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LETTER TO THE EDITOR

Can the quenching of axial coupling in nuclei be attributed to excess gluons?

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Abstract. It is suggested that enhancement of the gluon distribution in nuclei relative to free nucleons might be responsible for quenching of the axial vector coupling in nuclei. Using the Carlitz–Kaur model for quark spin distributions, the consequences of gluonic enhancement are explored numerically for a range of nuclei.

An unresolved problem in nuclear physics is the apparent quenching (reduction from the free nucleon value $g_A/g_V = 1.251 \pm 0.009$) of the nucleon axial vector coupling inside nuclei. Wilkinson [1] was the first to systematically explore the reduction in Gamow–Teller beta decay rates, which depend on the expectation of $g_A \Sigma_i \sigma_3(i) \tau_3(i)$ between nuclear states, and found that experimental rates were well reproduced by taking $(g_A/g_V)_{\text{eff}} = 1.122 \pm 0.045$. More recently Brown and Wildenthal [2] have done a similar calculation on s–d shell nuclei and find $(g_A/g_V)_{\text{eff}} = 0.951 \pm 0.039$. Interpretations of p–n reactions at forward angles [3] have also been in terms of quenched couplings. But in spite of this apparent evidence, the quenching of g_A/g_V in complex nuclei is controversial because of the nuclear model dependence arising from the finite size of the model space, the basis functions and the residual tensor force, [4]. This tensor force is very short ranged and it excites high-lying shell-model states, making the calculations quite model dependent. Perhaps more importantly, the issue of whether it is reasonable to use nucleonic degrees of freedom for high excitations (short distances) becomes significant [5]. Recently, Rho [6] has offered a picture of quenching wherein the nucleon, modelled as a skyrmion, expands by about 40% in a nuclear environment and has $(g_A/g_V)_{\text{eff}} \sim 1$. Thus, an intrinsic property of the nucleon is assumed to be altered by the medium. In this Letter we too shall explore the medium dependence of g_A, but with the change attributed entirely to an enhancement of the gluon distribution in nuclei. We have found no other work in the literature linking changes in g_A to gluonic effects.

At the present time the only real experimental evidence for enhancement of the gluon density $G(x)$ in nuclei comes from the EMC group [7, 8]. The procedure adopted was to compare cross-sections for the productions of J/ψ off iron and deuterium targets. For the range $0.02 < x < 0.08$ and $Q^2 \sim 10$ GeV^2 it was found [7, 8] that

$$G(x)^{\text{Fe}}/G(x)^{\text{d}} = 1.44 \pm 0.12\ (\text{stat.}) \pm 0.20\ (\text{syst.}).$$

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While the errors are large, these results are consistent with an important class of models originally devised to explain the EMC effect [9] observed in lepton–nucleus deep inelastic experiments. The 'rescaling' explanation of Close *et al* [10] (CJRR rescaling) and the colour conductivity model of Nachtmann and Pirner [11] both necessarily call for enhanced gluonic distributions. It therefore seems valid to speculate on how g_A/g_V may be affected by excess nuclear gluons.

Within the context of the QCD parton model the Björken sum rule [12, 13] (BSR), corrected for leading-order scaling violations [14], provides a connection between g_A and primordial quark distributions in a nucleon:

$$\int_0^1 dx[\Delta u(x, Q^2) + \Delta \bar{u}(x, Q^2) - \Delta d(x, Q^2) - \Delta \bar{d}(x, Q^2)] = \frac{g_A}{g_V}\left(1 - \frac{\alpha_s(Q^2)}{\pi}\right). \tag{1}$$

Here $\Delta q = q_{\uparrow\uparrow} - q_{\downarrow\uparrow}$ denotes the distribution of quarks in a proton with helicity of the quark parallel to the proton's helicity minus the corresponding antiparallel distribution. While the BSR has not been verified to adequate accuracy because of experimental difficulties [15], it is based on the solid foundations of current algebra and is strongly believed to be correct. Normally [16, 17] it is used as a *constraint* on phenomenological forms for Δq because polarised neutron DIS experiments have not been carried out so far. However, we shall use the BSR to calculate the *shift* in g_A/g_V for a nucleon when that nucleon is embedded in a nucleus.

