

Nucleon electromagnetic and axial-vector form factors.

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The vector and axial-vector nucleon form factors ($G_{E,M}^{p,n}(Q^2)$ and $G_A^{p,n}(Q^2)$) using the spin observables in the chiral constituent quark model (χ CQM) have been evaluated in light of the improved precision of the experimental measurements and enormous theoretical progress to understand the dynamical behavior of nucleons emerging from the theory of strong interactions between quarks. The Q^2 dependence of the vector and axial-vector form factors of the nucleon has been studied using the conventional dipole form of parametrization.

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One of the fundamental goals of particle physics is to understand the flavor-spin structure and behavior of strongly interacting matter in terms of its basic constituents, quarks and gluons. Confinement has limited our knowledge on the composition of hadrons and the understanding of their internal structure continues to remain a major unresolved problem in high energy spin physics. The deep inelastic scattering (DIS) experiments with polarized beams and/or targets is an useful probe of calculating the spin carried by the quarks in the nucleon [1, 2, 3, 4]. The electromagnetic form factors are among the most basic quantities containing information about the internal structure of the nucleons. Further, during the last few years, the standard electroweak theory has provided a firm basis for the role of weak interaction as a precision probe of the nucleon structure [5, 6, 7].

The hadronic matrix element of the electromagnetic current operators for a spin- $\frac{1}{2}$ nucleon with internal structure can be expressed in terms of the Dirac and Pauli form factors $F_1^{N,\gamma}$ and $F_2^{N,\gamma}$ ($N = p, n$) which are further related to the electric and magnetic Sachs form factors $G_E^{N,\gamma}(Q^2)$ and $G_M^{N,\gamma}(Q^2)$. The quark flavor structure of these form factors can be revealed from the matrix elements of individual quark currents in terms of form factors F_1^q and F_2^q ($j = u, d, \text{ or } s$). The nucleon form factors can be expressed in terms of the individual quark form factors with the electric charge of individual quarks as the coupling constants.

The hadronic matrix element of the neutral weak current operators for a spin- $\frac{1}{2}$ nucleon can be expressed in terms of the vector form factors $F_1^{N,Z}$ and $F_2^{N,Z}$ as well as the axial form factor $G_A^{N,Z}$ which can be expressed in terms of the individual quark form factors as

$$G_{E,M}^{p,Z}(Q^2) = \left(1 - \frac{8}{3} \sin^2 \theta_W\right) G_{E,M}^u(Q^2) + \left(-1 + \frac{4}{3} \sin^2 \theta_W\right) \left(G_{E,M}^d(Q^2) + G_{E,M}^s(Q^2)\right), \quad (1)$$

$$G_{E,M}^{n,Z}(Q^2) = \left(1 - \frac{8}{3} \sin^2 \theta_W\right) G_{E,M}^d(Q^2) + \left(-1 + \frac{4}{3} \sin^2 \theta_W\right) \left(G_{E,M}^u(Q^2) + G_{E,M}^s(Q^2)\right). \quad (2)$$

The basic idea in the χ CQM is the fluctuation process where the GBs are emitted by a constituent quark $q^{\uparrow(\downarrow)} \rightarrow \text{GB}^0 + q^{\downarrow(\uparrow)} \rightarrow (q\bar{q}')^0 + q^{\downarrow(\uparrow)}$, where $q\bar{q}' + q'$ constitute the sea quarks. For the details of the model the reader may refer to Refs. [8].

Apart from the spin of the the constituent quarks and spin of the sea quarks, the magnetic moment of a given baryon in the χ CQM also receives contribution from the orbital angular motion of the sea quarks. The total magnetic moment is expressed as [9] $\mu^{p,n} = \mu_C^{p,n} + \mu_S^{p,n} + \mu_O^{p,n}$, where the the contributions of constituent quark spin ($\mu_C^{p,n}$), sea quark spin ($\mu_S^{p,n}$), and sea orbital ($\mu_O^{p,n}$) can be defined in terms of quark magnetic moments and spin polarizations as

$$\mu_C^{p,n} = \sum_{q=u,d,s} \Delta q_C^{p,n} \mu^q, \quad \mu_S^{p,n} = \sum_{q=u,d,s} \Delta q_S^{p,n} \mu^q, \quad \mu_O^{p,n} = \sum_{q=u,d,s} \Delta q_O^{p,n} \mu(q_+ \rightarrow). \quad (3)$$

The Q^2 dependence of the vector electric and magnetic for factors as well as axial-vector form factors have been experimentally investigated from the PV electron scattering and from the DIS of neutrinos. The conventional dipole form of parametrization has been used to analyse the vector and axial-vector form factors [10]

$$G_{V,A}^{p,n}(Q^2) = g_{V,A}^{p,n}(0) G_{V,A}^D(Q^2) = \frac{g_{V,A}^{p,n}(0)}{\left(1 + \frac{Q^2}{M_{V,A}^2}\right)^2}, \quad (4)$$

where the electric and magnetic form factors of the proton and neutron at zero momentum transfer $g_V^{p,n}(0)$ for $V = E, M$ correspond to the charge and magnetic moment respectively. $g_A^p(0)$ and $g_A^n(0)$ are the isovector axial-vector coupling constants of the proton and neutron corresponding to the axial-vector form factors at zero momentum transfer.

