GAMOW–TELLER TRANSITIONS AND THE SPIN EMC EFFECT: THE BJORKEN SUM-RULE IN MEDIUM*

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(Received November 25, 2020; accepted December 17, 2020)

Gamow–Teller transitions in nuclei tell us that the nucleon's axial charge $g_{\rm A}^{(3)}$ 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.

DOI:10.5506/APhysPolB.52.43

1. 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 the recent discussion, see [3]. New experiments are planned at the Jefferson Laboratory with a polarized ^{7}Li target to look for a possible spin version of the EMC nuclear effect in the range of $0.06 < x < 0.8$ [4]. How is the internal spin structure of the proton modified when the proton is in a nuclear medium?

Here, we explain how the 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 Gamow–Teller transition 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 spin contributions to the proton's spin in the nuclear medium. The dynamics of this quenching of $g_A^{(3)}$ is driven by combination of the Ericson–Ericson–Lorentz–Lorenz effect and pion cloud effects in nuclei with short-range nucleon–nucleon correlations tending to reduce the axial-charge suppression [8, 9]. This result has important consequences for models of the EMC nuclear effect. Specific models of partonic spin structure in medium have been discussed in Refs. [10–18].

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 [3]. 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 [18], in contrast to the phenomenological constraint from the quenching found in the 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. Conclusions are given in Section 6.

2. 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

$$2MS_\mu \Delta q = \langle p,S|\bar{q}\gamma_\mu\gamma_5 q|p,S\rangle \tag{1}$$

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

$$\begin{aligned} g_{\rm A}^{(3)} &= \Delta u - \Delta d\,, \\ g_{\rm A}^{(8)} &= \Delta u + \Delta d - 2\Delta s\,, \\ g_{\rm A}^{(0)} &= \Delta u + \Delta d + \Delta s\,. \end{aligned} \tag{2}$$

Each spin term Δq ($q = u, d, s$) is understood to contain a contribution from polarized gluons, $-\frac{\alpha_{\rm s}}{2\pi}\Delta g$, where $\alpha_{\rm s}$ is the QCD coupling and Δg is the polarized gluon contribution to the proton's spin. This polarized gluon term contributes in $g_{\rm A}^{(0)}$ but cancels in $g_{\rm A}^{(3)}$ and $g_{\rm A}^{(8)}$. The value of the singlet $g_{\rm A}^{(0)}$ is also sensitive to a possible topological contribution, $\mathcal{C}_\infty$, which, if finite, is associated with the 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

$$\int_0^1 {\rm d}x g_1^{(p-n)}\left(x, Q^2\right) = \frac{g_{\rm A}^{(3)}}{6} C_{\rm NS}\left(Q^2\right)\,, \tag{3}$$

where x is the Bjorken variable, $g_{\rm A}^{(3)} = 1.270 \pm 0.003$ from neutron β-decays and $C_{\rm NS}(Q^2)$ is the perturbative QCD Wilson coefficient, $\simeq 0.85$ with QCD coupling $\alpha_{\rm s} = 0.3$ [1]. This sum-rule has been confirmed in polarized deep inelastic scattering experiments at the level of 5% [19]. 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 of $x > 0.2$ [20]. The size of $g_{\rm A}^{(3)}$ forces us to accept a large contribution from small x with the observed rise

$$g_1^{(p-n)} \sim x^{-0.22\pm0.07} \tag{4}$$

found in COMPASS data from CERN at $Q^2 = 3$ GeV^2 for small-x data down to $x_{\rm min} \sim 0.004$ [19]. Surprisingly, recent analysis [21] of high statistics data from the CLAS experiment at the Jefferson Laboratory and COMPASS reveals that the rising 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 $\alpha_{a_1} = 0.31 \pm 0.04$ [21] 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 [22].

The isoscalar spin structure function $g_1^{(p+n)} \sim 0$ for $x < 0.03$ at deep inelastic Q^2 [1], 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 ~ 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 [23], the colour hyperfine interaction or one-gluon-exchange current (OGE) [24], a modest polarized gluon correction $-3\frac{\alpha_s}{2\pi}\Delta g$ with Δg non-zero [25] and less than about 0.5 at the scale of the experiments [1], and a possible topological effect at $x = 0$ [2].

