Manifestation of the JLab proton polarization data on the behaviour of strange nucleon form factors

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Abstract

Special eight-resonance unitary and analytic model of nucleon electromagnetic structure is used to analyze, first the classical proton form factor data obtained by the Rosenbluth technique and then also the contradicting JLab proton polarization data on the ratio $\mu_p G_{Ep}(Q^2)/G_{Mp}(Q^2)$ with the aim to investigate a manifestation of the latter on the strange nucleon form factors behaviour.

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Owing to the quark structure of proton and neutron one doesn’t know explicit form of the nucleon matrix element of the electromagnetic (EM) current $J^{EM}_\mu = \frac{2}{3}\bar{u}\gamma_\mu u - \frac{1}{3}\bar{d}\gamma_\mu d - \frac{1}{3}\bar{s}\gamma_\mu s$ and as a result two independent scalar functions, called nucleon EM form factors (FF’s), of the squared four-momentum $t = -Q^2$, transferred by the exchanged virtual photon are introduced for proton and neutron, respectively. Very natural is an introduction of Dirac $F^{1}_{N}(t)$ and Pauli $F^{2}_{N}(t)$ FF’s

$$< N | J^{EM}_\mu | N > = \bar{u}(p')\{\gamma_\mu F^{1}_N(t) + i\frac{\sigma_{\mu\nu}q_\nu}{2m_N}F^{2}_N(t)\}u(p). \quad (1)$$

The most suitable in extracting of experimental information are Sachs electric $G_{EN}(t)$ and magnetic $G_{MN}(t)$ FF’s

$$G_{EN}(t) = F^{1}_N(t) + \frac{t}{4m_N^2}F^{2}_N(t), \quad G_{MN}(t) = F^{1}_N(t) + F^{2}_N(t) \quad (2)$$
giving in the Breit frame the charge and magnetization distributions within the nucleon, respectively. However, for a construction of various models of nucleon EM structure the isoscalar and isovector Dirac and Pauli FF’s, to be defined by the matrix elements

$$\langle p' | J^{I=0}_\mu | p \rangle = \bar{u}(p')\left[\gamma_\mu F^{I=0}_1(t) + i\frac{\sigma_{\mu\nu}q_\nu}{2m_N}F^{I=0}_2(t)\right]u(p) \quad (3)$$

of the isoscalar EM current $J^{I=0}_\mu = 1/6(\bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d) - 1/3\bar{s}\gamma_\mu s$ and

$$\langle p' | J^{I=1}_\mu | p \rangle = \bar{u}(p')\left[\gamma_\mu F^{I=1}_1(t) + i\frac{\sigma_{\mu\nu}q_\nu}{2m_N}F^{I=1}_2(t)\right]u(p) \quad (4)$$

of the isovector EM current $J^{I=1}_\mu = 1/2(\bar{u}\gamma_\mu u - \bar{d}\gamma_\mu d)$, are the most appropriate.

One of the important tasks of modern hadron physics is to clarify the role of hidden flavours in the structure of the nucleon. The contribution of
the strange quarks is of special interest as their mass is within the range of
the mass scale of QCD ($m_s \approx \Lambda_{QCD}$), so the dynamic creation of sea strange
quark-antiquark pairs could still be dominating in comparison with heavier
c, b and t quark-antiquarks pairs creation.

The momentum dependence of the nucleon matrix element of the strange-
quark vector current $J_{\mu}^s = \bar{s} \gamma_{\mu} s$ is contained in the Dirac $F_1^s(t)$ and Pauli $F_2^s(t)$
strange nucleon FF’s

$$\langle p' | \bar{s} \gamma_{\mu} s | p \rangle = \bar{u}(p') \left[ \gamma_{\mu} F_1^s(t) + i \frac{\sigma_{\mu\nu} q^\nu}{2m_N} F_2^s(t) \right] u(p)$$ (5)

or in the strange electric $G_E^s(t)$ and strange magnetic $G_M^s(t)$ FF’s

$$G_E^s(t) = F_1^s(t) + \frac{t}{4m_N^2} F_2^s(t), \quad G_M^s(t) = F_1^s(t) + F_2^s(t),$$ (6)

which, as a consequence of the isospin zero value of the strange quark, con-
tribute only to the behaviour of the isoscalar nucleon FF’s and never to
isovector ones.

