

Neutron electric form factor at large momentum transfer.

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Based on the recent, high precision data for elastic electron scattering from protons and deuterons, at relatively large momentum transfer Q^2 , we determine the neutron electric form factor up to $Q^2 = 3.5 \text{ GeV}^2$. The values obtained from the data (in the framework of the nonrelativistic impulse approximation) are larger than commonly assumed and are in good agreement with the Gari-Krümpelmann parametrization of the nucleon electromagnetic form factors.

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The internal structure of hadrons, their charge and magnetic distributions, can be conveniently described in terms of form factors. Elastic electron-hadron scattering is the traditional way to experimentally determine the electromagnetic form factors, and it allows a direct comparison with the theory.

Direct measurements of the electric neutron form factor have been recently made possible, at transfer momenta $Q^2 < 1 \text{ GeV}^2$, via inelastic electron scattering by deuteron or ^3He . These experiments require not only a polarized beam but either a polarized target or the measurement of the polarization of the outgoing neutron (for a recent update see [1] and refs. herein).

Having high precision data on the differential cross section for ed - elastic scattering, and assuming a reliable model for their description, one can extract, in principle, the dependence of the electric neutron form factor G_{En} on the momentum transfer Q^2 . Such a procedure has been carried out in ref. [2], up to $Q^2=0.7 \text{ GeV}^2$. The purpose of this paper is to extend such an analysis at larger Q^2 . This is motivated by the fact that the elastic ed -scattering data extend up to $Q^2=6 \text{ GeV}^2$, with high precision [3] and the recent data on the proton electric form factor [4] (which have been obtain by the recoil proton polarization measurement following an idea suggested more than 30 years ago [5]) extend up to $Q^2=3.5 \text{ GeV}^2$. A large program is under way at the Jefferson Laboratory (JLab) to improve the accuracy of the experimental data for the proton and deuteron elastic electromagnetic form factors up to relatively large values of momentum transfer [3,4,6], to measure the neutron electric form factor [7] and the electromagnetic transition form factors of the nucleon resonances [8].

Common assumptions, in the previous calculations of deuteron electromagnetic form factors, are that the proton electric form factor, G_{Ep} , follows a dipole-like Q^2 dependence (resulting from an exponential charge distribution), and that G_{En} is negligible (in the region of space-like momentum transfer).

The large sensitivity to the nucleon form factors of the models which describe the light nuclei structure, particularly the deuteron, was carefully studied in [9], and it was pointed out that the disagreement between the relativistic impulse approximation and the existing data [up to $Q^2=4 \text{ GeV}^2$] could be significantly reduced if G_{En} were different from zero.

On the other hand, recent studies focus primarily on other ingredients of the deuteron structure, such as the choice of the deuteron wave function or specific corrections like meson exchange currents (MEC), relativistic effects, and six-quark components in the deuteron (for a review see, for instance, [10]).

Here we take another approach: we look for a consistent explanation of JLab data about ed - and ep - scattering in the framework of the impulse approximation (IA) for ed -scattering, and derive the neutron electric form factor. A discussion of the role of the corrections to IA, in particular the MEC, will follow.

In the framework of non relativistic IA, where the calculation of the deuteron electromagnetic form factors is straightforward, only two ingredients are required: the S- and D-components of the deuteron wave function and the electromagnetic form factors of the nucleons, which are considered as free ones, without off-shell mass effects.

Let us recall here some useful formulas (for a complete derivation, see [11]). The differential cross section for ed elastic scattering can be expressed in terms of two structure functions, $A(Q^2)$ and $B(Q^2)$, in one photon approximation¹:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega} \right)_0 \cdot S, \quad S = A(Q^2) + B(Q^2) \tan^2(\theta_e/2)$$

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¹For a recent discussion of the validity of one-photon exchange in this momentum range, see ref. [12]

with

$$\left(\frac{d\sigma}{d\Omega}\right)_0 = \frac{\alpha^2 \cos^2(\theta_e/2) E'}{4 \sin^4(\theta_e/2) E^3},$$

where E (E') is the electron beam (the scattered electron) energy. The structure functions A and B can be expressed in terms of the three deuteron form factors, G_c (electric), G_m (magnetic) and G_q (electric quadrupole) as:

$$\begin{aligned} A(Q^2) &= G_c^2(Q^2) + \frac{8}{9}\tau^2 G_q^2(Q^2) + \frac{2}{3}\tau G_m^2(Q^2), \\ B(Q^2) &= \frac{4}{3}(1 + \tau)\tau G_m^2(Q^2), \quad \tau = \frac{Q^2}{4M_d^2} \end{aligned} \quad (1)$$

where M_d is the deuteron mass.

