Gamow-Teller transitions and the Spin EMC effect: the Bjorken sum-rule in medium

Steven D. Bass
Kitzbühel Centre for Physics, Kitzbühel, Austria and
Marian Smoluchowski Institute of Physics, Jagiellonian University, PL 30-348 Krakow, Poland

Gamow-Teller transitions in nuclei tell us that the nucleon’s axial charge $g_A^{(3)}$ is quenched in large nuclei by about 20%. This result tells us that the spin structure of the nucleon is modified in nuclei and disfavours models of the medium dependence of parton structure based only on nucleon short range correlations in nuclei. For polarized photoproduction the Gerasimov-Drell-Hearn integral is expected to be strongly enhanced in medium.

I. INTRODUCTION

Just about 30% of the proton’s spin is carried by the spin of its quarks. This surprising discovery from polarized deep inelastic scattering has inspired a 30+ years global programme of theory and experiments to understand the internal spin structure of the proton [1, 2]. In parallel, unpolarized deep inelastic scattering from nuclear targets has taught us that the quark structure of the proton is modified when the proton is inside an atomic nucleus. Detailed explanation of this EMC nuclear effect is still a matter of theoretical debate, for recent discussions see [3]. New experiments are planned at Jefferson Laboratory with a polarized $^7\text{Li}$ target to look for a possible spin version of the EMC nuclear effect in the range $0.06 < x < 0.8$ [4]. How is the internal spin structure of the proton modified when the proton is in a nuclear medium?

Here we explain how Gamow-Teller transitions (β-decays of large nuclei) constrain our understanding of nucleon spin structure in medium and models of the EMC nuclear effect. The effective isovector axial charge $g_A^{(3)}$ extracted from these experiments is quenched in large nuclei by about 20% [5]. Through the Bjorken sum-rule [6, 7], this means a corresponding reduction in the difference between up and down quark contributions to the proton’s spin in the nuclear medium.

Popular models of the EMC nuclear effect involve either modification of the properties of each nucleon in the nucleus through coupling of the valence quarks to the scalar and vector mean fields in the nucleus or where most nucleons are unmodified but a small number exist in short range correlations where the struck nucleon is far off mass shell [8]. Models of the EMC nuclear effect where the effect is driven only by nucleon short range correlations in nuclei predict a negligible spin effect in medium [9], in contrast to the phenomenological constraint from the quenching found in Gamow-Teller transitions.

In Section 2 we give a brief overview of present understanding of the proton’s spin structure. Section 3 discusses the constraints from medium modifications of $g_A^{(3)}$. In Section 4 we discuss the consequences for models of the EMC nuclear effect and outlook for future experiments. Section 5 addresses the extension to polarized photoproduction where the value of the Gerasimov-Drell-Hearn, GDH, sum-rule is expected to be strongly enhanced in medium.

II. THE SPIN STRUCTURE OF THE PROTON IN FREE SPACE

Information about the proton’s spin structure comes from the $g_1$ deep inelastic spin structure function. In QCD the first moment of $g_1$ is given by a linear combination of the nucleon’s isovector, octet and flavour-singlet axial charges, each times perturbative QCD coefficients which are calculated to $O(\alpha_s^3)$ precision. For quark flavour $q$, the axial-charges

$$2M S_\mu \Delta q = \langle p, S | \overline{q} T_\mu \gamma_5 q | p, S \rangle$$

measure the fraction of the proton’s spin that is carried by quarks and antiquarks of flavour $q$. Here $M$ is the proton’s mass and $S$ its spin vector. The isovector, octet and singlet axial charges are

$$g_A^{(3)} = \Delta u - \Delta d$$
$$g_A^{(8)} = \Delta u + \Delta d - 2\Delta s$$
$$g_A^{(0)} = \Delta u + \Delta d + \Delta s.$$  (2)

Each spin term $\Delta q$ ($q = u, d, s$) is understood to contain a contribution from polarized gluons, $-\frac{1}{2\pi} \Delta g$, where $\alpha_s$ is the QCD coupling and $\Delta g$ is the polarized gluon contribution to the proton’s spin. This polarized gluon term contributes in $g_A^{(0)}$ but cancels in $g_A^{(3)}$ and $g_A^{(8)}$. The value of the singlet $g_A^{(0)}$ is also sensitive to a possible topological contribution, $C_\infty$ which, if finite, is associated with Bjorken $x = 0$ and a subtraction constant from the “circle at infinity” in the dispersion relation for $g_1$ [2].

