taken from [30] under the assumption $|G_{E_p}|=|G_{M_p}|$. Bottom panel: the proton electric form factor $|G_{E_p}|$. The solid lines are from the present analysis and the dashed lines from [29].

$=0.515 (\text{GeV}/c)^{-2}$. These values differ somewhat from those obtained in the 1973 fit, although they retain most of their properties—namely, a large coupling to the ω meson in F_1 and a very large coupling to the ρ meson in F_2 . Also the spatial extent of the intrinsic structure is somewhat larger than in [9], $\langle r^2 \rangle^{1/2} \approx 0.49$ fm instead of ≈ 0.34 fm.

Figure 1 shows a comparison between the calculation with parameters given above and proton data for $R_p = \mu_p G_{E_p}/G_{M_p}$ (bottom panel) and for $G_{M_p}/\mu_p G_D$, where $G_D = (1 + Q^2/0.71)^{-2}$ (top panel). In this figure, the 1973 calculation, with no direct coupling to F_2^V , is also shown. One can see that the inclusion of the direct coupling pushes the zero in R_p to larger values of Q^2 [in [9] the zero is at $\approx 8 (\text{GeV}/c)^2$]. We note that any model parametrized in terms of F_1 and F_2 will produce results for R_p that are in qualitative agreement with the data, such as a soliton model [18] or relativistic constituent quark models [10,19]. Perturbation expansions of relativistic effects also produce results that go in the right direction [20]. Figure 2 shows the same comparison, but with neutron data: for $R_n = \mu_n G_{E_n}/G_{M_n}$ (bottom panel) and for $G_{M_n}/\mu_n G_D$ (top panel). Contrary to the case of the 1973 parametrization, the present parametrization is in excellent agreement with the neutron data. This is emphasized in Fig. 3 where the electric form factor of the neutron is shown and compared with additional data not included in the fit. However, as one can see from Fig. 1, the excellent agreement with the neutron data is at the expense of a slight disagreement with proton data. To settle the question of consistency between proton and neutron spacelike

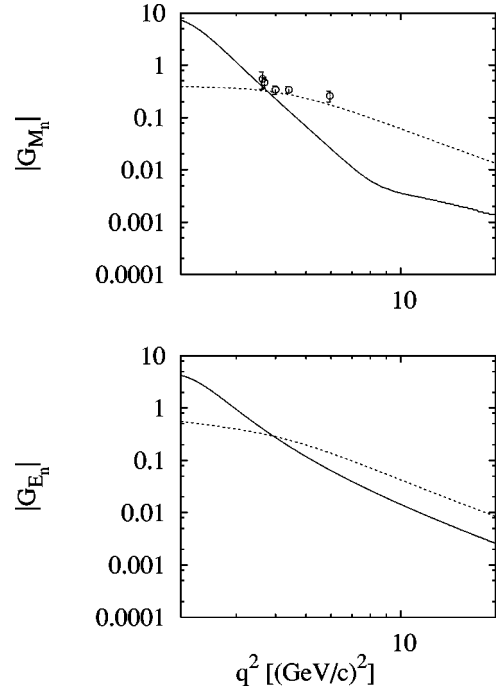


FIG. 5. Comparison between experimental and theoretical time-like nucleon form factors. Top panel: the neutron magnetic form factor $|G_{M_n}|$. The experimental values, not included in the fit, are taken from [31] under the assumption $|G_{E_n}|=0$. Bottom panel: the neutron electric form factor $|G_{E_n}|$. The solid lines are from the present analysis and the dashed lines from [29].

data, one needs to (i) measure $\mu_p G_{E_p}/G_{M_p}$ beyond $6 (\text{GeV}/c)^2$ (this is the approved JLab experiment E01-109 [24]), (ii) measure G_{M_n} beyond $2 (\text{GeV}/c)^2$ (this experiment is in the course of analysis [25]), and (iii) measure G_{E_n} beyond $1.4 (\text{GeV}/c)^2$ (this is the proposed experiment JLab PR04-003 [26]).

Recently it has been suggested that timelike form factors be also used in a global understanding of the structure of the nucleon [27,28]. The timelike structure of the nucleon form factors within the framework of the 1973 parametrization has been recently analyzed [29]. We use here the same method to analyze the timelike structure of the form factors discussed in this Brief Report. The method consists in analytically continuing the intrinsic structure to [28]

$$g(q^2) = \frac{1}{(1 - \gamma e^{i\theta} q^2)^2}, \quad (6)$$

where $q^2 = -Q^2$ and θ is a phase. The contribution of the ρ meson is analytically continued for $q^2 > 4m_\pi^2$ as [15]

$$\frac{m_\rho^2}{m_\rho^2 - q^2} \rightarrow \frac{m_\rho^2 + 8\Gamma_\rho m_\pi/\pi}{m_\rho^2 - q^2 + (4m_\pi^2 - q^2)\Gamma_\rho[\alpha(q^2) - i\beta(q^2)]/m_\pi}, \quad (7)$$

where

$$\alpha(q^2) = \frac{2}{\pi} \left[\frac{q^2 - 4m_\pi^2}{q^2} \right]^{1/2} \ln \left(\frac{\sqrt{q^2 - 4m_\pi^2} + \sqrt{q^2}}{2m_\pi} \right),$$

$$\beta(q^2) = \sqrt{\frac{q^2 - 4m_\pi^2}{q^2}}. \quad (8)$$

Our results for timelike form factors are shown in Figs. 4 and 5 together with those of [29]. The phase θ obtained from a best fit to the proton data is $\theta=0.397$ rad $\approx 22.7^\circ$, again somewhat different than the value $\approx 53^\circ$ obtained in [29]. It should be noted that the correction to the large- q^2 data discussed in [29] has not been done in these figures. One can see from these figures that while the proton form factor $|G_{M_p}|$ obtained from analytic continuation of the present parametrization is in marginal agreement with data, the neutron form factor $|G_{M_n}|$ is in major disagreement. This result points once more to the inconsistency between neutron spacelike and timelike data already noted by Hammer *et al.* [32] and in [29]. A remeasurement of neutron timelike data at FRASCATI-DAFNE [33] would help resolve this inconsistency. The result presented here is in contrast with that of the 1973 parametrization, which was in good agreement with both proton and neutron timelike form factors. In Figs. 4 and 5, the electric form factors $|G_{E_p}|$ and $|G_{E_n}|$ are also shown for

future use in the extraction of $|G_{M_p}|$ and $|G_{M_n}|$ from the data. This figure shows that the assumptions $|G_{E_p}|=|G_{M_p}|$ and $|G_{E_n}|=0$ used in the extraction of the magnetic form factors from the experimental data are not always justified.

In conclusion, we have performed a reanalysis of the combined spacelike and timelike data on the electromagnetic form factors of the nucleon and found that one can obtain a good fit to the spacelike neutron form factors measured recently, but this is at the expense of a slight deterioration of the fit for proton spacelike data and especially a failure to describe neutron timelike data. The picture emerging from the fit reported here is that of an intrinsic structure slightly larger in spatial extent than that of [9], $\langle r^2 \rangle^{1/2} \approx 0.49$ fm instead of 0.34 fm, and a contribution of the meson cloud ($q\bar{q}$ pairs) slightly smaller in strength than that of [9], $\alpha_p = 2.675$ instead of 3.706.

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