In order to disentangle the three form factors it is necessary to measure the cross section at least at two different angles for a fixed Q^2 (the Rosenbluth separation), and some polarization observables. In case of an unpolarized beam and target, the outgoing deuteron is tensor polarized and the components of the tensor polarization $t_{2,i}$ ($i = 0 - 2$) give useful combinations of form factors. In particular t_{20} is sensitive to G_c and G_q :

$$t_{20} = -\frac{1}{\sqrt{2}S} \left\{ \frac{8}{3}\tau G_c G_q + \frac{8}{9}\tau^2 G_q^2 + \frac{1}{3}\tau [1 + 2(1 + \tau) \tan^2(\theta_e/2)] G_m^2 \right\} \quad (2)$$

In the non relativistic IA, the deuteron form factors depend only on the deuteron wave function and on nucleon form factors:

$$\begin{aligned} G_c &= G_{Es} C_E, \quad G_q = G_{Es} C_Q, \\ G_m &= \frac{M_d}{M_p} \left(G_{Ms} C_S + \frac{1}{2} G_{Es} C_L \right), \end{aligned} \quad (3)$$

where M_p is the proton mass, $G_{Es} = G_{Ep} + G_{En}$ and $G_{Ms} = G_{Mp} + G_{Mn}$ are the charge and magnetic isoscalar nucleon form factors, respectively. The terms C_E , C_Q , C_S , and C_L describe the deuteron structure and can be calculated from the deuteron S and D wave functions, $u(r)$ and $w(r)$ [11]:

$$\begin{aligned} C_E &= \int_0^\infty dr j_0\left(\frac{Qr}{2}\right) [u^2(r) + w^2(r)], \\ C_Q &= \frac{3}{\sqrt{2}\eta} \int_0^\infty dr j_2\left(\frac{Qr}{2}\right) \left[u(r) - \frac{w(r)}{\sqrt{8}} \right] w(r), \\ C_S &= \int_0^\infty dr \left[u^2(r) - \frac{1}{2}w^2(r) \right] j_0\left(\frac{Qr}{2}\right) + \frac{1}{2} [\sqrt{2}u(r)w(r) + w^2(r)] j_2\left(\frac{Qr}{2}\right), \\ C_L &= \frac{3}{2} \int_0^\infty dr w^2(r) \left[j_0\left(\frac{Qr}{2}\right) + j_2\left(\frac{Qr}{2}\right) \right] \end{aligned} \quad (4)$$

where

$$j_0(x) = \frac{\sin x}{x}, \quad j_2(x) = \sin x \left(\frac{3}{x^3} - \frac{1}{x} \right) - 3 \frac{\cos x}{x^2}$$

are the spherical Bessel functions. The normalization condition is

$$\int_0^\infty dr [u^2(r) + w^2(r)] = 1.$$

With the help of expressions (3) and (4), the formula for $A(Q)^2$, Eq. (1), can be inverted into a quadratic equation for G_{Es} . Then G_{Es} is calculated using the experimental values for $A(Q)^2$. We assume, for the magnetic nucleon form factors G_{Mp} and G_{Mn} the following dipole dependence,

$$G_{Mp}(Q^2)/\mu_p = G_{Mn}(Q^2)/\mu_n = G_D,$$

with

$$\mu_p = 2.79, \mu_n = -1.91, \text{ and } G_D = \frac{1}{\left[1 + \frac{Q^2}{0.71 \text{ GeV}^2}\right]^2},$$

which is in agreement with the existing data at a 3% level, up to $Q^2 \simeq 10 \text{ GeV}^2$.

In Fig. 1 we illustrate the behavior of the different nucleon electric form factors: G_{Es} , G_{Ep} and G_{En} . The nucleon isoscalar electric form factor, derived from different sets of deuteron data, decreases when Q^2 increases. The solid line represents the Gari-Krümpelmann parametrization [14] for G_{Es} . The dipole behavior, which is generally assumed for the proton electric form factor is shown as a dotted line. We have approximated the last G_{Ep} data by a function of the form:

$$G_{Ep} = \frac{G_D}{1 + \frac{Q^2}{m_x^2}} \quad (5)$$

with $m_x^2 = 5.88 \text{ GeV}^2$, (thin dashed-dotted line). The new G_{Ep} data, which decrease faster than the dipole function, are also well reproduced by the Gari-Krümpelmann parametrization (thick dashed line).