For free protons, in QCD the isovector part of $g_1$ satisfies the fundamental Bjorken sum-rule

$$\int_0^1 dx g_1(x, Q^2) = \frac{g_A^{(3)}}{6} C_{NS}(Q^2).$$  (3)

* Steven.Bass@cern.ch
where \( x \) is the Bjorken variable, \( g^{(3)}_A = 1.270 \pm 0.003 \) from neutron beta-decays and \( C_{NS}(Q^2) \) is the perturbative QCD Wilson coefficient, \( \approx 0.85 \) with QCD coupling \( \alpha_s = 0.3 \) [4]. This sum-rule has been confirmed in polarized deep inelastic scattering experiments at the level of 5% [9]. About 50% of the sum-rule comes from Bjorken \( x \) values less than about 0.15. The \( g_1^{(p-n)} \) data is consistent with quark model and perturbative QCD predictions in the valence region \( x > 0.2 \) [10]. The size of \( g^{(3)}_A \) forces us to accept a large contribution from small \( x \) with the observed rise
\[
g_1^{(p-n)} \sim x^{-0.22 \pm 0.07}
\]
found in COMPASS data from CERN at \( Q^2 = 3 \) GeV\(^2\) for small \( x \) data down to \( x_{\text{min}} \sim 0.004 \) [9]. Surprisingly, recent analysis [11] of high statistics data from the CLAS experiment at Jefferson Laboratory and COMPASS reveals that the raising behaviour in Eq. (4) persists to low \( Q^2 \) \(< 0.5 \) GeV\(^2\) in contrast to the simplest Regge predictions based on a straight line \( a_1 \) trajectory. This finding remains to be fully understood in terms of the underlying QCD dynamics. The effective Regge intercept \( \alpha_{R1} = 0.31 \pm 0.04 \) [11] gives the high energy part (about 10%) of the Gerasimov-Drell-Hearn sum-rule for polarized photoproduction which is needed to match on to low energy contributions measured at Bonn and Mainz [12].

The isoscalar spin structure function \( g_1^{(p+n)} \) \( \sim 0 \) for \( x < 0.03 \) at deep inelastic \( Q^2 \) [11], in sharp contrast to the unpolarized structure function \( F_2 \) where the isosinglet part dominates through gluonic exchanges. The proton spin puzzle, why the quark spin content of the proton is so small \( \sim 0.3 \), concerns the collapse of the isoscalar spin sum structure function to near zero at this small \( x \). The spin puzzle involves contributions from the virtual pion cloud of the proton with transfer of quark spin to orbital angular momentum in the pion cloud [13], the colour hyperfine interaction or one-gluon-exchange current (OGE) [14], a modest polarized gluon correction \(-3 \frac{\Delta g}{\Delta q} \) with \( \Delta q \) non-zero [15] and less than about 0.5 at the scale of the experiments [1], and a possible topological effect at \( x = 0 \) [2].

\[ g_1^{(p-n)} \sim x^{-0.22 \pm 0.07} \] (4)

### III. \( g^{(3)}_A \) IN MEDIUM

Static properties of hadrons (masses, axial charges, magnetic moments...) are modified in a nuclear medium [3, 16, 18]. For axial structure, Gamow-Teller transitions (\( \beta \) decays of large nuclei) tell us that the effective axial charge in medium \( g^{(3)}_A \) is suppressed in large nuclei by about 20% [3]. This quenching is measured in the space component of the axial current with matrix element proportional to the nucleon spin vector \( \vec{S} \). Quenching of \( g^{(3)}_A \) in nuclei tells us that the spin structure of the nucleon is modified in nuclei with
\[
g^{(3)}_A = \Delta u^* - \Delta d^* \approx 1
\] (5)

close to nuclear matter density \( \rho_0 = 0.15 \text{ fm}^{-3} \) and with the Bjorken \( x \) dependence of the effect waiting to be discovered.

