On the physics behind the form factor ratio
\[ \mu_p G_E^p(Q^2)/G_M^p(Q^2) \]

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Abstract.
We point out that there exist two natural definitions of the nucleon magnetization densities: the density \( \rho_M^K(r) \) introduced in Kelly’s phenomenological analysis and theoretically more standard one \( \rho_M(r) \). We derive an explicit analytical relation between them, although Kelly’s density is more useful to disentangle the physical origin of the different \( Q^2 \) dependence of the Sachs electric and magnetic form factors of the nucleon. We evaluate both of \( \rho_M(r) \) and \( \rho_M^K(r) \) as well as the charge density \( \rho_{ch}(r) \) of the proton within the framework of the chiral quark soliton model, to find a noticeable qualitative difference between \( \rho_{ch}(r) \) and \( \rho_M^K(r) \), which is just consistent with Kelly’s result obtained from the empirical information on the Sachs electric and magnetic form factors of the proton.

PACS numbers: 13.40.Gp, 14.20.Dh, 12.39.Fe, 12.39.Ki, 12.39.Dc
The electromagnetic form factors are one of the most fundamental observables, which characterize the underlying composite structure of the nucleon [1]-[4]. As is widely known, the expectation from perturbative QCD (pQCD) is that the $Q^2$ dependence of the Sachs electric, $G_E(Q^2)$, and magnetic, $G_M(Q^2)$, form factors should be the same at large $Q^2$ [5],[6], and early experimental data obtained by the standard Rosenbluth technique appeared to be qualitatively consistent with this expectation [7]. However, the recent experiments at Jefferson Lab, utilizing the polarization transfer technique found the surprising fact that $G_E(Q^2)$ decreases more rapidly than $G_M(Q^2)$ at large $Q^2$ [8]-[10]. A number of theoretical analyses carried out since then, indicate that the discrepancy between the two different techniques for extracting form factor ratio is most likely to be resolved if the two-photon-exchange contributions in elastic $ep$ scatterings are taken into account [11]-[18], thereby providing a strong support to the discovery by the JLab measurements. (For more detail, see, for example, the recent global analysis of the nucleon form factors by Arrington, Melnitchouk and Tjon, and references therein [18].)

An interesting theoretical challenge is therefore how we can understand the physics behind this remarkable observation [19] -[30]. Natural objects of study here would be charge and magnetization densities, which are defined as Fourier transforms of the Sachs electric and magnetic form factors in the Breit frame. Here is a subtlety, however. The problem is that the Breit frame varies with $Q^2$ so that the electromagnetic densities so defined are frame-dependent quantities. To obtain electromagnetic densities in the nucleon rest frame, which have intrinsic physical meaning, Kelly proposed to introduce what-he-calls the intrinsic form factors defined as the Fourier transforms of the charge and magnetization densities at the nucleon rest frame [19]. It is assumed that these intrinsic form factors are directly related to the measured Sachs electric and magnetic form factors on account of some relativistic effects. (The most important relativistic effect is Lorentz contraction of spatial distributions in the Breit frame.) This allows him to extract the intrinsic charge and magnetization densities, $\rho_{ch}(r)$ and $\rho^K_M(r)$ in the nucleon rest frame from the available empirical information on the Sachs electric and magnetic form factors. The result of his analysis illustrated in Fig.7 of [19] clearly shows that the peak of the $r^2$-weighted magnetic density, i.e. $r^2 \rho^K_M(r)$ is located at smaller $r$ than the corresponding peak of the charge density $r^2 \rho_{ch}(r)$, which is thought to explain faster falloff of the electric form factor as compared with the magnetic one.

Now, the purpose of our present study is to give further theoretical support to Kelly’s phenomenological findings. Our strategy to accomplish it is as follows. First, we predict the intrinsic charge and magnetization densities defined by Kelly, within the framework of the chiral quark soliton model (CQSM) [31],[32]. (For early reviews of the CQSM, see [33]-[35].) We immediately notice that the magnetization density that naturally appear in the standard theoretical framework is different from the corresponding magnetization density introduced by Kelly. However, the point of our analysis is that we can readily derive an analytical relation between them. This then enables a direct calculation of the intrinsic charge and magnetization densities a la Kelly.
within a single theoretical framework, without worrying about the Lorentz Boost effects. The comparison of these two intrinsic form factors is then expected to provide us with a valuable hint for clarifying the physical origin of the different $Q^2$ behavior of the observed charge and magnetic form factors. Furthermore, to confirm that the predicted delicate difference between the intrinsic charge and magnetization densities is in fact an essential ingredient to explain the observed difference between the Sachs electric and magnetic form factors, we also evaluate the latters explicitly by taking account of the Lorentz boost effects with the simplest prescription proposed in the past studies.