The electric neutron form factor can be calculated from the isoscalar nucleon form factor, assuming for G_{Ep} a dipole behavior (solid stars) or Eq. (5) (open stars). The last option leads to values for G_{En} which are in very good agreement with the parametrization [14]. These results show that the neutron form factor is not going to vanish identically at large momentum transfer, but becomes more sizeable than predicted by other parametrizations, often used in the calculations [2,15] (thin dashed line). Starting from $Q^2 \simeq 2 \text{ GeV}^2$ the form factor G_{En} becomes even larger than G_{Ep} . Let us mention that a recent 'direct' measurement [16] at $Q^2 = 0.67 \text{ GeV}^2$ finds $G_{En} = 0.052 \pm 0.011 \pm 0.005$ in agreement with the present values.

In order to test the coherence of this description, we plot in Fig. 2 the prediction of the IA model, based on the Paris wave function and the parametrization [14], together with a sample of the existing data on the deuteron observables, $A(Q^2)$, $B(Q^2)$ and t_{20} .

The agreement is qualitatively good, even at large momentum transfer, for all the observables. Replacing the common dipole approximation with Eq. (5), based on the new data about G_{Ep} , induces little effect on the Q^2 - dependence of t_{20} and the structure function $B(Q^2)$, but the structure function $A(Q^2)$ gets much smaller, up to 40% at $Q^2 = 4 \text{ GeV}^2$. This explains the important role played by the neutron electric form factor, which is therefore larger than previously assumed. Replacing the Paris wave function with other N-N potentials gives qualitatively similar results. Introducing different corrections to the IA as relativistic effects, MEC, isobar, six-quark contributions etc.. brings to results which are largely model dependent [19]. Let us mention that the $\gamma^* \pi^\pm \rho^\mp$ -contribution, which is a good approximation for the isoscalar transition $\gamma^* \rightarrow \pi^+ \pi^- \pi^0$ (γ^* is a virtual photon), is typically considered as the main correction to IA, necessary, in particular, to improve the description of the SF $A(Q^2)$ [13]. However the relative role of MEC is strongly model dependent [20] as the coupling constants for meson-NN-vertexes are not well known and arbitrary form factors are often added [21,22].

It should be pointed out that the $\gamma^* \pi \rho$ vertex is of magnetic nature and its contribution to $A(Q^2)$ has to be of the same order of magnitude as the relativistic corrections. The general spin structure of the $\gamma^* \pi \rho$ -vertex can be written as: $\epsilon_{\mu\nu\rho\sigma} e_\mu k_\nu U_\rho q_\sigma$, where e and k (U and q) are the 4-vector of the photon (ρ -meson) polarization and corresponding 4-momentum. The equivalent 3-dimensional expression for the spin structure is: $\vec{e} \times \vec{k} \cdot \vec{U}$ (where \vec{k} is the photon 3-momentum), which allows the absorption of real (or virtual) $M1$ photon, only. A consequence is that the main contribution of $\gamma^* \pi \rho$ -MEC concerns $B(Q^2)$, which is proportional to the square of the deuteron magnetic form factor, and not $A(Q^2)$, which mostly depends on the deuteron electric charge and quadrupole form factors.

In conclusion, the description of the deuteron electromagnetic structure in the framework of IA is now possible up to large momentum transfer ($Q^2 \simeq 3.5 \text{ GeV}^2$) and it predicts a saturation of the isoscalar electric nucleon form factor by the neutron electric form factor at large Q^2 . This result is consistent with the predictions of [14]. There is no strong theoretical background in the ansatz $G_{En}=0$, often used in the literature concerning deuteron, in the considered region of space-like momentum transfer. The forthcoming data about G_{En} , planned at JLab up to $Q^2=2 \text{ GeV}^2$, [7] will be crucial in this respect. The large sensitivity of the deuteron structure to the nucleon form factors shows the necessity to reconsider the role of meson exchange currents in the deuteron physics at large momentum transfer.