3. $g_A^{(3)}$ in medium

Static properties of hadrons (masses, axial charges, magnetic moments ...) are modified in a nuclear medium [5, 26–28]. For axial structure, the Gamow–Teller transitions (β decays of large nuclei) tell us that the effective axial charge in medium $g_A^{*(3)}$ is suppressed in large nuclei by about 20% [5]; for recent reviews of experimental data, see [29, 30]. 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 $g_A^{*(3)}$ in nuclei tells us that the spin structure of the nucleon is modified in nuclei with

$$g_A^{*(3)} = \Delta u^* - \Delta d^* \simeq 1 \tag{5}$$

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

Quenching of $g_A^{*(3)}$ can be understood in terms of nucleon, Δ 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 [5, 9] and from interaction with the pion cloud in the nucleus [8]. These terms each give about 50% of the quenching effect. Any contribution from short-range nucleon correlations tends to reduce the quenching, see [8] 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 $g_A^{*(3)}$ at ρ_0 [31]. Here, medium modifications of hadron properties are calculated by treating the hadron as an MIT Bag and coupling the valence quarks to the scalar σ (correlated two pion) and vector ω and ρ 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 [32]. In recent QCD lattice calculations, modest suppression of $g_A^{*(3)}$, a few percent, is found for light nuclei [33].

What does the quenching of $g_A^{*(3)}$ mean for models of the EMC nuclear effect?

4. 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

$$\Delta R_A^H(x) = \frac{g_1^{AH}(x)}{P_{AH}^p g_1^p(x) + P_{AH}^n g_1^n(x)}\,, \tag{6}$$

where g_1^{AH} is the spin-dependent structure function for a nucleus with helicity H and mass number A, g_1^p and g_1^n 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 [13, 16].

Today, 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 [28]. In a different view, nucleons are unmodified most of the time but are modified substantially when they fluctuate into short-range correlated pairs, SRCs [34]. Experimentally, a correlation is observed between SRCs and the magnitude of the unpolarized EMC effect in nuclei [35] 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.

Early calculations in a model with explicit pion and Δ resonance degrees of freedom [10, 11, 13] plus more recent calculations of the nucleon's g_1 spin structure function in medium based on mean field approaches [14–17] suggest a large spin EMC effect in the valence region at medium x. Calculations in the QMC model give a ratio of in-medium to free nucleon spin structure functions similar in size to the unpolarized EMC nuclear effect with $g_A^{*(3)}$ reduced by about 10% at ρ_0 [17]. 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 $g_A^{*(3)}$ reduced by about 20% at ρ_0, and with a constant EMC ratio $\Delta R_A^H(x) \sim 0.93$ for $x < 0.7$ with $g_A^{*(3)}$ reduced by about 6% in ^{7}Li [16]. Shadowing at small x is considered in [12].

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 [18]. In SRCs, two nucleons meet with low relative momentum and relative angular momentum in 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 the order of -10 to -15% instead of $+100$% [18]. That is, any medium modification induced by the SRC in the unpolarized structure function is washed out in the spin structure function $g_1^{AH}(x)$ and in $\Delta R_A^H(x)$. This contrasts with the 20% quenching of $g_A^{*(3)}$ expected from the Gamow–Teller transitions.

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 the 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.

5. The GDH sum-rule in medium

One also expects medium dependence of the GDH sum-rule and the spin-dependent photoabsorption cross sections with polarized real photon scattering, $Q^2 = 0$. The GDH sum-rule for polarized photon–proton scattering reads [36, 37]

$$\int_{M^2}^{\infty} \frac{\mathrm{d}s_{\gamma p}}{s_{\gamma p} - M^2} (\sigma_\mathrm{P} - \sigma_\mathrm{A}) = 2\pi^2 \alpha_\mathrm{QED} \kappa^2 / M^2 \,. \tag{7}$$

Here, σ_P and σ_A are the spin-dependent photoabsorption cross sections for a transversely polarized photon with spin parallel σ_P and antiparallel σ_A to the spin of the target proton. $s_{\gamma p}$ is the photon–proton centre-of-mass energy squared with κ 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 μb, whereas the current value extracted from experiments is 211 ± 13 μb [21]. The dominant contribution to the GDH sum-rule comes from the Δ resonance excitation [22] 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 a centre-of-mass energy greater than about 2.5 GeV [21].