There have already been several investigations of the nucleon electromagnetic form factors within the framework of the CQSM. In all these studies, however, the treatment of the nucleon center-of-mass motion is essentially nonrelativistic, which means that the reliability of the theoretical predictions is limited to the low-momentum-transfer domain $Q^2 \ll M_N^2$ with $M_N$ being the nucleon mass. Although a complete relativistic treatment of a bound state is an extremely difficult problem especially for a field theoretical model like the CQSM, there is an approximate way, adopted by Kelly's phenomenological analysis, to implement the relativistic recoil corrections, or equivalently the effects of Lorentz boost from the rest frame to the Breit frame. (By the term field theoretical model, here we mean a model of the nucleon, which contains not only the lowest $q^3$ (3-quark) Fock space but also higher $q^3 (\bar{q}q)^n$ Fock spaces.) In this prescription, one first introduces the intrinsic charge, $\tilde{\rho}_{ch}(k)$, and magnetic, $\tilde{\rho}_{m}(k)$, form factors through the relations [19]:

$$\tilde{\rho}_{ch}(k) = G_E(Q^2)(1 + \tau)^{\lambda_E},$$

$$\mu_p \tilde{\rho}_{m}(k) = G_M(Q^2)(1 + \tau)^{\lambda_M},$$

with $G_E(Q^2)$ and $G_M(Q^2)$ corresponding to the observed electric and magnetic form factors. In the above equations, $k$ is the intrinsic spatial frequency corresponding to the momentum transfer $Q^2$:

$$k^2 = \frac{Q^2}{1 + \tau},$$

where $\tau = Q^2 / (4M_B^2)$ with $M_B$ being the boost mass, which ideally should coincide with the physical nucleon mass. The parameters $\lambda_E$ and $\lambda_M$ are integers, whose values are model dependent. In Kelly's phenomenological analysis, he used the choice $\lambda_E = \lambda_M = 2$ [19], which was first suggested by Mitra and Kumari in the cluster model [41]. (For other choices, see [19], [28]-[30], [41]-[43], for instance.) Kelly then defines the intrinsic charge and magnetization densities as Fourier transforms of the above intrinsic form factors [19]:

$$\rho_{ch}(r) = \frac{2}{\pi} \int_0^\infty dk \, k^2 \, j_0(kr) \, \tilde{\rho}_{ch}(k),$$

$$\rho^K_{m}(r) = \frac{2}{\pi} \int_0^\infty dk \, k^2 \, j_0(kr) \, \tilde{\rho}_{m}(k).$$

They are the quantities to be identified with the static densities in the nucleon rest frame, so that they can be predicted, for instance, by the CQSM, or by any other
On the physics behind the form factor ratio $\mu_p G_E^p(Q^2)/G_M^p(Q^2)$ models, without any difficulty. (This statement is true for the charge density, but the magnetization density defined above is different from more standard one, which appears naturally in the theoretical formula of the Sachs magnetic form factor. See the discussion below.) Since the theoretical expressions for the charge and magnetic form factors within the framework of the CQSM were already given in several previous papers [38]-[40], we recall here only their general theoretical structures, i.e. the dependence on the collective angular velocity $\Omega$ of the rotating soliton, which scales as $1/N_c$ [31]. By definition, the intrinsic charge form factor $\tilde{\rho}_{ch}(k)$ is the Fourier transform of the intrinsic charge density $\rho_{ch}(r)$:

$$\tilde{\rho}_{ch}(k) = \int_0^\infty dr \, r^2 \, j_0(kr) \, \rho_{ch}(r),$$

(6)

Note that the intrinsic charge density $\rho_{ch}(r)$ is an easily tractable theoretical object, since it can be calculated in the nucleon rest frame, without worrying about the effects of Lorentz boost. Within the CQSM, the intrinsic charge density of the proton $\rho_{ch}(r)$ is obtained as the sum of the isoscalar and the isovector parts as

$$\rho_{ch}(r) = \rho_{ch}^{(I=0)}(r) + \rho_{ch}^{(I=1)}(r).$$

(7)

The isoscalar part receives the zeroth order contribution in the collective angular velocity $\Omega$ of the soliton, while the isovector part survives only at the 1st order in $\Omega$:

$$\rho_{ch}^{(I=0)}(r) \sim O(\Omega^0), \quad \rho_{ch}^{(I=1)}(r) \sim O(\Omega^1).$$

(8)