Recent measurements [1]-[3] of recoil polarization in elastic scattering
of polarized electrons on unpolarized protons at JLab have been used to ex-
tract data on the ratio $\mu_p G_{Ep}(Q^2)/G_{Mp}(Q^2)$ for $0.49 GeV^2 \leq Q^2 \leq 5.54 GeV^2$,
which disagree with Rosenbluth extractions from cross-section measurements.
Taking into account the dominance of $G_{Mp}(t)$ in the unpolarized cross-
section, we believe the behaviour of $G_{Ep}(t)$ is responsible for this discrepancy.
As a result there are two sets of experimental data on nucleon EM FF’s, dif-
fering from each other by the different spacelike behaviour of $G_{Ep}(t)$. Further
we will predict from them strange nucleon FF’s behaviours by the specific
eight-resonance unitary and analytic model and look for distinctive features.
The main idea [4] of the prediction of strange nucleon FF’s behaviours is based on two assumptions:

- on the $\omega - \phi$ mixing to be valid also for coupling constants between EM (quark) current and vector-mesons

\[
\begin{align*}
\frac{1}{f_{\omega}} &= \frac{1}{f_{\omega_0}} \cos \epsilon - \frac{1}{f_{\phi_0}} \sin \epsilon \\
\frac{1}{f_{\phi}} &= \frac{1}{f_{\omega_0}} \sin \epsilon + \frac{1}{f_{\phi_0}} \cos \epsilon \\
\end{align*}
\]  

(7)

- on the assumption that the quark current of some flavour couples with universal strength $\kappa$ exclusively to the vector-meson wave function component of the same flavour

\[
\langle 0|\bar{q}_t \gamma q_t|(\bar{q}_t q_t)_V \rangle = \kappa m_V^2 \delta_{rt} \delta_{\mu},
\]  

(8)

which result in the relations

\[
\begin{align*}
(f_{\omega NN}/f_{\omega}) &= -\sqrt{6} \frac{\sin \epsilon}{\sin(\epsilon + \theta_0)} (f_{\omega NN}/f_{\omega}) \\
(f_{\phi NN}/f_{\phi}) &= -\sqrt{6} \frac{\cos \epsilon}{\cos(\epsilon + \theta_0)} (f_{\phi NN}/f_{\phi}) \\
\end{align*}
\]  

(9)

\[i = 1, 2\]

where $f_{\omega}^s, f_{\phi}^s$ are strange-current $\leftrightarrow V = \omega, \phi$ coupling constants and $\epsilon = 3.7^0$ is a deviation from the ideally mixing angle $\theta_0 = 35.3^0$.

So, if one knows from the fit of nucleon FF data free parameters $(f_{\omega NN}/f_{\omega})$, $(f_{\phi NN}/f_{\phi})$ (i=1,2) of the suitable eight-resonance model for isoscalar parts
of the Dirac and Pauli FF’s

\[
F_{1}^{t=0}[V(t)] = \left(1 - \frac{V^2}{1 - V_N^2}\right)^4 \left\{ \frac{1}{2} L(V_{\omega''})L(V_{\omega'}) + \right.
\]
\[
\left[ L(V_{\omega''})L(V_{\omega}) \left( \frac{C_{\omega''} - C_{\omega}}{C_{\omega''} - C_{\omega'}} \right) - L(V_{\omega'})L(V_{\omega}) \left( \frac{C_{\omega'} - C_{\omega}}{C_{\omega''} - C_{\omega'}} \right) - \right.
\]
\[
L(V_{\omega''})L(V_{\omega'}) \left( \frac{f_{\omega NN}^{(1)}}{f_{\omega}^{(e)}} \right) +
\]
\[
\left[ L(V_{\omega''})L(V_{\omega}) \left( \frac{C_{\omega''} - C_{\phi}}{C_{\omega''} - C_{\omega'}} \right) - L(V_{\omega'})L(V_{\omega}) \left( \frac{C_{\omega'} - C_{\phi}}{C_{\omega''} - C_{\omega'}} \right) - \right.
\]
\[
L(V_{\omega''})L(V_{\omega'}) \left( \frac{f_{\phi NN}^{(1)}}{f_{\phi}^{(e)}} \right) \right\}
\]

