Effect of gluon-exchange pair-currents on the ratio $\mu_p G_E^p/G_M^p$

Murat M. Kaskulov and Peter Grabmayr

Physikalisches Institut, Universität Tübingen, D-72076 Tübingen, Germany

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The effect of one-gluon-exchange (OGE) pair-currents on the ratio $\mu_p G_E^p/G_M^p$ for the proton is investigated within a nonrelativistic constituent quark model (CQM) starting from $SU(6) \times O(3)$ nucleon wave functions, but with relativistic corrections. We found that the OGE pair-currents are important to reproduce well the ratio $\mu_p G_E^p/G_M^p$. With the assumption that the OGE pair-currents are the driving mechanism for the violation of the scaling law we give a prediction for the ratio $\mu_n G_E^n/G_M^n$ of the neutron.

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Introduction: Recently the ratio $\mu_p G_E^p/G_M^p$ between the electric $G_E^p(Q^2)$ and magnetic $G_M^p(Q^2)$ form factors of the proton has been extracted from experimental data on the recoil proton polarization in elastic electron scattering with polarized electrons up to $Q^2 \sim 5$ GeV$^2$ [1,2,3,4]. These experiments are of importance because they are direct measurements of the form factor ratio, and the present results are in contradiction to previous analyses [5,6,7,8]. Historically, the determination of the electric and magnetic form factors up to several GeV were based on the Rosenbluth separation, and they were found compatible with the scaling laws:

$$G_E^p(Q^2) = G_M^p(Q^2)/\mu_p = G_D(Q^2) \cdot (1)$$

where $G_D(Q^2)$ represents the dipole form factor.

The form factors and particularly the ratio give insight to the main features of the dynamical processes and are very useful for a test of the nucleon models [9,10]. The remarkable feature of the new experimental data is that they show a decrease of the ratio $\mu_p G_E^p/G_M^p$ from unity, indicating a significant deviation from this simple scaling law, but also from the simple constituent quark model.

Within different hadronic models the calculations for the proton ratio $\mu_p G_E^p/G_M^p$ became available, with Ref. [11] presenting one of the earliest. We will restrict this discussion to the most recent calculations which agree reasonably well with the trend of the experimental data and which will allow to make predictions at higher $Q^2$ than the present data. In the cloudy bag model (CBM) [8], the pion field required by chiral symmetry is quantized and coupled to the MIT bag [9]. Addition of the pion cloud improves the MIT bag model results [10], in which the decrease of $\mu_p G_E^p/G_M^p$ is an inherent property. It was shown for a CBM formulated on the light cone [11], that the combination of Poincaré invariance and pion effects is sufficient to describe $\mu_p G_E^p/G_M^p$. Several groups have studied different effects within CQMs. In the Goldstone boson exchange CQM [12] the baryon is considered as a system of three constituent quarks with an effective $qq$ hyperfine interaction mediated by the octet of pseudoscalar mesons. This model together with the point-form spectator approximation [13], which provides a covariant framework, leads to a rather close description of the nucleon form factors and the available $\mu_p G_E^p/G_M^p$ data. Calculations of Ref. [14] performed within CQM and light-front formalism, showed that a suppression of the ratio can be expected in the CQM, if the relativistic effects generated by kinematical $SU(6)$ breaking due to the Melosh rotation of the constituent spins are taken into account. Finally, the most recent calculations based on relativistic quark models are from Ref. [15], where the hadron helicity nonconservation induced by the Melosh transformation was recognised to affect the ratio. The implementation of relativity is a common feature of all these works and all emphasize the necessity of both kinematical and dynamical relativistic corrections for the interpretations of the decrease of the ratio $\mu_p G_E^p/G_M^p$.

In the non-relativistic constituent quark model (NR-CQM) [16], the effective degrees of freedom are the massive quarks moving in a self-consistent potential whose specific form is dictated by considerations of QCD. Other degrees of freedom like Goldstone bosons or gluons are not considered in the original version and effectively absorbed into the constituent quarks.