The probabilities of fluctuations to pions, K , η , η' represented by a , $a\alpha^2$, $a\beta^2$, and $a\zeta^2$ respectively can be calculated in the χ CQM at $Q^2 = 0$ after taking into account strong physical considerations and carrying out a fine grained analysis using the well known experimentally measurable spin and flavor distribution functions.

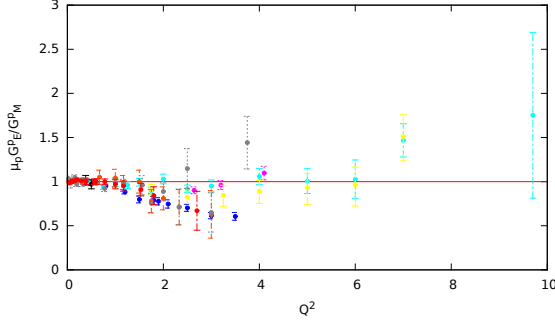


Figure 1: (color online). The ratio $\mu_p G_E^p(Q^2)/G_M^p(Q^2)$ as a function of Q^2 . The data has been taken from Ref. [11].

In Fig. 1, we have presented the ratio $\mu_p G_E^p(Q^2)/G_M^p(Q^2)$ corresponding to the electric ($G_E^p(Q^2)$) and magnetic ($G_M^p(Q^2)$) form factors of the proton with Q^2 . A fair agreement with data is obtained. Even though the data varies from 0.95 – 1.05, it stays close to 1. More data for $Q^2 > 4\text{GeV}^2$ may be needed so see if there is some variation from 1. The proton form factors and their ratios have been measured in the polarization experiments, recoil polarization experiments and beam-target asymmetry measurements [12, 13, 14, 15]. The data from different experiments are in general agreement with each other. A real break-through was made towards the understanding of the internal structure of the proton with the measurements of the electromagnetic form factor ratio of the proton, G_E^p/G_M^p at Q^2 is larger than 1GeV^2 [16]. The data shows a clear deviation of the ratios from unity.

In Fig. 2, we have presented the variation of the ratio $\mu_n G_E^n(Q^2)/G_M^n(Q^2)$ of the neutron form factors with Q^2 . In Fig. 3, we have presented the ratio $G_E^n(Q^2)/G_M^n(Q^2)$. G_E^n is zero at $Q^2 = 0$ since the neutron has zero charge and the slope at $Q^2 = 0$ is related to the mean-square radius of the neutron. The neutron form factors have been measured in a series of experiments [20], however, in the absence of free neutron targets, the measurements of neutron form factors are more difficult as compared to the measurements of the proton form factors. Our results are in fair agreement with the available experimental data. More data is needed for the profound understanding of the form factors of the neutron.

To summarize, the χ CQM helps in the understanding the dynamics of the constituents of the nucleon affected by chiral symmetry breaking in terms of the explicit quark contributions. Further, in light of the precision data available for increased Q^2 range as well as to present a comprehensive analysis of the vector and axial-vector form factors, the calculations have been extended to anal-

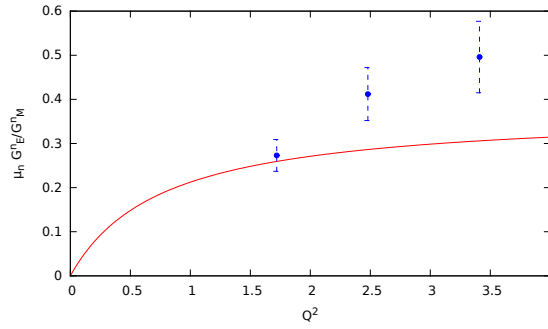


Figure 2: (color online). The ratio $\mu_n G_E^n(Q^2)/G_M^n(Q^2)$ as a function of Q^2 . The data has been taken from Ref. [17, 18].

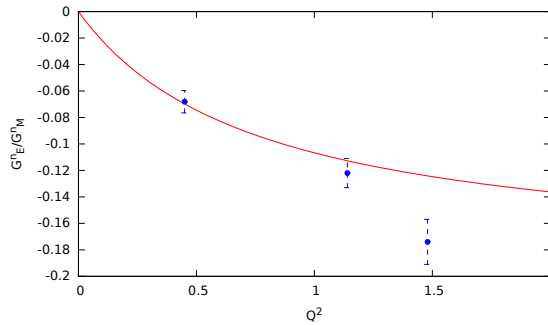


Figure 3: (color online). The ratio $G_E^n(Q^2)/G_M^n(Q^2)$ as a function of Q^2 . The data has been taken from Ref. [19].

use the Q^2 dependence of these quantities using the conventional dipole form of parametrization. Our results provide important constraints on the future experiments to describe the explicit role of constituent and non-constituent degrees of freedom particularly the strangeness contribution. Different experiments are contemplating the possibility of performing the high precision measurements over a wide Q^2 region in the near future which will help in the profound understanding of the nonperturbative properties of QCD.

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