On the other hand, the intrinsic magnetic form factor is given in the form:

$$\mu_p \tilde{\rho}_m(k) = \mu_p \int_0^\infty dr \, r^2 \, \frac{3 j_1(kr)}{kr} \rho_m(r),$$

(9)

with

$$\rho_m(r) = \rho_m^{(I=0)}(r) + \rho_m^{(I=1)}(r).$$

(10)

Here, the isoscalar part survives only at the 1st order in $\Omega$, while the isovector part consists of the leading-order term and the 1st order rotational correction:

$$\rho_m^{(I=0)}(r) \sim O(\Omega^1), \quad \rho_m^{(I=1)}(r) \sim O(\Omega^0) + O(\Omega^1).$$

(11)

(It is known that the existence of the 1st order rotational correction in the CQSM, which is absent in the Skyrme type effective meson theories, is essential for reproducing the correct magnitude of the isovector magnetic moment of the nucleon as well as that of the isovector axial charge [44]-[47].) Here, for the sake of comparison to be made later, not only the intrinsic charge density in Eq.(6) but also the intrinsic magnetization density in Eq.(9) is defined so that they satisfy the normalization conditions:

$$1 = \int_0^\infty dr \, r^2 \, \rho_{ch}(r) = \int_0^\infty dr \, r^2 \, \rho_m(r).$$

(12)

An important notice here is that the intrinsic magnetization density appearing in Eq.(9) is different from the corresponding Kelly’s magnetization density $\rho_m^K(r)$ appearing in Eq.(4). The magnetization density $\rho_m(r)$ appears naturally in a theoretical formula
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for the magnetic form factor. On the other hand, as is obvious from Eqs. (4) and (5), Kelly’s magnetization density is defined completely in parallel with the charge density, as a Fourier-Bessel transform of the intrinsic magnetic form factor, so that it is more useful to unravel the coordinate space origin of the different behaviors of the Sachs electric and magnetic form factors. Comparing their definitions, however, it is an easy exercise to derive the relation between these two magnetization densities. Using the identity of the spherical Bessel function

$$\int_0^\infty j_l(kr_1)j_{l+1}(kr_2)\,k\,dk = \frac{\pi}{2} \frac{r_1^{l+1}}{r_2^{l+2}} \theta(r_2 - r_1),$$

(13)

we readily find the desired relation

$$\rho^K_m(r) = 3 \int_r^\infty dr' \frac{\rho_m(r')}{r'},$$

(14)

or, inversely

$$\rho_m(r) = -\frac{1}{3} r \frac{d}{dr} \rho^K_m(r).$$

(15)

Note that $\mu_p \rho_m(r)$ and $\mu_p \rho^K_m(r)$ would have totally different radial dependence, but they have a common normalization,

$$\mu_p = \int_0^\infty dr \, r^2 \mu_p \rho_m(r) = \int_0^\infty dr \, r^2 \mu_p \rho^K_m(r),$$

(16)

so that both are qualified to be called the magnetization density of the proton.

Now, we are ready to show what the predictions of the CQSM are like. For the regularization scheme, we use here the Pauli-Villars one with double subtraction proposed in [48]. Setting the pion mass to the physical value, i.e. 138 MeV, the model contains only one parameter, i.e. the dynamical quark mass $M$, playing the role of quark-pion coupling strength. Favorable physical predictions of the model were known to be obtained with use of the dynamical quark mass $M \approx (375 - 400)$ MeV [49]. Since the purpose of our present study is not to precisely reproduce the observed electromagnetic form factors of the nucleon but to understand the origin of the remarkable qualitative difference between the observed Sachs electric and magnetic form factors, we simply use the value $M = 375$ MeV in the following. (Our strategy should, for instance, be contrasted with Holzwarth’s analysis [28]-[30], which introduces many adjustable parameters to precisely reproduce the observed electromagnetic form factors of the nucleon, although based on a similar soliton model, i.e. the generalized Skyrme model with vector mesons.)

Almost parameter free predictions of the CQSM for the intrinsic charge and magnetization densities are shown in Fig. 1. The magnetization density shown here is the standard one appearing in Eq. (9). In both panels, the dashed and dash-dotted curves stand for the contribution of the $N_c (= 3)$ valence quarks and that of the deformed Dirac-sea quarks, while their sums are shown by the solid curves. A stronger effect of the Dirac-sea contribution in the magnetization density might be an indication of the importance of the pion clouds effects in this quantity [50], [51]. To pursue the coordinate
space interpretation of the different $Q^2$-dependence of the electric and magnetic form factors, it is preferable to compare the charge density $\rho_{ch}(r)$ with the magnetization density $\rho_m^K(r)$ introduced by Kelly rather than with the magnetization density $\rho_m(r)$ appearing in Eq.\(\text{(9)}\). The density $\rho_m^K(r)$ can easily be obtained from the theoretical $\rho_m(r)$ through the relation (14). We emphasize again that, since Eq.\(\text{(14)}\) directly relates the two magnetization densities in the intrinsic frame or the nucleon rest frame, the density $\rho_m^K(r)$ obtained in that way is completely free from the boost procedure, especially from the choice of the boost mass $M_B$ as well as the parameters $\lambda_E$ and $\lambda_M$.