Theoretically, the explicit introduction of the additional degrees of freedom in the nucleon structure will change its properties compared to expectations based on simple quark models in which the baryon is described as a three-quark state only. Among different improvements to the naive CQM which could be essential for dynamical properties of the nucleons, the most important ones are relativistic kinematical corrections, the introduction of a mesonic cloud via pion-loop corrections, and dynamical corrections due to the interaction currents and to the creation of quark-antiquark ($q\bar{q}$) pairs. For low momentum transfer, $q\bar{q}$ pairs (sea-quarks) are dominant and the mesonic degrees of freedom become increasingly important. However, in a recent study [17] on “unquenching” the quark model, strong cancellations between the hadronic components of the $q\bar{q}$ sea were found which tend to make the nucleon transparent to photons. These studies provide a natural way of understanding the success of the valence quark model even though the $q\bar{q}$ sea...
is very strong. At higher momentum transfer and in the presence of residual $qq$ interaction, the e.m. operators must be supplemented by the two-body exchange currents. The inclusion of two-body terms leads beyond the single-quark impulse approximation, and in dependence on the model for the $qq$ interaction effectively represents the gluonic or mesonic exchange degrees of freedom in the e.m. current operator. In this sense the physical picture should be similar to nuclear physics, where at low momentum transfer the nucleons are reasonable degrees of freedom, but at higher momentum transfer the meson-exchange currents play a prominent role.  

In this work we continue our studies \[19\] of the possible role of interaction currents, in particular OGE pair-currents, for the e.m. properties of the nucleon. We use the NRCQM with relativistic corrections, coming from the Lorentz boost of the nucleon wave function, together with gluonic corrections for the calculation of the proton ratio $\frac{G_E^p}{G_M^p}$ at momentum transfers beyond 1 GeV$^2$, where effects of the soft pionic cloud should be less important. We show that gluonic corrections to the CQM are important, and that the ratio $\frac{G_E^q}{G_M^q}$ is well reproduced by the $SU(6) \times O(3)$ wave function of the nonrelativistic quark model.

The nucleon in the NRCQM: In the quark model, baryons are considered as three-quark configurations. The ground state has positive parity with all three quarks in their lowest state, and the total angular momentum (isospin) of baryons is obtained by appropriately combining the quark spins (isospins). In the NRCQM \[16\] a baryon is treated as a non-relativistic three-quark system, and in the simplest case of equal quark masses $m_q$ it is described by the Hamiltonian:

$$ H_{3q} = \sum_{i=1}^{3} \left( m_q + \frac{P^2_{i}}{2m_q} \right) - \frac{\mathbf{P}^2}{6m_q} + \sum_{i<j}^{3} V^{(con)}(r_i, r_j) + \sum_{i<j}^{3} V^{(res)}(r_i, r_j) $$

(2)

where $r_i, p_i$ are the spatial and momentum coordinates of the $i$-th quark, respectively, and $\mathbf{P}$ is the centre-of-mass momentum. The Hamiltonian $H_{3q}$ consists of the nonrelativistic kinetic energy, a confinement potential $V^{(con)}$, and a residual interaction $V^{(res)}$. Here, we take a two-body harmonic oscillator (h.o.) confinement potential: $V^{(con)}(r_i, r_j) \sim \lambda_i \cdot \lambda_j (r_i - r_j)^2$, where $\lambda_i$ are the Gell-Mann colour matrices of the $i$-th quark, with $\langle \lambda_i \cdot \lambda_j \rangle = -8/3$ for a $qq$ pair in a baryon.

The phenomenological residual interaction $V^{(res)}$ can be based on various $qq$ potentials \[12\ \[13\], which reflect the symmetries and properties of QCD. Up to now, its dynamical origin is rather uncertain. We use a standard OGE interaction, the strength of which is determined by the strong coupling constant $\alpha_s$. However, unlike perturbative QCD, where the strong coupling constant $\alpha_s$ goes to zero at large inter-quark momenta, we take $\alpha_s$ of the NRCQM as an effective momentum independent constant.

