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New possible insight into JLab proton polarization data puzzle by DIS

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Proton is compound of **quarks** $\Rightarrow$ **non-pointlike** - in EM interactions it **manifests EM structure** to be described (equally well neutron EM structure) by **two independent scalar functions (form factors FF's) of one variable** $t = -Q^2$, the squared four-momentum transferred by the exchanged virtual photon.

There is some **freedom in the choice of proton EM FF's**.

The most suitable in extracting of experimental information are **Sachs electric** $G_{Ep}(t)$ and **magnetic** $G_{Mp}(t)$ FF's, giving in the Breit frame the **charge and magnetization distributions** within the proton, respectively.

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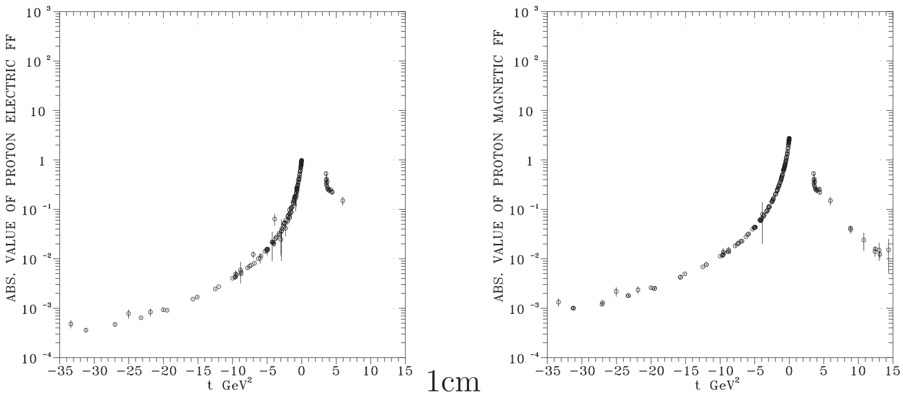


Figure 1: Experimental data on proton electric and magnetic form factors.

1.- Between the discovery of proton EM structure in the middle of the 1950's and 2000, **abundant proton EM FF data** (from DESY,SLAC and Bonn) in the space-like region ($t < 0$) appeared (see Fig.1).

They have been obtained from the measured cross section of the **elastic scattering of unpolarized electrons on unpolarized protons** in the laboratory reference frame

$$\frac{d\sigma^{lab}(e^-p \to e^-p)}{d\Omega} = \frac{\alpha^2}{4E^2}\frac{\cos^2(\theta/2)}{\sin^4(\theta/2)}\frac{1}{1+(\frac{2E}{m_p})\sin^2(\theta/2)}.$$
$$\left[A(t) + B(t)\tan^2(\theta/2)\right] \tag{1}$$

$\alpha = 1/137$, E-the incident electron energy

$$A(t) = \frac{G_{Ep}^2(t) - \frac{t}{4m_p^2}G_{Mp}^2(t)}{1 - \frac{t}{4m_p^2}}, \quad B(t) = -2\frac{t}{4m_p^2}G_{Mp}^2(t) \qquad (2)$$

by **Rosenbluth technique**.

Note:

Take notice that in (2) - the proton magnetic FF is multiplied by $-t/(4m_p^2)$ factor, i.e. as $-t$ increases, the measured cross-section (1) **becomes dominant by** $G_{Mp}^2(t)$ part contribution, making the extraction of $G_{Ep}^2(t)$ more and more difficult. As a result, **one can have confidence only in the proton magnetic FF data** obtained by the Rosenbluth technique.

2.- On the other hand, more recently at Jefferson Lab,

M.K.Jones et al, Phys. Rev. Lett. 84 (2000) 1398

O.Gayou et al, Phys. Rev. Lett. 88 (2002) 092301

measuring simultaneously **transverse**

$$P_t = \frac{h}{I_0}(-2)\sqrt{\tau(1+\tau)}G_{Mp}G_{Ep}\tan(\theta/2) \qquad (3)$$

and **longitudinal**

$$P_l = \frac{h(E+E')}{I_0 m_p}\sqrt{\tau(1+\tau)}G_{Mp}^2\tan^2(\theta/2) \qquad (4)$$