Quenching of \( g^{(3)}_A \) can be understood in terms of nucleon, \( \Delta \) and pion degrees of freedom (without explicit quark and gluon degrees of freedom) and through coupling the valence quarks in the nucleon to the scalar and vector mean fields in the medium. In the first approach, important contributions come from the Ericson-Ericson-Lorentz-Lorenz effect [3, 19] and from interaction with the pion cloud in the nucleus [20]. These terms each give about 50% of the quenching effect. Any contribution from short range nucleon correlations tends to reduce the quenching, see [20] and Section 4 below. In a nuclear medium or nucleus relativistic invariance is lost and the space and time components of the axial vector current become disconnected. Meson exchange currents provide extra renormalization of the time component of the axial current with enhancement seen in the time component in \( 0^+ \leftrightarrow 0^- \) transitions, in contrast to the quenching seen in the space component. Chiral symmetry quenching effects are universal to the space and time components.

In a QCD motivated approach the quark meson coupling model, QMC, predicts about 10% reduction in \( g^{(3)}_A \) at \( \rho_0 \) [21]. Here medium modifications of hadron properties are calculated by treating the hadron as an MIT Bag and coupling the valence quarks to the scalar \( \sigma \) (correlated two pion) and vector \( \omega \) and \( \rho \) mean fields in the nucleus. Since one works in mean field there is no explicit Ericson-Ericson-Lorentz-Lorenz term in this model. About 14% reduction is found when OGE and pion cloud effects are included in the model [22]. In recent QCD lattice calculations modest suppression of \( g^{(3)}_A \), a few percent, is found for light nuclei [23].

What does the quenching of \( g^{(3)}_A \) mean for models of the EMC nuclear effect?

### IV. CONSEQUENCES FOR THE EMC NUCLEAR EFFECT

The EMC nuclear effect [3] involves suppression of the unpolarized \( F_2 \) structure function in medium relative to the free nucleon structure function in the valence region with Bjorken \( x \) between about 0.3 and 0.85. There is enhancement around \( x = 0.15 \), the ratio comes with constant negative slope between 0.15 and 0.7, plus shadowing suppression at smaller \( x \) which is expected to saturate at some small value of \( x \) corresponding to \( A \) independent effective Regge intercepts, with \( A \) the mass number.

What do we expect for spin? The polarized EMC effect is defined through
\[
\Delta R^H_A(x) = \frac{g^{4H}_A(x)}{P^{4H}_A g^0_1(x) + P^3_A g^0_1(x)}
\] (6)

where \( g^{4H}_1 \) is the spin dependent structure function for a nucleus with helicity \( H \) and mass number \( A \), \( g^0_1 \) and \( g^0_1 \)
are free nucleon structure functions and \( P_{AH}^p \) and \( P_{AH}^n \) are the effective polarization of the protons and neutrons in the nucleus \([24]\).

There are two leading approaches for describing the unpolarized EMC effect in the valence region. Mean-field models have all of the nucleons slightly modified through coupling their valence quarks to the scalar and vector mean fields in the nucleus \([18]\). In a different view, nucleons are unmodified most of the time but are modified substantially when they fluctuate into short range correlated pairs, SRCs \([23]\). Experimentally, a correlation is observed between SRCs and the magnitude of the unpolarized EMC effect in nuclei \([24]\), raising the question whether SRCs cause the EMC effect or whether both might have a common origin so that one might have a spin EMC effect without SRCs having to induce it.

Model calculations of the nucleon’s \( g_1 \) spin structure function in medium based on mean field approaches \([24, 27, 29]\) suggest a large spin EMC effect in the valence region at medium \( x \). QMC model calculations give a ratio of in-medium to free nucleon spin structure functions similar in size to the unpolarized EMC nuclear effect with \( g_{A}^{s(3)} \) reduced by about 10% at \( \rho_0 \) \([28]\). NJL model calculations give double the unpolarized effect in the valence region with larger suppression of the ratio of spin structure functions for large nuclei and \( g_{A}^{s(3)} \) reduced by about 20% at \( \rho_0 \), and with a constant EMC ratio \( \Delta R_{A}^{H}(x) \sim 0.93 \) for \( x < 0.7 \) with \( g_{A}^{s(3)} \) reduced by about 6% in \(^7\)Li \([24]\). Shadowing at small \( x \) is considered in \([30]\).