We start from the simplest form of the NRCQM, i.e. without configuration mixing, in which the nucleon $|N\rangle$ is described by the lowest h.o. three quark configurations $(0s)^3[3]_X$ in the translationally-invariant shell model (TISM):

$$ |N\rangle = \left( (0s)^3[3]_X \right) \left( L = 0, ST = \frac{1}{2}, P^e = \frac{1}{2} \right) $$

(3)

where the colour part is omitted. After having removed the centre-of-mass coordinate $\mathbf{R}$ from the TISM configuration, the ground state eigenfunction depends only on the Jacobi relative coordinates $\rho_1$ and $\rho_2$ of the quarks:

$$ \langle (0s)^3(\rho_1, \rho_2) \rangle \sim \exp \left( -\frac{1}{4\pi^2} \rho_1^2 - \frac{1}{4\pi^2} \rho_2^2 \right) $$

(4)

where the constant $b$ determines the average hadronic size of the baryon. Note that the elimination of $\mathbf{R}$ is crucial for correctly counting the baryonic states. This is one reason why the nonrelativistic approach is so successful in spectroscopy.

The nucleon e.m. Sachs form factors: The nucleon e.m. form factors are functions of the square of the momentum transfer in the scattering process $Q^2 = -q^\mu q_\mu$. The Sachs form factors, $G_E(M), G_M(M)$, fully characterize the charge and current distributions inside the nucleon \[20\] and can be written in terms of Dirac and Pauli form factors $F_1$ and $F_2$, respectively. The most general form of the nucleon e.m. operator $J^\mu_{em}(x)$, which defines $F_1$ and $F_2$, satisfies the requirements of relativistic covariance and the condition of gauge invariance; it is of the form

$$ \langle N(p', s') | J^\mu_{em}(0) | N(p, s) \rangle = \bar{u}(p', s') \left[ i \sigma^{\mu\nu} F_1(Q^2) + i \sigma^{\nu\mu} F_2(Q^2) \right] u(p, s) $$

(5)

where $q^\nu = p'^\nu - p^\nu$. The Breit frame, where the incoming momentum $p = -q/2$ is scattered to the momentum $p' = q/2$, is characterized by $Q^2 = q^2$. In this frame the nucleon electric $G_E$ and magnetic $G_M$ form factors can be interpreted as Fourier transforms of the distributions of charge and magnetization, respectively:

$$ \langle N_s(\frac{q}{2}) | J_{em}(0) | N_s(\frac{-q}{2}) \rangle = \chi_{s}^E \chi_{s} M(q^2) $$

(6)

$$ \langle N_s(\frac{q}{2}) | J^{\mu}_{em}(0) | N_s(\frac{-q}{2}) \rangle = \chi_{s}^{\mu} \chi_{s} G(q^2) $$

(7)

where $\chi_{s}^E$ and $\chi_{s}$ are Pauli spinors for the initial and final nucleons.

Starting from the rest frame, the spherical nucleon is expected to undergo a Lorentz contraction along the direction of motion. Results of previous studies suggest that the consistent treatment of the form factors should
be supplemented by the relativistic boost \[21\]. But a complete solution of a covariant many-body problem is difficult; the use of the light-cone dynamics \[22\] for constituent quarks leads to the introduction of additional parameters. Thus, a semiclassical prescription proposed in Ref. \[23\] and successfully applied in a CBM \[10\] is used here. Thereby, the relativistic form factors can be derived in the Breit frame from the corresponding nonrelativistic ones by a simple substitution:

\[G_{E(M)}(Q^2) \to \eta G_{E(M)}(\eta Q^2),\]  

where \(\eta = M_N^2/E_N^2\) and \(E_N^2 = M_N^2 + q^2/4\). The scaling factor \(\eta\) in the argument of \(G_{E(M)}\) arises from the coordinate transformation of the struck quark, and the pre-factor in Eq. (8) comes from the reduction of the integral measure of the two spectator quarks in the Breit frame. This simple boost together with the NRCQM nucleon wave function does not mix configurations with nonzero orbital angular momentum; it leads to the hadron helicity conserving solution. Note, that imposing Poincaré invariance in a relativistic CQM causes substantial violation of the helicity conservation rule \[13\], and results in an asymptotic behaviour of form factors which differs from that as expected in pQCD \[24\].