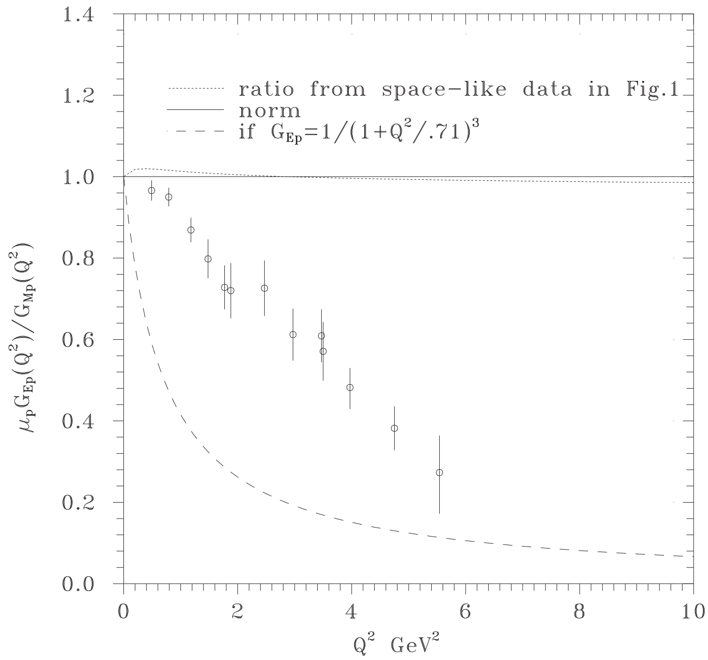


Figure 2: New JLab polarization data on the ratio $\mu_p G_{Ep}(t)/G_{Mp}(t)$

components of the **recoil proton's polarization** in the electron scattering plane of the polarization transfer process $\overrightarrow{e}^- p \to e^- \overrightarrow{p}$ (h is the electron beam helicity, I_0 is the unpolarized cross-section excluding σ_{Mott} and $\tau = Q^2/4m_p^2$) one obtained the data (see Fig.2) on

$$G_{Ep}/G_{Mp} = -\frac{P_t}{P_l}\frac{(E+E')}{2m_p}\tan(\theta/2). \qquad (5)$$

They are in strong disagreement with data obtained by Rosenbluth technique.

Important note:

The expressions (1) for $\frac{d\sigma^{lab}(e^- p \to e^- p)}{d\Omega}$ and (3), (4) for P_t, P_l, respectively, were calculated in the **one photon exchange approximation** to be justified **theoretically**

J.Pine, in Int. Symp. on Electron and Photon Interactions at High Energies, SLAC, California (1967)

as well as **experimentally**

J.Mar et al, Phys. Rev. Lett. 21 (1968) 482.

Despite of this fact - in the papers

P.A.M.Guichon, M.Vanderhaeghen, Phys. Rev. Lett. 91 (2003) 142303-1

P.G.Blunder, W.Melnitchouk, J.A.Tjon, Phys. Rev. Lett. 91 (2003) 142304-1

Y.-C.Chen et al, Phys. Rev. Lett. 93 (2004) 122301-1

it has been suggested - the additional radiative correction terms, related to **two-photon exchange corrections**, could lead to a solution of the puzzle.

The analysis revealed:

- the two-photon exchange has a much **smaller effect on the polarization transfer** than on the Rosenbluth extractions.
- the size of the two-photon exchange correction is **less than half** the size necessary to explain discrepancy

Summary of our discussion:

- experimental ratio of $\sigma(e^+p)$ to $\sigma(e^-p)$ is consistent with the value **1**
- theoretical estimates have given $[\sigma(e^+p)-\sigma(e^-p)]/[\sigma(e^+p)+\sigma(e^-p)] \leq 0.02$
- new studies of the two-photon exchange do not explain discrepancy
- $\Rightarrow$ the **one photon exchange approximation is enough precise** in both approaches to measure proton EM FF's
- however, the extraction of $G_{Ep}(Q^2)$ by the traditional **Rosenbluth technique becomes unreliable** with increased Q^2

So, we came to the conclusion that the **disagreement of ratios in Fig.2** is caused by contradicting behaviours of $G_{Ep}(Q^2)$ and on no account by $G_{Mp}(Q^2)$

We have tested this hypothesis in the framework of the **ten-resonance Unitary and Analytic model of nucleon EM structure**

S.Dubnicka, A.Z.Dubnickova, P.Weisenpacher, J. Phys. G29 (2003) 405

which is formulated in the language of **isoscalar** $F^{s,v}_{1,2}(t)$ and **isovector** $F^{s,v}_{1,2}(t)$ parts of the Dirac and Pauli FF's

$$\begin{aligned}
G^p_E(t) &= [F^s_1(t)] + F^v_1(t)] + \frac{t}{4m_p^2}[F^s_2(t) + F^v_2(t)]; \\
G^p_M(t) &= [F^s_1(t) + F^v_1(t)] + [F^s_2(t) + F^v_2(t)]; \\
G^n_E(t) &= [F^s_1(t) - F^v_1(t)] + \frac{t}{4m_n^2}[F^s_2(t) - F^v_2(t)]; \\
G^n_M(t) &= [F^s_1(t) - F^v_1(t)] + [F^s_2(t) - F^v_2(t)],
\end{aligned} \tag{6}$$

and **comprises all known nucleon FF properties** like

- ➢ experimental fact of a creation of unstable vector meson resonances in electron-positron annihilation processes into hadrons
- ➢ analytic properties of FF's
- ➢ reality conditions
- ➢ unitarity conditions
- ➢ normalizations
- ➢ asymptotic behaviours as predicted by the quark model of hadrons.

