WHAT CHARGE DISTRIBUTION IS REALLY INSIDE OF THE PROTON

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By using the unitary and analytic model of nucleon electromagnetic structure the problem of inconsistency of proton electric form factor data in space-like region (obtained from $e^- p \to e^- p$ process by the Rosenbluth technique) with recent Jefferson Lab data on ratio $G_{Ep}(t)/G_{Mp}(t)$ (measured in precise polarization $\vec{e^-} p \to e^- \vec{p}$ experiment) has been solved in favour of the latter. However, the new data strongly require an existence of a zero, i.e. a diffraction minimum in $G_{Ep}(t)$ around $t = -Q^2 = -15$ GeV^2, which may change our conception about the charge distribution inside of the proton.

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1 Introduction

The proton p is compound of $(u,\, u,\, d)$ quarks, then it is non-point-like and one does not know an explicit form of the matrix element of the electromagnetic (EM) current $J_\mu^{EM} = 2/3\bar{u}\gamma_\mu u - 1/3\bar{d}\gamma_\mu d - 1/3\bar{s}\gamma_\mu s$ necessary in a description of the one-photon-exchange approximation of the proton EM interactions in the framework of local quantum field theory. Therefore currently it is parametrized in the form

$$\langle p|J_\mu^{EM}|p\rangle = \bar{u}(p')\{\gamma_\mu F_{1p}(t) + i\frac{\sigma_{\mu\nu}q_\nu}{2m_p}F_{2p}(t)\}u(p), \tag{1}$$

where $F_{1p}(t)$ is Dirac and $F_{2p}(t)$ Pauli form factor (FF) and $t = q^2 = -Q^2$ is square four-momentum transferred by the photon. From a practical point of view, however, it is suitable to introduce electric and magnetic FF's

$$G_{Ep}(t) = F_{1p}(t) + \frac{t}{4m_p^2}F_{2p}(t); \quad G_{Mp}(t) = F_{1p}(t) + F_{2p}(t), \tag{2}$$

which have a specific interpretation in the Breit reference frame. Their inverse Fourier transforms give charge and magnetization distributions inside of the proton, respectively.

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Prior to the year 2000 all data on $G_{Ep}(t)$ in $t < 0$ region are obtained (mainly in SLAC) by measurement of

$$\frac{d\sigma^{lab}(e^-p \to e^-p)}{d\Omega} = \frac{\alpha^2}{4E^2}\frac{\cos^2(\theta/2)}{\sin^4(\theta/2)}\frac{1}{1+(\frac{2E}{m_p})\sin^2(\theta/2)} \times$$

$$\times \quad \left[\frac{G^2_{Ep}(t) - \frac{t}{4m_p^2}G^2_{Mp}(t)}{1-\frac{t}{4m_p^2}} - 2\frac{t}{4m_p^2}G^2_{Mp}(t)\tan^2(\theta/2)\right] \tag{3}$$

and utilization of the Rosenbluth technique to separate $G_{Ep}(t)$ and $G_{Mp}(t)$. It is straightforward to see that the cross-section (3) is (for increased values of $Q^2 = -t$) dominated by $G_{Mp}(t)$ term and thus the obtained data on $G_{Ep}(t)$ must be in principle less precise than the data on $G_{Mp}(t)$.

More recently new Jefferson Lab data on $\mu_p G_{Ep}(Q^2)/G_{Mp}(Q^2)$ appeared [1,2] (see Fig. 1) by measuring simultaneously the transverse

$$P_t = \frac{h}{I_0}(-2\sqrt{\tau(1+\tau)}G_{Mp}G_{Ep}\tan^2(\theta/2) \tag{4}$$

and the longitudinal

$$P_l = \frac{h(E+E')}{I_0 m_p}(\sqrt{\tau(1+\tau)}G^2_{Mp}\tan^2(\theta/2) \tag{5}$$

components of the recoil proton's polarization in the electron scattering plane of the polarization transfer process $\vec{e}^-p \to e^-\vec{p}$, where h is the electron beam helicity, I_0 is the unpolarized cross-section excluding σ_{Mott} and $\tau = Q^2/4m_p^2$.