The left panel of Fig.2 represents the theoretical charge and Kelly’s magnetization densities. Remember that the standard magnetization density $\rho_m(r)$ shown in Fig.1 has an entirely different radial shape from the charge density $\rho_{ch}(r)$. Nonetheless, the radial dependence of Kelly’s magnetization density $\rho_m^K(r)$, which is obtained from $\rho_m(r)$ through the relation (14), is unexpectedly close to that of $\rho_{ch}(r)$. Still, we observe a noticeable qualitative difference between $\rho_{ch}(r)$ and $\rho_m^K(r)$. The proton charge density is a little broader than its magnetization density, although the size of the difference predicted by the CQSM might not be large enough as compared with the one suggested by Kelly’s phenomenological analysis. This tendency can more clearly be seen by comparing the $r^2$-weighted densities, i.e. $r^2\rho_{ch}(r)$ and $r^2\rho_m^K(r)$, illustrated in the right panel of Fig.2. One confirms that the peak position of $r^2\rho_m^K(r)$ is located at smaller $r$ than the charge density $r^2\rho_{ch}(r)$, in consistent with Kelly’s result shown in Fig.7 of [19]. Putting it another way, $r^2\rho_m^K(r)$ is larger than $r^2\rho_{ch}(r)$ in the inner region $r \lesssim 0.5$ fm, while the converse is true in the range in the range $0.5$ fm $\lesssim r \lesssim 1.0$ fm.
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Undoubtedly, this qualitative difference between the intrinsic charge and magnetization density must be the source of the observed fast decrease of the ratio \( G_E(Q^2) / G_M(Q^2) \) at high-momentum transfer in the JLab measurements.

To convince that the predicted delicate difference between the intrinsic charge and magnetization densities is in fact an essential ingredient to generate the observed difference between the Sachs electric and magnetic form factors, we next try to evaluate the latters by using a simple prescription given by (1),(2),(3) and (4),(5). For the parameters \( \lambda_E \) and \( \lambda_M \), we use here the simplest choice \( \lambda_E = \lambda_M = 0 \), which amounts to taking in only the Lorentz contraction of the spatial distributions of the constituents. Then, only one remaining parameter of our analysis below is the boost mass \( M_B \), which ideally should coincide with the physical nucleon mass, or the classical soliton mass in our theoretical treatment. Following the previous studies [28]-[30], here we treat it as additional parameter of the analysis. It was determined to be \( M_B \simeq 1.2 \text{ GeV} \) so that it reproduces the general trend of the \( Q^2 \)-dependence of the ratio \( R \equiv \mu_p G_E(Q^2) / G_M(Q^2) \).

Fig. 3 shows the CQSM prediction for the ratio \( \mu_p G_E(Q^2) / G_M(Q^2) \) obtained in the above way, in comparison with the recent global fit obtained by taking account of two-photon exchange contributions and their associated uncertainties [18]. As one can see, the agreement between the theoretical prediction and the empirical data is pretty good. (This agreement should not be overestimated too much, however, since the gross \( Q^2 \)-dependence beyond the range \( \sqrt{Q^2} \gtrsim M_N \) is largely controlled by our approximate treatment of the Lorentz boost effects.) A natural question here is why a fairly small
difference between the two intrinsic electromagnetic densities causes such a significant difference between the $Q^2$-dependencies of the electric and magnetic form factors in a few GeV region. As already indicated in Holzwarth’s analysis based on the generalized Skyrme model [29],[30], the existence of a zero in the electric form factor may provide the simplest answer.