Both sides of the GDH sum-rule are expected to be enhanced in medium. The nucleon and Δ effective masses and the nucleon magnetic moments are expected to change in nuclei. Let us consider a polarized proton in symmetric nuclear matter. In the QMC model, the difference in nucleon and Δ 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 ρ is the nuclear density [28]. Within the same model, the nucleon magnetic moments increase by a factor of $(1 + 0.1\rho/\rho_0)$ with $\mu_N^*/\mu_N \sim g_\mathrm{A}^{(3)}/g_\mathrm{A}^{*(3)}$ [31]. That is, the proton and Δ resonance masses decrease in medium, whereas the proton magnetic moment increases with increasing nuclear density. For the GDH integral, Eq. (7), the Δ resonance contribution to the integral will be enhanced at smaller effective Δ mass, weighted by 1/(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 a factor of 2.1 at ρ_0. As an independent estimate, the effective mass of anti-protons is observed in heavy-ion collisions to be reduced by about 100–150 MeV at density $2\rho_0$ [38]. Making the usual linear density approximation for this (anti-)proton effective mass reduction, combined with a 20% reduction in $g_\mathrm{A}^{*(3)}$, while still assuming $\mu_N^*/\mu_N \sim g_\mathrm{A}^{(3)}/g_\mathrm{A}^{*(3)}$, gives an enhancement in the GDH integral of factor of 2.2 at ρ_0, similar to the QMC estimate for this quantity.

6. Conclusions

Quenching of the nucleon's axial charge in medium revealed in the Gamow–Teller transitions provides a sum-rule constraint on the nucleon's spin structure in medium. Pions in nuclei and the Ericson–Ericson–Lorentz–Lorenz effect modify $g_{\rm A}^{(3)}$ and the partonic spin structure of nucleons in nuclei relative to free nucleons. Models of the medium dependence of parton structure based only on short-range nucleon correlations are disfavoured with SRCs acting to suppress the quenching of $g_{\rm A}^{(3)}$. While a 20% suppression of the Bjorken sum-rule of polarized deep inelastic scattering is expected when scattering from nucleons in nuclei at nuclear matter density, a much larger effect — factor of two enhancement — is expected in the Gerasimov–Drell–Hearn sum-rule for polarized photoproduction. Future experimental study of the GDH sum-rule in medium would be very interesting and complement deep inelastic measurements of QCD spin effects in nuclei. Studies of polarized photoproduction with nuclear targets might be possible in future experiments at the Jefferson Laboratory [39].

I thank C. Aidala for helpful discussion.

REFERENCES

[1] C.A. Aidala, S.D. Bass, D. Hasch, G.K. Mallot, «The spin structure of the nucleon», *Rev. Mod. Phys.* **85**, 655 (2013).

[2] S.D. Bass, «The spin structure of the proton», *Rev. Mod. Phys.* **77**, 1257 (2005).

[3] I.C. Cloët *et al.*, «Exposing novel quark and gluon effects in nuclei», *J. Phys. G: Nucl. Part. Phys.* **46**, 093001 (2019).

[4] W. Brooks *et al.*, JLab experiment proposal PR12-14-001, https://www.jlab.org/exp_prog/proposals/14/PR12-14-001.pdf

[5] T.E.O. Ericson, W. Weise, «Pions and Nuclei», *Oxford University Press*, 1988.

[6] J.D. Bjorken, «Applications of the chiral $U(6) \otimes U(6)$ algebra of current densities», *Phys. Rev.* **148**, 1467 (1966).

[7] J.D. Bjorken, «Inelastic scattering of polarized leptons from polarized nucleons», *Phys. Rev. D* **1**, 1376 (1970).

[8] M. Ericson, «Chiral symmetry restoration and parity mixing», *Acta Phys. Pol. B* **29**, 2349 (1998).

[9] M. Ericson, A. Figureau, C. Thevenet, «Pionic field and renormalization of the axial coupling constant in nuclei», *Phys. Lett. B* **45**, 19 (1973).

[10] L. de Barbaro, K.J. Heller, J. Szwed, «The spin dependent structure function inside a nucleus», Jagiellonian University preprint TPJU-24/84.

[11] J. Szwed, «The EMC effect for spin dependent structure functions», *J. Phys. Colloq.* **46**, 269 (1985).

[12] V. Guzey, M. Strikman, «Nuclear effects in $g_1^A(x,Q^2)$ at small x in deep inelastic scattering on ^{7}Li and ^{3}He», *Phys. Rev. C* **61**, 014002 (2000).

[13] A. Sobczyk, J. Szwed, «Nuclear effects on the spin dependent structure functions», *Acta Phys. Pol. B* **32**, 2947 (2001).

[14] I.C. Cloët, W. Bentz, A.W. Thomas, «Spin-dependent structure functions in nuclear matter and the polarized EMC effect», *Phys. Rev. Lett.* **95**, 052302 (2005).