These new data (see Fig. 1) are in rather strong disagreement with the separate data on $G_{Ep}(Q^2)$ and $G_{Mp}(Q^2)$ obtained by the Rosenbluth technique, the corresponding ratio of which in Fig. 1 is represented by the dotted line.

Recently it was suggested [3–5] that the two-photon corrections could resolve a large part of the discrepancy between the two abovementioned experimental techniques in the Born approximation.

A content of the next section is an another attempt to solve the puzzle.

2 Analysis of old and new $G_{Ep}(t)$ data by unitary and analytic model of nucleon EM structure

Similarly to the proton FF's (2), one can define also the neutron electric and magnetic FF's

$$G_{En}(t) = F_{1n}(t) + \frac{t}{4m_n^2}F_{2n}(t); \quad G_{Mn}(t) = F_{1n}(t) + F_{2n}(t). \tag{6}$$

the data on which, however, cannot be obtained in a straightforward way. Nowadays, besides the $G_{Ep}(t)$ and $G_{Mp}(t)$ data in space-like ($t < 0$) region, there are also (more poor) the time-like $|G_{Ep}(t)|$ and $|G_{Mp}(t)|$ data above the $t = 4m_p^2$ threshold.

What is concerned of the neutron FF data, there are only space-like (not very reliable) $G_{En}(t)$ data up to $t = -4$ GeV^2 and no points in $t > 0$ region.

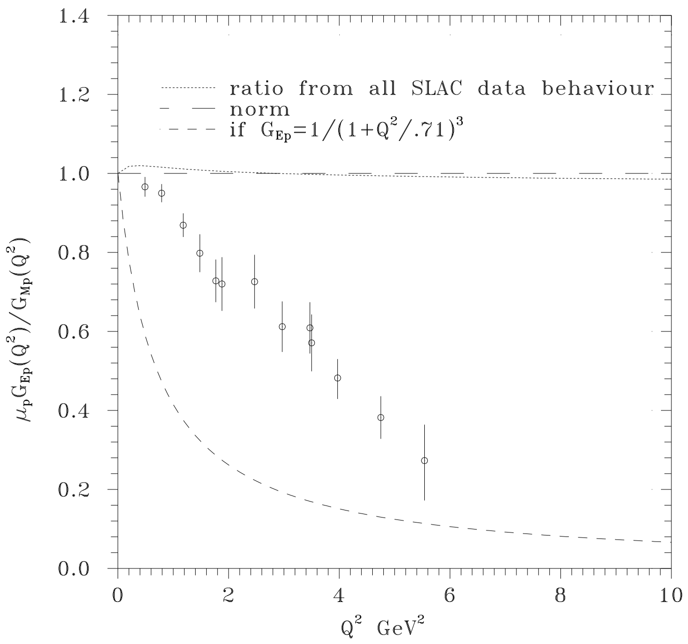

Fig. 1. Remarkable fall of $G_{Ep}(Q^2)$ with increased Q^2 (in comparison with $G_{Mp}(Q^2)$) revealed by new JLab polarization data [1,2].

The neutron magnetic FF data in space-like ($t < 0$) region are experimentally known up to $t = -10$ GeV^2. In time-like region there are five experimental points on $|G_{Mn}(t)|$ known above the $t = 4m_n^2$ threshold.

So, there are all together more than 500 experimental points in space-like and time-like regions on the proton and neutron electric and magnetic FF's.

In order to describe them theoretically it is suitable to split Dirac and Pauli proton and neutron FF's in (2) and (6) into common isoscalar and isovector parts

$$F_{1p}(t) = F_1^s(t) + F_1^v(t); \qquad F_{2p}(t) = F_2^s(t) + F_2^v(t); \qquad (7)$$
$$F_{1n}(t) = F_1^s(t) - F_1^v(t); \qquad F_{2n}(t) = F_2^s(t) - F_2^v(t)$$

and to construct models in the language of the latter. Just this is the reason why the proton and the neutron EM FF data have to be analyzed always simultaneously.

There was a general problem of a simultaneous description of all existing data on nucleon EM FF's, especially the neutron time-like data (5 points) with all others.

