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Proton electromagnetic form factors at large momentum transfer

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Abstract. We review the current experimental and theoretical status of the proton electromagnetic form factors.

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1. Introduction

The electromagnetic form factors of hadrons provide us with fundamental information about their internal structure. The form factors are measured by elastic scattering of electrons with target protons. The process is assumed to be dominated by one-photon exchange. The basic kinematic variables are shown in figure 1. Here k, k' are initial and final state electron momenta and p, p' the corresponding proton momenta. Since the electron vertex is well-known, one can reliably extract the proton electromagnetic vertex Γ^μ by such an experiment. The vertex can be parametrized in terms of two form factors F_1 and F_2,

$$\Gamma_\mu(p,p') = \gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2M}\kappa_{\rm p}F_2(q^2), \tag{1}$$

where M is the proton mass, $\kappa_{\rm p}$ its anomalous magnetic moment and $q = k - k'$ the momentum transfer. In the t-channel process $q^2 < 0$. We also define $Q^2 = -q^2 \geq 0$. The form factors are functions of q^2 and basically describe the modification of the proton electromagnetic vertex due to strong interactions. The functions F_1 and F_2 are referred to as the Dirac and Pauli form factors respectively. The Pauli form factor describes the amplitude for chirality flip at the electromagnetic vertex.

Besides the form factors F_1 and F_2, it is also convenient to define the electric and magnetic form factors (or the Sachs form factors) $G_{\rm E}$ and $G_{\rm M}$ which are more suitable for experimental extraction,

$$G_{\rm E}(Q^2) = F_1(Q^2) - \tau\kappa_p F_2(Q^2),$$
$$G_{\rm M}(Q^2) = F_1(Q^2) + \kappa_p F_2(Q^2), \tag{2}$$

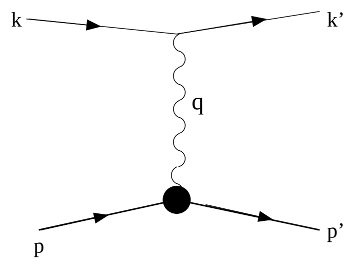

Figure 1. The one-photon exchange diagram contributing to the elastic electron–proton scattering. Here k, k' refer to electron momenta and p, p' to the proton momenta.

where $\tau = Q^2/4M^2$. At $Q^2 = 0$, $F_1 = F_2 = 1$ and $G_{\rm E} = G_{\rm M}/\mu_{\rm p} = 1$, where $\mu_{\rm p}$ is the magnetic moment of the proton. The form factor $G_{\rm M} \approx \mu_{\rm p} G_{\rm D}$ where $G_{\rm D}$ is the dipole function,

$$G_{\rm D} = \frac{1}{(1+\frac{Q^2}{0.71})^2}. \tag{3}$$

At low momenta, $G_{\rm E}$ is also approximately equal to $G_{\rm D}$. At large momenta, $Q^2 \gg 1$ GeV^2,

$$G_{\rm M}, F_1 \propto \frac{1}{Q^4}. \tag{4}$$

The experimental status of $G_{\rm E}$ and F_2 are, however, currently unclear at large momentum transfer.

2. Rosenbluth separation

The standard technique for the extraction of proton form factors is through Rosenbluth separation [1]. Here one considers the unpolarized elastic scattering of electrons on target protons. In the one-photon exchange approximation the cross-section can be written as

$$\frac{{\rm d}\sigma}{{\rm d}\Omega} = \frac{\sigma_{\rm Mott}}{\epsilon(1+\tau)}\left[\tau G_{\rm M}^2(Q^2) + \epsilon G_{\rm E}^2(Q^2)\right], \tag{5}$$

where $\epsilon = 1/[1+2(1+\tau)\tan^2(\theta_{\rm e}/2)]$ is the longitudinal polarization of the photon and $\theta_{\rm e}$ is the electron scattering angle. One finds that the reduced cross-section $\sigma_{\rm R} = \tau G_{\rm M}^2(Q^2) + \epsilon G_{\rm E}^2(Q^2)$ depends linearly on ϵ. By making a linear fit to the observed $\sigma_{\rm R}$ as a function ϵ at fixed Q^2, one can, therefore, extract both $G_{\rm M}$ and $G_{\rm E}$. At large Q^2, $G_{\rm M}$ dominates at all values of ϵ. Hence the uncertainty in the extraction of $G_{\rm E}$ can be large at large Q^2. Recent results for Rosenbluth separation are available from SLAC in 1994 [2] and much more precisely from JLAB in 2004 [3]. The SLAC data show that $(\mu_p G_E/G_M) \approx 1$ up to momentum transfer $Q^2 \approx 6$ GeV^2. The JLAB data are available at $Q^2 = 2.64, 3.20$ and 4.10 GeV^2 and show a similar trend. This result also implies that the ratio $F_2/F_1 \propto 1/Q^2$.

