NUCLEON ELECTROMAGNETIC FORM FACTORS

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Abstract. We review data for nucleon electromagnetic form factors, emphasizing recent measurements of $G_E/G_M$ that use recoil or target polarization to minimize systematic errors and model dependence. The data are parametrized in terms of densities that are consistent with the Lorentz contraction of the Breit frame and with pQCD. The dramatic linear decrease in $G_{Ep}/G_{Mp}$ for $1 \leq Q^2 \leq 6 \text{(GeV/c)}^2$ demonstrates that the charge is broader than the magnetization of the proton. High precision recoil polarization measurements of $G_{En}$ show clearly the positive core and negative surface charge of the neutron. Combining these measurements, we display spatial densities for $u$ and $d$ quarks in nucleons.

1. Introduction

The electromagnetic structure of nucleons provides fundamental tests of the QCD confinement mechanism, as calculated on the lattice or interpreted with the aid of models. From elastic electron scattering one obtains the Sachs electric and magnetic form factors, which are closely related to the charge and magnetization densities. Dramatic improvements in the quality of these measurements have recently been achieved by using beams that combine high polarization with high intensity and energy together with either polarized targets or measurements of recoil polarization. In this paper we review the current status of nucleon elastic form factors, emphasizing recent polarization measurements, and analyze these data using a model that permits visualization of the underlying charge and magnetization densities.

Matrix elements of the nucleon electromagnetic current operator $J^\mu$ take the form

$$\langle N(p', s')|J^\mu|N(p, s)\rangle = \bar{u}(p', s')\gamma^\mu u(p, s)$$  \hspace{1cm} (1)
where \( u \) is a Dirac spinor, \( p, p' \) are initial and final momenta, \( q = p - p' \) is the momentum transfer, \( s, s' \) are spin four-vectors, and where the vertex function
\[
\Gamma^\mu = F_1(Q^2)\gamma^\mu + \kappa F_2(Q^2) \frac{i\sigma^{\mu\nu} q_\nu}{2m}
\]
(2)
features Dirac and Pauli form factors, \( F_1 \) and \( F_2 \), that depend upon the nucleon structure. Here \( e \) is the elementary charge, \( m \) is the nucleon mass, \( \kappa \) is the anomalous part of the magnetic moment, and \( \gamma^\mu \) and \( \sigma^{\mu\nu} \) are the usual Dirac matrices (e.g., [1]). The interpretation of these form factors appears simplest in the nucleon Breit frame where the energy transfer vanishes. In this frame the nucleon approaches with initial momentum \(-\vec{q}_B/2\), receives three-momentum transfer \( \vec{q}_B \), and leaves with final momentum \( \vec{q}_B/2 \). Thus, the nucleon Breit frame momentum is defined by \( q_1^2 = Q_2^2 = q_1^2/(1 + \tau) \) where \((\omega, \vec{q})\) is the momentum transfer in the laboratory, \( Q_2^2 = q_1^2 - \omega^2 \) is the spacelike invariant four-momentum transfer, and \( \tau = Q_2^2/4m^2 \). In the Breit frame for a particular value of \( Q_2^2 \), the current separates into electric and magnetic contributions [2]
\[
\bar{u}(p', s') \Gamma^\mu u(p, s) = \chi_{s'}^\dagger \left( G_E + \frac{i\vec{\sigma} \times \vec{q}_B}{2m} G_M \right) \chi_s
\]
(3)
where \( \chi_s \) is a two-component Pauli spinor and where the Sachs form factors are given by
\[
G_E = F_1 - \tau\kappa F_2 \quad G_M = F_1 + \kappa F_2
\]
(4)
Early experiments with modest \( Q_2^2 \) suggested that
\[
G_{Ep} \approx \frac{G_{Mp}}{\mu_p} \approx \frac{G_{Mn}}{\mu_n} \approx G_D
\]
(5)
where \( G_D(Q^2) = (1 + Q^2/\Lambda^2)^{-2} \) with \( \Lambda^2 = 0.71 \) (GeV/c)^2 is known as the dipole form factor [3, 4].

2. Form Factors from Polarization Measurements

In the one-photon exchange approximation, the differential cross section for elastic scattering of an electron beam from a stationary nucleon target is given by
\[
\frac{d\sigma}{d\Omega} = \frac{\sigma_{NS}}{e(1 + \tau)} \left( \tau G_M^2 + eG_E^2 \right)
\]
(6)
where \( e = (1 + (1 + \tau)2 \tan^2 \theta_e/2)^{-1} \) is the transverse polarization of the virtual photon for electron scattering angle \( \theta_e \) and \( \sigma_{NS} \) is the cross section for a structureless Dirac target. Thus, the traditional Rosenbluth technique separates the electric and magnetic form factors by varying \( e \), but extraction