However, recently new 10-resonance (5 isoscalar and 5 isovector vector-mesons) unitary and analytic model of the nucleon EM structure has been elaborated [6]. It unifies consistently all known FF properties, like the experimental fact of a creation of unstable vector-meson resonances in e^+e^--annihilation processes to hadrons, the hypothetical analytic properties of nucleon EM FF's, unitarity condition, normalization, reality condition, the asymptotic behaviour as predicted by quark model of hadrons and provides a very effective framework for superposition of complex

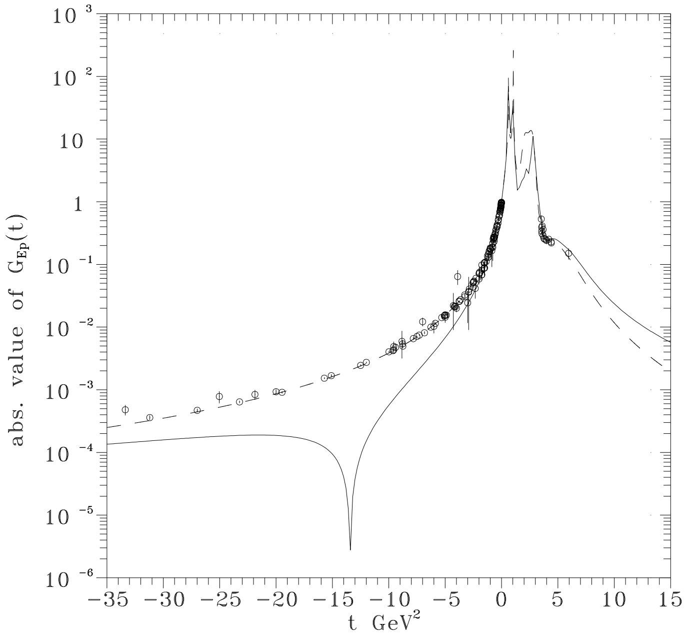

Fig. 2. Results of the SLAC and JLab $G_{Ep}(t)$ $t < 0$ data analysis in the framework of the unitary and analytic model of nucleon EM structure. Only all old SLAC $G_{Ep}(t)$ data are explicitly presented in figure and dashed-line is their best simultaneous description with all other nucleon FF data. The full-line represents $G_{Ep}(t)$ behaviour following from the analysis of the new JLab polarization data on $\mu_p G_{Ep}(Q^2)/G_{Mp}(Q^2)$.

conjugate vector-meson pole pairs on unphysical sheets and continuum contributions in nucleon EM FF's.

In the framework of this model [6] a consistent description of all existing nucleon FF data, including also data on $G_{Ep}(t)$ in $t < 0$ region and five neutron time-like experimental points has been achieved for the first time. In consequence of this fact latter the data on $G_{Ep}(t)$ and $G_{Mp}(t)$, obtained in $t < 0$ region by the Rosenbluth technique from $d\sigma/d\Omega$, are compatible with all other existing nucleon FF data and nucleon FF properties (especially analyticity), following from the basic physical principles including also the asymptotic behaviour of QCD, but $G_{Ep}(t)$, as we have mentioned in Introduction, are significantly less precise at higher values of Q^2 than the data on $G_{Mp}(t)$.

On the other hand the very precise data on $\mu_p G_{Ep}(Q^2)/G_{Mp}(Q^2)$ obtained by measuring P_t and P_l of recoil proton's polarization in Jefferson Lab contradict to the prediction of the perturbation QCD (PQCD). Are then new data consistent with analyticity and other known FF properties explicitly included in the 10-resonance unitary and analytic model of nucleon EM structure [6]?

Further we consider as follows. If $G_{Ep}(Q^2)$ gives smaller and smaller contributions (at Q^2=-$t \simeq 3$ GeV^2 $G_{Ep}(t)$ contributes only 5%) to $d\sigma/d\Omega$ with increased Q^2, may be, the data on $G_{Ep}(Q^2)$ extracted by the Rosenbluth technique are completely incorrect and they have to be excluded from the analysis.