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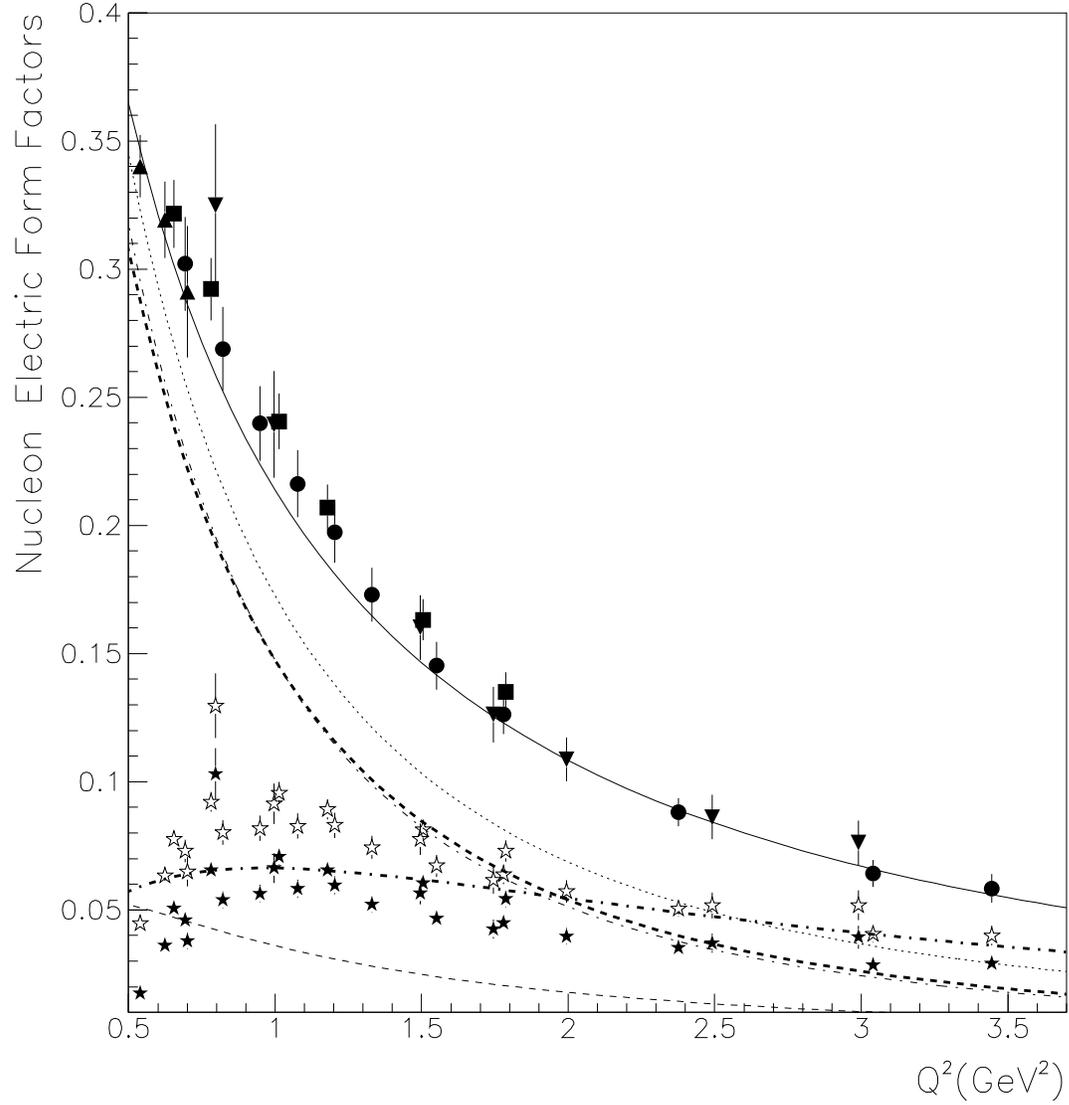


FIG. 1. Nucleon electric form factors as functions of the momentum transfer Q^2 . in the framework of IA with Paris potential. Isoscalar electric form factors are derived from the deuteron elastic scattering data: [2] (solid triangles), [3] (solid circles), [6] (solid squares), and [13] (solid reversed triangles). The electric neutron form factors are shown as solid stars when calculated from the dipole representation of G_{E_p} (dotted line) and open stars when Eq. (5) is taken for G_{E_p} (thin dashed-dotted line). The parametrization [14] is shown for G_{E_s} (solid line), for G_{E_n} (thick dashed-dotted line) and for G_{E_p} (thick dashed line). The thin dashed line is the parametrization [15] for G_{E_n} .