To confirm it, we show in Fig.4 the prediction of the present model for $G_E(Q^2)$ and $G_M(Q^2)$. One sees that the first zero of $G_E(Q^2)$ appears around $Q^2 \approx 7$ GeV$^2$, while $G_M(Q^2)$ still remains positive in the investigated $Q^2$ range. Since the magnitude of the electric form factor decreases rapidly as $Q^2$ approaches its zero, the fast falloff of the ratio $R(Q^2) \equiv \mu_p G_E(Q^2)/G_M(Q^2)$ when coming close to this $Q^2$ region is easily understood. Just to be sure, we never claim that our model is quantitative enough to be able to predict precise position of the zero of the electric form factor. Still, its qualitative prediction that the first zero of the charge form factor appears at much lower momentum transfer than that of the magnetic form factor would be intact and that the cause of this feature can be traced back to the predicted qualitative difference of the two intrinsic electromagnetic densities. Now, admitting that the above interpretation on the strong $Q^2$-dependence of the form factor ratio $R$ is correct, the breakdown of the pQCD counting rule applied to this ratio seems only natural. After all, zeros of the elastic form factors are outside the applicability range of the pQCD counting rule.

To show a subtle difference between the two form factors $G_E(Q^2)$ and $G_M(Q^2)$, it is customary to compare the ratio of each form factor to the dipole form factor $G_D(Q^2) = (1 + Q^2/M_D^2)^{-2}$. The dipole mass $M_D$, which reproduce the gross $Q^2$-
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The dependence of the observed electric and magnetic form factors is known to be $M_D^2 = 0.71 \text{ GeV}^2$. Unfortunately, the CQSM slightly overestimates the nucleon electromagnetic sizes. Accordingly, the dipole mass, which reproduces the average $Q^2$-dependence of the two theoretical form factors $G_E(Q^2)$ and $G_M(Q^2)$ turns out to be a little smaller than the standard one, i.e. $M_D^2 \simeq 0.62 \text{ GeV}^2$. The left and the right panels of Fig.5 respectively stand for the form factor ratios $G_E^p(Q^2)/G_D^p(Q^2)$ and $G_M^p(Q^2)/G_D^p(Q^2)$ obtained with this dipole mass. Although the agreement between the theoretical predictions and the empirical data is far from perfect, a remarkable qualitative difference between the $Q^2$-dependence of $G_E^p(Q^2)/G_D^p(Q^2)$ and $G_M^p(Q^2)/G_D^p(Q^2)$ is clearly seen. Since we are using the same $\lambda$ parameters, i.e. $\lambda_E = \lambda_M = 0$, and a common boost mass $M_B$ for obtaining the electric and magnetic form factors, the cause of this difference must purely be attributed to the difference of the intrinsic charge and magnetization densities predicted by the CQSM.

To summarize, in pursuit of the physical origin of the observed behavior of the form factor ratio $\mu_p G_E^p(Q^2)/G_M^p(Q^2)$ of the proton, we have carried out a comparative analysis of the intrinsic charge and magnetization densities defined in the nucleon rest frame, within the framework of the CQSM containing only one parameter, i.e. the dynamical quark mass. The point is that our predictions for these two intrinsic densities are completely free from the difficult problem of relativistic recoil effects. We find that the predicted intrinsic charge density of the proton is a little broader than the intrinsic magnetization density a la Kelly in qualitatively consistent with Kelly’s conclusion.
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Figure 5. The CQSM predictions for the ratios, $G_E^p(Q^2)/G_D(Q^2)$ (left panel), and $G_M^p(Q^2)/\mu_p G_D(Q^2)$ (right panel), where $G_D(Q^2)$ is the dipole form factor with the dipole mass $M_D^2 = 0.62\,\text{GeV}^2$. The empirical data are from [15].

obtained from the empirical information on the Sachs electric and magnetic form factors. This then gives a strong theoretical support to Kelly’s coordinate space interpretation of the faster falloff of the electric form factor than the magnetic one. Just to be sure, we have further checked that the predicted delicate difference between the theoretical intrinsic charge and magnetization densities, supplemented with a simple introduction of Lorentz contraction effects, can reproduce the observed difference between the charge and magnetic form factors up to $Q^2 \approx 6\,\text{GeV}^2$. It was indicated there that the existence of a zero of the electric form factor $G_E(Q^2)$ around $Q^2 \approx 7\,\text{GeV}^2$ is a likely reason of remarkably fast decrease of the form factor ratio $R \equiv \mu_p G_E(Q^2)/G_M(Q^2)$ beyond $Q^2 \approx 2\,\text{GeV}^2$. Although this latter part of study is of totally approximate nature and should be taken as qualitative, we believe that our present analysis all together has succeeded to give a valuable insight into the physics behind the form factor ratio $\mu_p G_E^p(Q^2)/G_M^p(Q^2)$.

Acknowledgement

This work is supported in part by a Grant-in-Aid for Scientific Research for Ministry of Education, Culture, Sports, Science and Technology, Japan (No. C-16540253)
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