It is quite possible that the new data at the up-to-now measured interval demonstrate only finite momentum effect and they are not at all in disagreement with other existing (except for $t < 0$ $G_{Ep}(t)$) nucleon FF data and predictions of PQCD.

In order to justify this hypothesis we exclude from the compilation of the nucleon FF data all old space-like data on $G_{Ep}(t)$, then substitute them by new Jefferson Lab data on $\mu_p G_{Ep}(t)/G_{Mp}(t)$ only and analyze the latter together with all $|G_{Ep}(t)|$ time-like and $G_{Mp}(t)$, $G_{En}(t)$ and $G_{Mn}(t)$ space-like and time-like data by means of the unitary and analytic model [6], in which also QCD asymptotics of $G_{Ep}(t)$ are explicitly included. The results are surprising. Almost nothing is changed in a description of $G_{Mp}(t)$, $G_{En}(t)$ and $G_{Mn}(t)$ in both, the space-like and the time-like regions and $|G_{Ep}(t)|$ in the time-like region. However, new Jefferson Lab data on $\mu_p G_{Ep}(t)/G_{Mp}(t)$ strongly require the existence of a zero (see the full-line in Fig. 2) , i.e. the diffraction minimum in space-like region of $G_{Ep}(t)$ around $t = -Q^2 = -15$ GeV^2, which may change our present conception about the charge distribution inside of the proton.

3 Conclusions

The problem of inconsistency of $G_{Ep}(t)$ data in $t < 0$ region, obtained from $e^- p \to e^- p$ process by the Rosenbluth technique, with recent Jefferson Lab data on $\mu_p G_{Ep}(t)/G_{Mp}(t)$, obtained in precise polarization transfer $\vec{e}^- p \to e^- \vec{p}$ experiment, has been solved in the framework of the unitary and analytic model of the nucleon EM structure [6]:

The unitary and analytic model [6] manifested by small changes of its free coupling constant ratios to be enough flexible to describe separately equally well both sets, old SLAC $G_{Ep}(t)$ data obtained by Rosenbluth technique and new JLab polarization $\mu_p G_{Ep}(Q^2)/G_{Mp}(Q^2)$ data, with all other existing nucleon FF data, conserving almost unchanged behaviour of $| G_{Ep}(t) |$ in $t > 0$ region and $G_{Mp}(t), G_{En}(t)$ and $G_{Mn}(t)$ in both , $t < 0$ and $t > 0$, regions. However, as we have stressed in Introduction, the $G_{Ep}(t)$ SLAC data cannot be very reliable as $G_{Ep}(t)$ gives negligible contribution into the differential cross-section (3) with increased values of $Q^2 = -t$, from experimental behaviours of which just the $G_{Ep}(t)$ $t < 0$ data are drawn out.

On the other hand there is no doubt on the method of obtaining of new JLab polarization $\mu_p G_{Ep}(Q^2)/G_{Mp}(Q^2)$ data, but till now measured experimental points manifest violation of PQCD behaviour of $G_{Ep}(t)$. As a consequence a natural question has arisen, if $\mu_p G_{Ep}(Q^2)/G_{Mp}(Q^2)$ data are consistent with analyticity and other known FF properties, including PQCD asymptotics. A successful description of $\mu_p G_{Ep}(Q^2)/G_{Mp}(Q^2)$ data together with all other existing nucleon FF data simultaneously, besides all old $t < 0$ SLAC $G_{Ep}(t)$ data, in the framework of the unitary and analytic nucleon EM structure model convinces us that all is all right. The new JLab $\mu_p G_{Ep}(Q^2)/G_{Mp}(Q^2)$ polarization data are consistent with all known nucleon FF properties and also with all other existing nucleon FF data, besides the SLAC $t < 0$ $G_{Ep}(t)$ data. They don't contradict the PQCD asymptotics and the steeper falling of the measured $\mu_p G_{Ep}(Q^2)/G_{Mp}(Q^2)$ data can be considered to be a local effect. However, they strongly require the existence of the zero of $G_{Ep}(t)$ around $t = -15$ GeV^2.

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