QCD cannot, as yet, be used to calculate *ab initio* the primordial quark spin distributions $\Delta q(x, Q^2)$ since these lie in the non-perturbative domain. However, much insight can be gained from the broken SU(6) model of Carlitz and Kaur [17]. This happens to be the only QCD-based model compatible with the SLAC data [15]. (For a comparison of different models see reference [18].) The physics of the model is as follows: a valence quark embedded in a sea of gluons has a non-zero probability of flipping its helicity. Consequently, spin is transferred from valence quarks to gluons, leaving the quarks relatively less polarised. If $N(x)$ denotes the density in x of gluons relative to valence quarks, then a measure of the spin dilution caused by gluons is [17]

$$\cos 2\theta(x) = 1/(1 + H_0 N(x)) \tag{2}$$

with

$$N(x) = x^{-1/2}(1-x)^2. \tag{3}$$

Here H_0 is a phenomenological coupling constant for quark–gluon spin-flip interactions. We shall have some words to say about the physics incorporated in it later. The factor $x^{-1/2}$ arises from the low-x Regge behaviour of parton densities, and $(1-x)^2$ from the assumed gluon fall-off. Actually the results are quite insensitive to the exponent of $(1-x)$ because $\cos 2\theta(x)$ differs substantially from one only near $x \sim 0$. In terms of this spin dilution factor, the quark spin distributions are

$$\begin{aligned} \Delta u(x) &= \cos 2\theta(x)(u_v(x) - \tfrac{2}{3} d_v(x)) \\ \Delta d(x) &= -\tfrac{1}{3}\cos 2\theta(x) d_v(x) \\ \Delta \bar{u}(x) &= \Delta \bar{d}(x) = 0. \end{aligned} \tag{4}$$

Note that the quark sea is assumed to be unimportant in taking angular momentum away from valence quarks. This can perhaps be justified since gluons carry much more of the hadron's *linear momentum* ($\sim 50\%$) than sea quarks. For any given set of quark and gluon distributions, such as those of Duke and Owens [19], the value of H_0 is fixed by the BSR together with $g_A/g_V = 1.251 \pm 0.009$. To do so, a slight generalisation of equation (3) is called for:

$$N(x, Q^2) = \frac{G(x, Q^2)}{\frac{1}{2}(\frac{1}{2}u_v(x, Q^2) + d_v(x, Q^2))}. \tag{5}$$

This leaves the fit to the polarised electroproduction data intact as in figure 1.9 of reference [13]. One could imagine taking separate forms of $N(x)$ for u and d quarks, but this is an inessential generalisation and the numerical consequences were found to be small as well.

Now imagine embedding the nucleon inside a nucleus, as a consequence of which $q_v \to q'_v$ and $G \to G'$. At this point, for numerical estimation one needs to consider specific models for q'_v and G', the valence quark and gluon densities inside nuclei.

(i) *CJRR rescaling [10].* This theory, the most notable success of which was in predicting the A dependence of the EMC effect, assumes that gluons and quarks undergo partial deconfinement in a nucleus. Consequently the phase space for a quark to radiate gluons (bremsstrahlung) increases, causing a 'softening' of gluon and quark densities (i.e. a shift towards smaller x). Quantitatively, from renormalisation group arguments $q_v(x, Q^2) \to q_v(x, \xi Q^2)$ and $G(x, Q^2) \to G(x, \xi Q^2)$, where $\xi > 1$ is determined from the degree of overlap of quark clusters and also depends weakly on Q^2. For the purpose of estimating g_A/g_V in nuclei we make the following observation: whereas both q_v and G are softened, the small x Regge behaviours $q_v(x) \to x^{-1/2}$ and $G(x) \to x^{-1}$ mean that the softening of $G(x)$ will dominate and will therefore *increase* the degree of spin quenching. In other words, more spin gets transferred from valence quarks to gluons; therefore, from the BSR in equation (1), g_A/g_V will be effectively quenched in a nucleus. In figure 1 this quenching is shown for a range of nuclei. The quark and gluon distributions (first set only) of Duke and Owens [19] were used together with the values of ξ given by CJRR [10]. It should be mentioned that rescaling must be used for soft gluons as well. This may not be totally justified, but the same problem is also encountered in the ψ/J production calculations [10].