Models of the EMC nuclear effect where the effect is induced only by the contribution of short range nucleon correlations give only negligible spin dependence in both free nucleons and in SRCs two nucleons meet with low relative momentum \( S \)–wave. Through the SRC the nucleons will be scattered into a high relative momentum \( D \)–wave state by the tensor force. Evaluating the relevant Clebsch-Gordon coefficients, one finds that this process significantly depolarizes the correlated struck proton which is far off mass shell because of the high momentum carried away by its partner nucleon. The polarization of the struck nucleon participating in the SRC will be of order -10% to -15% and with a constant EMC ratio \( \Delta R_{A}^{H}(x) \sim 0.93 \) for \( x < 0.7 \) with \( g_{A}^{s(3)} \) reduced by about 6% in \(^7\)Li \([24]\). Shadowing at small \( x \) is considered in \([30]\).

In future experiments if no suppression is found in the valence region of the isovector part of \( g_1 \) in medium, then \( g_1^{(p-n)} \) in medium should be strongly suppressed at smaller \( x < 0.15 \), where 50% of the Bjorken sum-rule for free protons comes from, to be consistent with the expectation based on Gamow-Teller transitions. For the isoscalar part of \( g_1 \), it would be interesting to see whether the collapse in \( g_1^{(p+n)} \) at small \( x \) persists at finite nuclear density. A priori, different contributions to resolving the proton spin puzzle (pion cloud, polarized glue) will come with different \( A \) dependence, e.g. gluons do not directly couple to the meson mean-fields in the nucleus in the QMC approach, so any cancellation which works for free nucleons might break down at finite density.

**V. THE GDH SUM-RULE IN MEDIUM**

One also expects medium dependence of the GDH sum-rule and the spin-dependent photo-absorption cross-sections with polarized real photon scattering, \( Q^2 = 0 \). The GDH sum-rule for polarized photon-proton scattering reads \([31, 32]\)

\[
\int_{M^2}^{\infty} \frac{ds_{\gamma p}}{s_{\gamma p} - M^2} (\sigma_p - \sigma_A) = 2\pi^2 \alpha_{\text{QED}} \kappa^2 / M^2 \tag{7}
\]

where \( \sigma_p \) and \( \sigma_A \) are the spin dependent photo-absorption cross-sections, \( s_{\gamma p} \) is the photon-proton centre of mass energy squared with \( \kappa \) the target’s anomalous magnetic moment and \( M \) the target mass. For free protons with \( \kappa = 1.79 \) the sum-rule predicts a value of 205 \( \mu \)b whereas the current value extracted from experiments is \( 211 \pm 13 \mu \)b \([11]\). The dominant contribution to the GDH sum-rule comes from the \( \Delta \) resonance excitation \([12]\) with other resonance contributions averaging to about zero. There is a \( \sim 10\% \) high-energy Regge contribution in the isovector channel with negligible isoscalar contribution from centre of mass energy greater than about 2.5 GeV \([11]\).

Both sides of the GDH sum-rule are expected to be enhanced in medium. The nucleon and \( \Delta \) effective masses and the nucleon magnetic moments are expected to change in nuclei. Consider a polarized proton in symmetric nuclear matter. In the QMC model the difference in nucleon and \( \Delta \) masses, \( M_N - M_\Delta \), is taken as density independent, with the nucleon mass decreasing by a factor of \((1 - 0.2\rho/\rho_0)\) where \( \rho \) is the nuclear density \([13]\). Within the same model the nucleon magnetic moments increase by factor of \((1 + 0.1\rho/\rho_0)\) with \( \mu_N^*/\mu_N \sim g_A^{(3)}/g_{A}^{s(3)} \) \([21]\). That is, the proton and \( \Delta \) resonance masses decrease in medium whereas the proton magnetic moment increases with increasing nuclear density. For the GDH integral, Eq. (7), the \( \Delta \) resonance contribution to the integral will be enhanced at smaller effective \( \Delta \) mass, weighted by \( 1/(\text{the incident photon energy in the LAB frame}) \). Taking the QMC values for the proton effective mass and magnetic moment in medium, one finds an enhancement in the GDH integral by factor of 2.1 at \( \rho_0 \). Future experimental study would be very interesting and complement deep inelastic measurements of QCD spin effects in nuclei.

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