We first consider the nucleon single-quark current \(j_{\mu n}(x)\) contribution:

\[j_{\mu n}^{\mu}(x) = \sum_{i=1}^3 j_{\mu n}^{i}(x).\]

In the CQM the e.m. vertex of the internal quarks should be assumed to have a spatially extended structure that may be described by a form factor \(F_q(q^2)\). The most general form for the covariant e.m. current operator of the constituent quarks is written as \[24\]:

\[j_{\mu n}^{\mu}(x) = Q_n q_i(x) \left\{ \gamma^\mu + \left( F_q(q^2) - 1 \right) \left[ \gamma^\mu - \frac{\gamma \cdot q}{q^2} \right] \right\} q_i(x),\]  

where \(q_i(x)\) is the quark field operator, \(Q_i\) is its charge in units of \(e\): \(Q_i = 1/2 \left[ 1/3 + \tau_i^3 \right]\). This vertex, in which the first term corresponds to pointlike quarks, maintains the requirement of current conservation, as the form factor modification appears only in a purely transverse term. The nonrelativistic reduction of Eq. (9) for pointlike quarks, \(F_q(q^2) = 1\), leads to the standard one-body e.m. current operators: \(\hat{\rho}_{3q}(\mathbf{q}) = \sum_{i=1}^3 Q_i e^{iq \cdot \mathbf{r}_i}\) and \(\hat{\jmath}_{3q}(\mathbf{q}) = \frac{1}{m_n} \sum_{i=1}^3 Q_i e^{iq \cdot \mathbf{r}_i} \left( \mathbf{p}_i^\prime + \mathbf{p}_i + i\sigma_i \times \mathbf{q} \right)\), where we have retained only the lowest order contributions. This is in spirit of a NRCQM, where the main contribution to the e.m. moments is expected to come from the nonrelativistic single quark currents, which by the choice of the effective quark mass already incorporates substantial relativistic corrections \[24\]. It follows that one should not use next-to-leading order relativistic corrections proportional to \(q^2/8m_n^2\) in the charge operator \(\hat{\rho}_{3q}(\mathbf{q})\), for example the Darwin-Foldy term, if one ignores them in the kinetic energy.

The naive CQM results in the following nucleon e.m. form factors \(G_{E}^{(3q)}\) and \(G_{M}^{(3q)}\):

\[G_{E}^{(3q)}(q^2) = e_N \exp \left(-q^2b^2/6\right)\]  
\[G_{M}^{(3q)}(q^2) = \frac{M_N}{m_q} \mu_N \exp \left(-q^2b^2/6\right)\]

where \(\mu_N\) are the charge and CQM magnetic moment of the nucleon: \(\mu_N = \frac{1}{2}(N\left(1 + \tau_3\right) + N\left(1 + 5\tau_3\right))\). Due to the same momentum dependence, Eqs. (10) and (11) lead to the scaling law noted in Eq. (4): a ratio of unity is obtained as presented by the long dashed line in Fig. 1. Clearly, the scaling law is in contradiction with the recent proton experiments \[1, 2, 2, 4\].

**FIG. 1:** The ratio \(\mu_p G_{E}^{p}/G_{M}^{p}\) for the proton is calculated within the NRCQM for \(m_q = 400\) MeV and \(b = 0.5\) fm and 3 values of \(\alpha_s\). The interaction is assumed to be pointlike. The calculations are compared to data from Refs. \[1, 2, 2, 4\]. The insert shows the ratio over an extended range of \(Q^2\) for the best value \(\alpha_s=0.4\), without Lorentz boost (dashed line) or with a \(p\) vertex form factor (dotted line).