[15] J.R. Smith, G.A. Miller, «Polarized quark distributions in nuclear matter», *Phys. Rev. C* **72**, 022203 (2005).

[16] I.C. Cloët, W. Bentz, A.W. Thomas, «EMC and polarized EMC effects in nuclei», *Phys. Lett. B* **642**, 210 (2006).

[17] S. Tronchin, H.H. Matevosyan, A.W. Thomas, «Polarized EMC effect in the QMC model», *Phys. Lett. B* **783**, 247 (2018).

[18] A.W. Thomas, «Reflections on the origin of the EMC effect», *Int. J. Mod. Phys. E* **27**, 1840001 (2018).

[19] COMPASS Collaboration (M.G. Alekseev *et al.*), «The spin-dependent structure function of the proton g_1^p and a test of the Bjorken sum rule», *Phys. Lett. B* **690**, 466 (2010).

[20] S.D. Bass, «Constituent quarks and g_1», *Eur. Phys. J. A* **5**, 17 (1999).

[21] S.D. Bass, M. Skurzok, P. Moskal, «Updating spin-dependent Regge intercepts», *Phys. Rev. C* **98**, 025209 (2018).

[22] K. Helbing, «The Gerasimov–Drell–Hearn Sum Rule», *Prog. Part. Nucl. Phys.* **57**, 405 (2006).

[23] S.D. Bass, A.W. Thomas, «The nucleon's octet axial-charge $g_A^{(8)}$ with chiral corrections», *Phys. Lett. B* **684**, 216 (2010).

[24] F. Myhrer, A.W. Thomas, «A possible resolution of the proton spin problem», «A possible resolution of the proton spin problem», *Phys. Lett. B* **663**, 302 (2008).

[25] D. de Florian, R. Sassot, M. Stratmann, W. Vogelsang, «Evidence for polarization of gluons in the proton», *Phys. Rev. Lett.* **113**, 012001 (2014).

[26] S.D. Bass, P. Moskal, «η' and η mesons with connection to anomalous glue», *Rev. Mod. Phys.* **91**, 015003 (2019).

[27] V. Metag, M. Nanova, E.Y. Paryev, «Meson–nucleus potentials and the search for meson–nucleus bound states», *Prog. Part. Nucl. Phys.* **97**, 199 (2017).

[28] K. Saito, K. Tsushima, A.W. Thomas, «Nucleon and hadron structure changes in the nuclear medium and the impact on observables», *Prog. Part. Nucl. Phys.* **58**, 1 (2007).

[29] J. Suhonen, «Quenching of the Weak Axial-vector Coupling Strength in β Decays», *Acta Phys. Pol. B* **49**, 237 (2018).

[30] J.T. Suhonen, «Value of the Axial-Vector Coupling Strength in β and $\beta\beta$ Decays: A Review», *Front. Phys.* **5**, 55 (2017).

[31] K. Saito, A.W. Thomas, «Variations of hadron masses and matter properties in dense nuclear matter», *Phys. Rev. C* **51**, 2757 (1995).

[32] S. Nagai, T. Miyatsu, K. Saito, K. Tsushima, «Quark–meson coupling model with the cloudy bag», *Phys. Lett. B* **666**, 239 (2008).

[33] NPLQCD Collaboration (E. Chang *et al.*), «Scalar, axial, and tensor interactions of light nuclei from lattice QCD», *Phys. Rev. Lett.* **120**, 152002 (2018).

[34] O. Hen, G.A. Miller, E. Piasetzky, L.B. Weinstein, «Nucleon–nucleon correlations, short-lived excitations, and the quarks within», *Rev. Mod. Phys.* **89**, 045002 (2017).

[35] L.B. Weinstein *et al.*, «Short range correlations and the EMC effect», *Phys. Rev. Lett.* **106**, 052301 (2011).

[36] S.B. Gerasimov, «A sum rule for magnetic moments and the damping of the nucleon magnetic moment in nuclei», *Sov. J. Nucl. Phys.* **2**, 430 (1966), *Yad. Fiz.* **2**, 598 (1965).

[37] S.D. Drell, A.C. Hearn, «Exact sum rule for nucleon magnetic moments», *Phys. Rev. Lett.* **16**, 908 (1966).

[38] A. Schröter *et al.*, «Subthreshold anti-proton and K^- production in heavy ion collisions», *Z. Phys. A* **350**, 101 (1994).

[39] M. Dalton, private communication.