3. Polarization transfer

A direct extraction of the ratio G_E/G_M is possible by elastic scattering of longitudinally polarized electrons on target proton $\vec{e} + p \to e + \vec{p}$ [4]. In the one-photon exchange approximation, the recoil proton acquires only two polarization components, P_l, parallel to the proton momentum and P_t, perpendicular to the proton momentum in the scattering plane. The ratio

$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{E_e + E'_e}{2M}\tan\left(\frac{\theta_e}{2}\right), \tag{6}$$

where E_e and E'_e are the energies of the initial and final electron. This technique, therefore, directly yields the ratio G_E/G_M. The results [5,6], available from JLAB, show $\mu_p G_E/G_M$ decreases with Q^2. A straight line fit to the data gives

$$\frac{\mu_p G_E}{G_M} = 1 - 0.13(Q^2 - 0.04) \tag{7}$$

in the momentum range $0.5 < Q^2 < 5.6$ GeV^2. The ratio, therefore, becomes as small as 0.2 at $Q^2 = 5.6$ GeV^2, the maximum momentum transfer in this experiment. The polarization transfer results also imply that $QF_2/F_1 \sim 1$ for $Q^2 > 1$ GeV^2. The observed trend in the polarization transfer experiment is, therefore, completely different from what is measured using the Rosenbluth separation. This is clearly a serious problem and has attracted considerable attention in the literature.

4. Higher order corrections

An obvious source of error is the higher order corrections to the elastic scattering process. A reliable extraction of the form factors requires a careful treatment of the radiative corrections including the soft photon emission, which give a significant correction to the cross-section [7,8]. These contributions are calculated by keeping only the leading order terms in the soft photon momentum. Furthermore, only the infra-red divergent terms, which are required to cancel the divergences in the soft photon emission, are included in the radiative corrections. It is possible that the terms not included in these calculation may be responsible for the observed difference. Any such correction is likely to be small and hence cannot significantly change the results of the polarization transfer experiment. However, a small correction to the Rosenbluth separation could imply a large correction to the extracted form factor G_E. A possible correction is the two-photon exchange diagram which has attracted considerable attention in the literature [9–13]. Such a diagram is taken into account while computing the radiative corrections, but only the infra-red divergent contribution is included. It is possible that the remaining contribution gives a significant correction. One may also consider next to leading order corrections in the soft photon momenta to the soft photon emission diagrams. Both of these contributions receive unknown hadronic corrections and cannot be calculated in a model independent manner.

4.1 *Two-photon exchange*

The two-photon exchange contribution has received considerable attention in the literature. In ref. [9] the authors made the most general decomposition of the electron–proton elastic scattering amplitude in the limit of zero electron mass. The scattering matrix T can be written as

$$T = \frac{e^2}{Q^2}[\bar{u}(k')\gamma_\mu u(k)]\ \bar{u}(p')\left[\tilde{G}_{\rm M}\gamma^\mu - \tilde{F}_2\frac{P^\mu}{M} + \tilde{F}_3\frac{\not{K}}{M^2}P^\mu\right]u(p), \tag{8}$$

where $P = (p + p')/2$, $K = (k + k')/2$ and $\tilde{G}_{\rm M}$, $\tilde{F}_2$ and $\tilde{F}_3$ are complex functions of $\nu = \vec{K} \cdot \vec{P}$ and Q^2. Then, making simplifying assumptions, they obtain these generalized form factors by fitting the data. Their results suggest that two-photon exchange diagram can provide an explanation for the observed discrepancy. It was further argued in ref. [10] that additional constraints can be imposed on these generalized form factors by considering positron proton elastic scattering. The two-photon contribution has also been obtained by model calculations in refs [11,12]. The authors find that they are able to partially reconcile the discrepancy. However, the results of Afanasev *et al* [12] show that the predicted Rosenbluth plots are no longer linear in ϵ. This clearly is a problem since the experimental results show no evidence of deviation from linearity. In ref. [13] the authors argue, using charge conjugation and crossing symmetry, that two-photon exchange contribution must necessarily be nonlinear in ϵ. If this is confirmed then it will rule out two-photon exchange as an explanation of the observed anomaly. We are currently using the nonlocal field theoretic framework to calculate the two-photon exchange contributions [14].

5. Theoretical calculations

Theoretically the form factors may be described by the Brodsky–Lepage [15] short distance formalism. It is expected to work at sufficiently large Q^2. The formalism is based on the assumption that the exclusive hadronic processes at large momentum transfer are dominated by short distance amplitudes. However, the precise value of Q^2 where it may be applicable is not known. The formalism predicts $F_1 \propto 1/Q^4$ and $F_2/F_1 \propto 1/Q^2$. However, there are many indications that the formalism is not really applicable at laboratory momenta. For example, the observed color transparency ratio does not agree with the theoretical expectations of the short distance model [16]. Furthermore, a leading-order perturbative QCD calculation of the color transparency ratio for $eA \to e'p(A-1)$ scattering predicted an almost flat transparency ratio as a function of Q^2 [17], in agreement with experimental observations [18] but not with the predictions of the short distance model [16]. The observed ratio $F_2/F_1 \propto 1/Q$ in the polarization transfer experiment [5,6] is also in disagreement with the short distance predictions. It was recently argued in refs [19,20] that this result can be explained if we invoke the quark orbital angular momentum and do not impose short distance domination. By assuming the presence of large distance amplitudes the observed color transparency results can also be explained naturally.

6. Conclusions

Recent experimental observations of proton electromagnetic form factors have revealed several surprises, with different methods of extraction giving different results. This anomaly may be explained in terms of two-photon exchange processes. The theoretical calculations performed so far indicate that the two-photon contribution gives a significant correction to the extracted ratio $G_{\mathrm{E}}/G_{\mathrm{M}}$. However it is not clear so that the correction may explain the data. Furthermore the form factor ratio obtained by the polarization transfer experiment, which is likely to be very reliable, is in disagreement with expectations of the Brodsky–Lepage short distance model. This result, therefore, provides another evidence for the failure of this model. The observed ratio provides a very good evidence for the presence of quark orbital angular momentum in the proton.

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