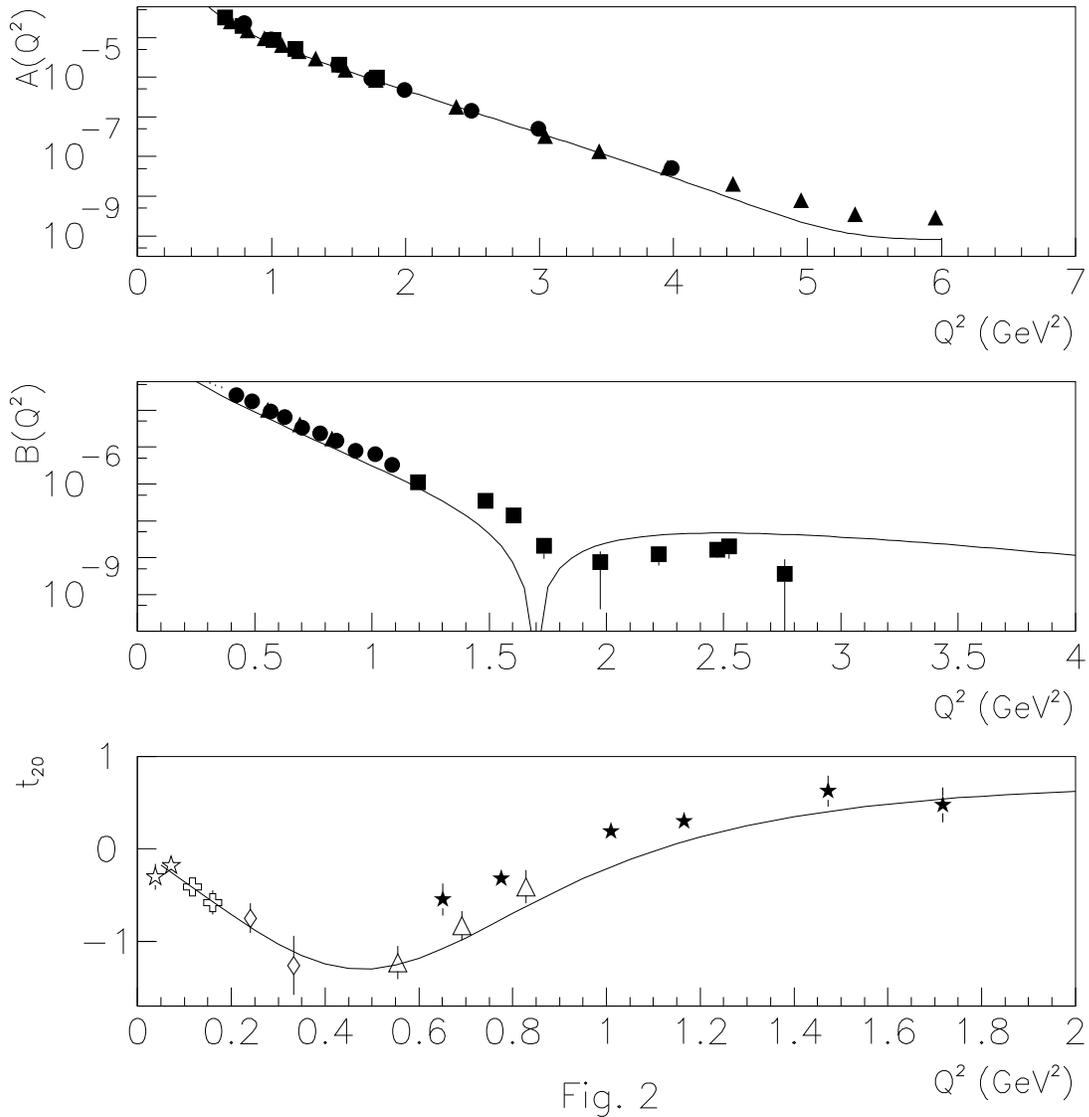


FIG. 2. Impulse approximation prediction for the structure functions $A(Q^2)$, $B(Q^2)$, and the tensor deuteron polarization t_{20} . The $A(Q^2)$ data are from [3,6,13], the $B(Q^2)$ data are from [17], the t_{20} data are from [18].