The **OGE pair-current:** In the presence of residual OGE interactions between the quarks the total current operator of the hadron cannot simply be a sum of free quark currents, but must be supplemented by two-body currents. These two-body currents are closely related to the \(qq\) potential from which they can be derived by minimal substitution. Since the effect of the residual \(qq\) potential is clearly seen in the excited spectra of hadrons, one expects the corresponding two-body currents to play an important role in various e.m. properties of hadrons.

Both, the photon and the gluons interacting with quarks can produce \(q\bar{q}\) pairs leading to pair-current contributions to e.m. current as provided by OGE. The two-body terms we consider are depicted in Fig. 2. The nonrelativistic reduction of these diagrams leads to
These OGE pair-currents describe a $q\bar{q}$ pair creation process induced by the external photon with subsequent annihilation of the $q\bar{q}$ pair into a gluon, which is then absorbed by another quark. These currents are of relativistic origin as reflected in the higher powers of $1/m_q^2$ as compared to the one-body electromagnetic current operators. Because the gluon does not carry any isospin the OGE pair-current has the same isospin structure as the one-body currents. Eqs. \ref{eq:OGE1} and \ref{eq:OGE2} result in the following electric $G_E^{(OGE)}$ and magnetic $G_M^{(OGE)}$ form factors:

\begin{align}
\left\{ \begin{array}{l}
G_E^{(OGE)} \\
G_M^{(OGE)}
\end{array} \right\} &= \frac{-\alpha_s}{m_q} q e^{-q^2b^2/24} \left\{ \begin{array}{l}
\frac{1}{3} \\
-\frac{2}{9}
\end{array} \right\} \mathcal{K}(q)
\end{align}

\begin{align}
\left\{ \begin{array}{l}
G_E^{(OGE)} \\
G_M^{(OGE)}
\end{array} \right\} &= \frac{\alpha_s}{m_q^2} \frac{M}{q} e^{-q^2b^2/24} \left\{ \begin{array}{l}
\frac{2}{3} \\
-\frac{2}{9}
\end{array} \right\} \mathcal{K}(q)
\end{align}

The function $\mathcal{K}$ in the above expressions is:

\begin{equation}
\mathcal{K}(q) = 4\pi \left(\frac{1}{2\pi b^2}\right)^{3/2} \int_0^\infty dr \ e^{-r^2/(2b^2)} j_1(qr/2)
\end{equation}

where $j_1(qr/2)$ is the spherical Bessel function. The interaction of the incoming photon with a $q\bar{q}$ pair can be considered as a point-like interaction or as being dominated by intermediate vector mesons. The latter leads to an additional dipole form factor, $F_{\gamma q\bar{q}}(q^2) = \Lambda_{\gamma q\bar{q}}^2/(\Lambda_{\gamma q\bar{q}}^2 + q^2)$, reflecting the extended structure of the $\gamma q\bar{q}$ vertex. $\Lambda_{\gamma q\bar{q}}$ can be considered as a free parameter or simply can be taken equal to the $\rho$-meson mass.

**Results:** In this work we consider the effect of the OGE pair-current corrections to the NRCQM nucleon electromagnetic form factors, particularly for the ratio $\mu_p G_E^{p}/G_M^{p}$. The ratio is calculated for a quark mass of $m_q = 400$ MeV and the respective quark core radius of $b=0.5$ fm. In Fig. 3 calculations with different $\alpha_s$ are shown to indicate the sensitivity. In the insert of Fig. 3 we show results towards higher values of $Q^2$ for the best description of the present data by $\alpha_s = 0.4$ (with solid curve) and without Lorentz boost (dashed curve). Our results indicate that the $\mu_p G_E^{p}/G_M^{p}$ ratio for the proton continues to decrease and that it will cross zero at $Q^2 \sim 8.1$ GeV$^2$. From this, a negative value of the ratio must be expected for the planed measurements at JLAB at $Q^2 \sim 9$ GeV$^2$. Deviations could be explained due to an extended $\gamma q\bar{q}$ vertex as demonstrated by using a $\Lambda_{\gamma q\bar{q}} = 770$ MeV (dotted line). The introduction of such states does not affect much our results up to $\sim 10$ GeV$^2$, but strongly influences the behaviour of $\mu_p G_E^{p}/G_M^{p}$ for higher $Q^2$. For quark masses in the range $m_q \sim 313 \div 400$ MeV and bag radii of $b \sim 0.4 \div 0.6$ fm one can find also a good description of the data with reasonable values for $\alpha_s \sim 0.2 \div 0.6$ \[20\]. However, these are not able to reproduce the $N - \Delta$ mass splitting in the case of pure OGE. It seems likely that the observed mass splitting is the result of a linear combination of the pion-loop contributions and OGE \[9\]. In this sense pionic contributions could produce the desirable effect of reducing the size of the strong coupling constant $\alpha_s$, needed for the reproduction of $\mu_p G_E^{p}/G_M^{p}$.