(10)

\[
F_{2}^{t=0}[V(t)] = \left(1 - \frac{V^2}{1 - V_N^2}\right)^6 \left\{ L(V_{\omega''})L(V_{\omega'})L(V_{\omega}) \right.
\]
\[
\left[ 1 - \frac{C_{\omega}}{C_{\omega''} - C_{\omega'}} \left( \frac{C_{\omega''} - C_{\omega}}{C_{\omega'} - C_{\omega'}} \right) - \right.
\]
\[
\left( \frac{f_{\omega NN}^{(2)}}{f_{\omega}^{(e)}} \right) + L(V_{\omega''})L(V_{\omega'})L(V_{\omega}) \right.
\]
\[
\left[ 1 - \frac{C_{\phi}}{C_{\omega''} - C_{\omega'}} \left( \frac{C_{\omega''} - C_{\phi}}{C_{\omega'} - C_{\omega'}} \right) - \right.
\]
\[
\left( \frac{f_{\phi NN}^{(2)}}{f_{\phi}^{(e)}} \right) \right\}
\]

(11)

with

\[
L(V_{r}) = \frac{(V_N - V_r)(V_N - V_r^*)(V_N - 1/V_r)(V_N - 1/V_r^*)}{(V - V_r)(V - V_r^*)(V - 1/V_r)(V - 1/V_r^*)},
\]

\[
(r = \omega, \phi, \omega', \omega'')
\]

\[
C_r = \frac{(V_N - V_r)(V_N - V_r^*)(V_N - 1/V_r)(V_N - 1/V_r^*)}{-(V_r - 1/V_r)(V_r^* - 1/V_r^*)},
\]

\[
(r = \omega, \phi, \omega', \omega'')
\]

\[
V(t) = i \sqrt{\left[ \frac{[t_{NN} - t_{N \omega}^0]}{t_{0 \omega}^0} \right]^{1/2} + \left[ \frac{[t_{NN} - t_{N \phi}^0]}{t_{0 \phi}^0} \right]^{1/2} - \left[ \frac{[t_{NN} - t_{N \omega'}^0]}{t_{0 \omega'}^0} \right]^{1/2} - \left[ \frac{[t_{NN} - t_{N \omega''}^0]}{t_{0 \omega''}^0} \right]^{1/2}}
\]

(12)
\[ V_N = V(t)_{|t=0}; \quad V_r = V(t)_{|t=(m_r - m_r/2)^2}; \quad (r = \omega, \phi, \omega', \omega''). \quad (13) \]

and \( t_{N\bar{N}} = 4m_N^2 \), then the unknown free parameters \( (f^{(i)}_{\omega NN}/f_\omega^s), (f^{(i)}_{\phi NN}/f_\phi^s) \) of the strange nucleon FF’s model

\[
F_1^s[V(t)] = \left( \frac{1 - V^2}{1 - V_N^2} \right)^4 \left\{ \begin{align*}
[L(V_{\omega}) L(V_{\omega})] & \frac{(C_{\omega''} - C_{\omega}) (C_{\omega} - C_{\omega'})}{(C_{\omega''} - C_{\omega'})} - L(V_{\omega'}) L(V_{\omega'}) \frac{(C_{\omega'} - C_{\omega})}{(C_{\omega''} - C_{\omega'})} - \\
L(V_{\omega}) L(V_{\omega'}) \right\} \left[ f_{\omega NN}^{(1)} / f_\omega^s \right] + \\
[L(V_{\omega'}) L(V_{\phi})] & \frac{(C_{\omega''} - C_{\phi}) (C_{\phi} - C_{\omega'})}{(C_{\omega''} - C_{\omega'})} - L(V_{\omega'}) L(V_{\phi'}) \frac{(C_{\omega'} - C_{\phi})}{(C_{\omega''} - C_{\omega'})} - \\
L(V_{\omega}) L(V_{\omega'}) \right\} \left[ f_{\phi NN}^{(1)} / f_\phi^s \right]
\]