First, we have carried out the **analysis of all proton and neutron data obtained by Rosenbluth technique** together with all proton and neutron data in time-like region.

Then all $|G_{Ep}(t)|$ space-like data obtained by Rosenbluth technique were excluded and the new JLab proton polarization data on $\mu_p G_{Ep}(Q^2)/G_{Mp}(Q^2)$ for $0.49 GeV^2 \leq Q^2 \leq 5.54 GeV^2$ were analysed together with all electric proton time-like data and all space-like and time-like magnetic proton, as well as electric and magnetic neutron data.

The results are presented in Fig.3 from where three conse-

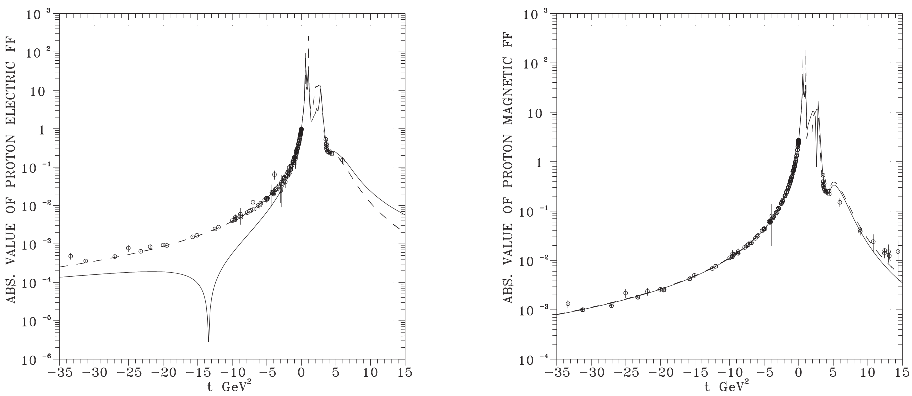


Figure 3: Theoretical behavior of proton electric and magnetic form factors.

quences follow:

- The fact, that **almost nothing is changed** in a description of $G_{Mp}(t)$, $G_{En}(t)$ and $G_{Mn}(t)$ in both, the space-like and time-like regions, and also $|G_{Ep}(t)|$ in the time-like region, confirms our hypothesis that the **discrepancy between the old and new ratios** $G_{Ep}(t)/G_{Mp}(t)$ is really **created by different behaviors** of $G_{Ep}(t)$.

- The new behavior of $G_{Ep}(t)$ (the **full line in Fig.3**) extracted from the JLab polarization data on $G_{Ep}(t)/G_{Mp}(t)$ is **consistent with all known FF properties**, including also the asymptotic behavior.

- The Jlab proton polarization data strongly require an **existence of the zero**, i.e. the diffraction minimum in the space-like region of $G_{Ep}(t)$ around $t = -Q^2 = 13GeV^2$.

Is really the new predicted $t < 0$ behavior of $G_{Ep}(t)$ in Fig.3 correct ?

It seems to us that this **question could be also verified by DIS, using the new sum rule** giving into a relation proton and neutron Dirac and Pauli FF's with a difference of the differential proton and neutron cross-sections describing Q^2 distribution in DIS.

New sum rule:

Let us consider the amplitude $\tilde{A}(s_1, \mathbf{q})$

- which by a construction is only a part of the total forward virtual Compton scattering amplitude $A(s_1, \mathbf{q})$ on nucleon
- it does not contain any crossing Feynman diagram contribution
- as a result there is no u-channel pole in s_1 plane

On the other hand, considering the **very high-energy electron-nucleon scattering**

$$e^-(p_1) + N(p) \to e^-(p_1') + X$$

with one photon exchange approximation matrix element

$$M = i\frac{\sqrt{4\pi\alpha}}{q^2}\bar{u}(p_1')\gamma_\mu u(p_1)\langle X \mid J_\nu^{QED} \mid N^{(r)}\rangle g^{\mu\nu}$$

the corresponding **cross-section** takes the form

$$d\sigma = \frac{4\pi\alpha}{s(q^2)^2} p_1^\mu p_1^\nu \times$$

$$\sum_{X \neq N} \sum_{r=-1/2}^{1/2} \langle N^{(r)} \mid J_\mu^{QED} \mid X\rangle^* \langle X \mid J_\nu^{QED} \mid N^{(r)}\rangle d\Gamma_X \qquad (7)$$