The ratio $F_2^{p}/F_1^{p}$ can be directly derived from $G_E^{p}/G_M^{p}$. It is predicted in Ref. \[11\] to be constant for values of $Q^2$ up to 20 GeV$^2$ and it is understood as a result of the Melosh transformation, which reflects relativistic effects. Our results are shown in Fig. 3. The “kinematical” background formed by the naive CQM results (dot-dashed curve), $F_2^{p}/F_1^{p} = 1/(1+\kappa Q^2/4M^2)$, underestimates the data and is not affected by the Lorentz boost, a failure which is overcompensated when adding the OGE pair-currents (dashed curve). It is due to the Lorentz boost.

**FIG. 2:** Diagrams for OGE pair-currents.

**FIG. 3:** The $Q^2$ behavior. The quark and gluon contributions are shown in a).
We can treat the neutron ratio assumption that the OGE pair-currents are the driving Eqs. 10, 11, 14 and 15 leads to a simple approximate result of a broad maximum occurring near $Q^2$ at $0,4$. Following Ref. [15], we also study the high $Q^2$-behavior. The ratio falls for asymptotic values of $Q^2$ as $Q F_p^2 / F_1^2 \sim 1/Q$, and allows to make a smooth transition to the scaling behavior as expected from pQCD [27]. In Ref. [15] the ratio $Q F_p^2 / F_1^2$ falls less quickly as in our case and in pQCD, both stated a notion of the hadron helicity conservation. We also confirm the statement of Ref. [15], that a plateau seen in Fig. 4 is the result of a broad maximum occurring near $Q^2 \sim 10 \text{ GeV}^2$.

Recent experimental progress in using polarized nuclear targets will allow to obtain the neutron ratio $G_E^n/G_M^n$. As well known in the $SU(6)$ limit $G_E^n(Q^2)$ is zero [28]. We can treat $G_E^n(Q^2)$ as a result of the residual OGE-force in the picture of gluonic currents and with the assumption that the OGE pair-currents are the driving mechanism of the scaling law violation we can calculate the neutron ratio $G_E^n/G_M^n$ using the best results for the proton. The results are shown in Fig. 4. Recombining Eqs. [14], [15], and [16] leads to a simple approximate result in analytic form between $G_E^n/G_M^n$ and that of the proton, $G_E^n/G_M^n$:

$$\mu_n G_E^n / G_M^n \simeq \frac{2}{3} \left(1 - \mu_p G_E^n / G_M^n \right),$$

which works remarkably well from low up to very high $Q^2$, and actually insensitive to the choice of the parameters (insert Fig. 4).

In conclusion, we would like to mention that the internal dynamics of the nucleon are much more complex than we have presented in this work. First of all it is interesting to examine the effect of nonvalence Fock states [21]:

$$\Psi_N = \begin{pmatrix} \Psi(3q) \\ \Psi(3q + q\bar{q}) \end{pmatrix}$$

reflecting $q\bar{q}$ fluctuations of the constituent quarks. This question is closely related to the possible role of the mesonic cloud.

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* Electronic address: kaskulov@physik.uni-tuebingen.de
† Electronic address: grabmayr@uni-tuebingen.de

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