\[
F_2^s[V(t)] = \left( \frac{1 - V^2}{1 - V_N^2} \right)^6 \left\{ \begin{align*}
[L(V_{\omega''}) L(V_{\omega'''})] & \frac{(C_{\omega''} - C_{\omega}) (C_{\omega} - C_{\omega'})}{(C_{\omega''} - C_{\omega'})} - \\
[L(V_{\omega'}) L(V_{\omega'})] & \frac{(C_{\omega'} - C_{\omega})}{(C_{\omega''} - C_{\omega'})} - \\
L(V_{\omega}) L(V_{\omega}) \right\} \left[ f_{\omega NN}^{(2)} / f_\omega^s \right] + \\
[L(V_{\omega''}) L(V_{\omega''})] & \frac{(C_{\omega''} - C_{\phi}) (C_{\phi} - C_{\omega'})}{(C_{\omega''} - C_{\omega'})} - \\
[L(V_{\omega'}) L(V_{\omega'})] & \frac{(C_{\omega'} - C_{\phi})}{(C_{\omega''} - C_{\omega'})} - \\
L(V_{\omega}) L(V_{\omega}) \right\} \left[ f_{\phi NN}^{(2)} / f_\phi^s \right]
\]

of the same analytic structure, but with different normalization of the Dirac FF, are calculated by the relations \( (9) \).

The expressions \( (10) \) and \( (11) \) for \( F_1^{l=0}, F_2^{l=0} \), together with similar expressions \( 5 \) for \( F_1^{l=1}, F_2^{l=1} \) to be saturated by \( \rho, \rho', \rho'', \rho''' \) isovector vector-mesons, have been used

- first to describe Rosenbluth \( G_{Ep}(t) \) data in \( t < 0 \) region together with all other existing nucleon EM FF data with the result \( \chi^2/(ndf) = 1.76 \).
then instead of the Rosenbluth $G_{Ep}(t)$ data in $t < 0$ region the JLab proton polarization data on $\mu_p G_{Ep}(Q^2)/G_{Mp}(Q^2)$ for $-5.54 GeV^2 \leq t \leq -0.49 GeV^2$ together with all other existing nucleon EM FF data were analyzed with the result $\chi^2/(ndf) = 1.34$.

Finally, the strange coupling constant ratios $(f^{(i)}_{\omega NN}/f^{(5)}_{\omega})$, $(f^{(i)}_{\phi NN}/f^{(5)}_{\phi})$ according to the prescribed procedure given by (9) were calculated and the behaviour of $G^s_E(Q^2)$, $G^s_M(Q^2)$ by means of (14) and (15), as presented in Fig.1, are predicted. As one can see from Fig.1b, a reasonable positive value of the strangeness nucleon magnetic moment is found to be $\mu_s = +0.19[\mu_N]$.

A reasonable description of the recent data [6] on the combination $G^s_E(Q^2) + \eta(Q^2)G^s_M(Q^2)$ for $0.12 GeV^2 < Q^2 < 1.0 GeV^2$ is achieved (see Fig.2) as well. Similar results were obtained also by Bijker [7] recently, exploiting very simple parametrization [8] of the nucleon EM FF in the spacelike region.

As one can see from Figs.1 and 2, the predicted behaviour of the strange
Figure 2: Predicted combination $G_E^0(Q^2) + \eta(Q^2)G_M^0(Q^2)$ from Rosenbluth and JLab data by 8-resonance U&A model and its comparison with the $G0$ collaboration data.

nucleon FF’s by the special eight-resonance unitary and analytic model doesn’t feel too much the difference in contradicting behaviours of $G_{Ep}(t)$ in the spacelike region.

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