$\Rightarrow$ using the **current conservation condition**,

one can write

$$\int p_1^\mu p_1^\nu \sum_{X \neq N} \sum_{r=-1/2}^{1/2} \langle N^{(r)} \mid J_\mu^{QED} \mid X\rangle^* \times$$

$$\langle X \mid J_\nu^{QED} \mid N^{(r)}\rangle d\Gamma_X = 2i \frac{s^2}{s_1^2} \mathbf{q^2} Im \tilde{A}^{(N)}(s_1, \mathbf{q}) \qquad (8)$$

with

$d\Gamma_X = (2\pi)^4 \delta^4(q + p - \sum_j p_j) \prod_j \frac{d^3 p_j}{2\varepsilon_j (2\pi)^3}$, $s = (p_1 + p)^2$, $s_1 = 2(qp)$ and $\mathbf{q^2} = Q^2$.

Now, integrating the cross-section (7) **over the phase-space volume of the final hadronic state** X, substituting the expression (8) into (7) and integrating it now **over the invariant mass squared** m_X^2, to be interested only in **q distribution**,

$\Rightarrow$ **for a difference of differential proton and neutron electroproduction cross-sections** one finds

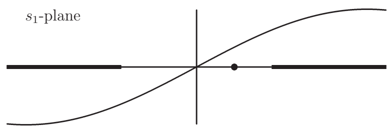
$$(\mathbf{q^2})^2 \left(\frac{d\sigma^{e^- p \to e^- X}}{d\mathbf{q^2}} - \frac{d\sigma^{e^- n \to e^- X}}{d\mathbf{q^2}} \right) = \tag{9}$$

$$\frac{\alpha}{4\pi}\mathbf{q^2} \int\limits_{2m_N m_\pi + m_\pi^2 + \mathbf{q^2}}^{\infty} \frac{ds_1}{s_1^2} \left[Im\tilde{A}^{(p)}(s_1, \mathbf{q}) - Im\tilde{A}^{(n)}(s_1, \mathbf{q}) \right].$$

If one defines the **path integral** in s_1 plane

$$I = \int\limits_C ds_1 \frac{p_1^\mu p_1^\nu}{s^2} \left(\tilde{A}^{(p)}_{\mu\nu}(s_1, \mathbf{q}) - \tilde{A}^{(n)}_{\mu\nu}(s_1, \mathbf{q}) \right) \tag{10}$$

as presented in Fig.4a



a

b

Figure 4: Sum rule interpretation in s_1 plane.

then once the contour C is closed to upper half-plane, another one to lower half-plane (Fig.4b) and considering (8), the following sum rule

$$\pi\left(\mathrm{Res}^{(n)} - \mathrm{Res}^{(p)}\right) = \mathbf{q}^2 \int\limits_{r.h.}^{\infty} \frac{ds_1}{s_1^2}\left(Im\tilde{A}^{(p)}(s_1,\mathbf{q}) - Im\tilde{A}^{(n)}(s_1,\mathbf{q})\right) \tag{11}$$

appears with (an averaging through the initial nucleon and photon spins is performed)

$$Res^{(N)} = 2\pi\alpha\left(F_{1N}^2 + \frac{\mathbf{q}^2}{4m_N^2}F_{2N}^2\right) \tag{12}$$

to be the **one-nucleon intermediate state pole contribution** and the left-hand ($l.h.$) cut contributions from the difference $\left(Im\tilde{A}^{(p)} - Im\tilde{A}^{(n)}\right)$ are mutually annulated.

Substituting (12) into (11), taking into account the Eq.(9) and renormalizing the left-hand side of (11) one gets

new sum rule

$$1 + F_{1n}^2(-\mathbf{q}^2) + \frac{\mathbf{q}^2}{4m_n^2} F_{2n}^2(-\mathbf{q}^2)$$
$$-F_{1p}^2(-\mathbf{q}^2) - \frac{\mathbf{q}^2}{4m_p^2} F_{2p}^2(-\mathbf{q}^2) = \tag{13}$$
$$2\frac{(\mathbf{q}^2)^2}{\pi\alpha^2}\left(\frac{d\sigma^{e^-p\to e^-X}}{d\mathbf{q}^2} - \frac{d\sigma^{e^-n\to e^-X}}{d\mathbf{q}^2}\right),$$

giving into a **relation**:

- **nucleon electromagnetic form factors**
- with **difference of deep inelastic electron-proton and electron-neutron differential cross-sections**.

By measurements of the right hand side of (13):

- one could verify the **general validity of the new sum rule**
- by comparison of the left hand side, using Dirac and Pauli FF's corresponding to the old and new behaviors of $G_{Ep}(t)$, the **true $t < 0$ behavior of the electric proton FF could be chosen**.