(ii) *Colour conductivity model [11].* This model basically allows highly energetic quarks to travel more freely through the nucleus, thereby simulating deconfinement. In common with CJRR rescaling, changing the confinement scale of quarks is equivalent to considering structure functions at a shifted Q^2: $q_v(x, Q^2) \to q_v(x, Q^2 R_A^2/R_d^2)$ and $G(x, Q^2) \to G(x, Q^2 R_A^2/R_d^2)$ with R_A and $R_d (R_d = 2.17\ \mathrm{fm})$ being the RMS radii of the nucleus and deuteron respectively. The predictions for g_A/g_V in this model are also shown in figure 1. The smooth behaviour as a function of A arises because $R_A \sim r_0 A^{1/3}$ and the substantially larger quenching is a consequence of greater deconfinement in this model relative to CJRR rescaling. Both models, however, suggest much less quenching than in models using quark bags and skyrmions, in which up to 30% quenching is claimed [5, 6]. The present results show that quenching is a relatively small, but still interesting, effect which is compatible within the uncertainties of existing nuclear structure calculations.

The numerical results obtained above were in the specific context of a model for quark spin distributions, and one would like to understand the essential physics better.

In QCD parton model language g_A/g_V measures the distribution of hadron spin among various partons, and is a non-perturbative quantity reflecting the nature of spin-dependent forces. In a hypothetical nucleon in which all the angular momentum is carried by gluons, and in which quarks are completely depolarised, the value of g_A/g_V would be zero. For nuclear physics the interesting question is: how can one estimate the *shift* induced in the parton spin distributions by the nuclear environment? If nuclei contain excess gluons then one needs to understand how the quark spin distribution responds. So consider the matrix element for the gluon–quark interaction in figure 2. The incoming and outgoing quark

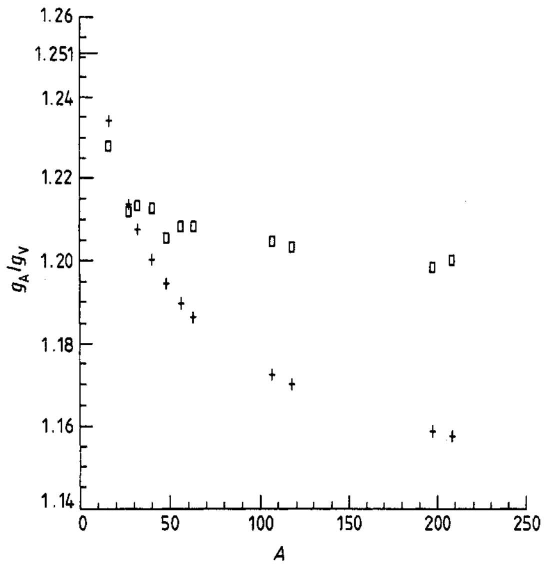

Figure 1. Axial coupling strengths for nucleons embedded in nuclei calculated using the Carlitz–Kaur model with nuclear quark and gluon distributions obtained from CJRR rescaling [10] (boxes) and the colour conductivity model [11] (crosses).

have *opposite helicities*, and transverse gluon polarisations are summed over. A quick calculation yields

$$\begin{aligned}|M_{\lambda_+\lambda_-}|^2 &= |M_{\lambda_-\lambda_+}|^2 \\ &= \sum_{\text{gluon pol.}} |\bar{u}(p_f\lambda_+)\gamma_\mu u(p_i\lambda_-)\varepsilon^\mu|^2 \\ &= m^2\frac{1+x^2}{x}.\end{aligned} \tag{6}$$

The above calculation is in the infinite momentum frame with $p_i=(p, \boldsymbol{O}_T, p)$ and $p_f=(xp+\boldsymbol{p}_T^2/2xp, \boldsymbol{p}_T, xp)$. It serves to illustrate several points. First, no spin can ever be transferred between quarks and gluons if $m^2\equiv 0$. This also means that the phenomenological parameter H_0 of the Carlitz–Kaur model would vanish for zero quark mass. Quark masses are non-perturbative, gauge-dependent quantites [20] and are largely determined by properties of the quark condensate $\langle\bar{q}q\rangle$. Although they are of importance for small x only, it is precisely here that angular momentum is exchanged between quarks and gluons. One should therefore view H_0, or perhaps a generalisation to $H_0(x, Q^2)$, as a

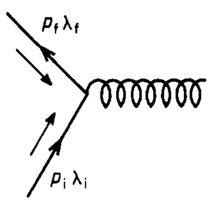

Figure 2. Spin-flip quark–gluon scattering.

phenomenological way of allowing for spin-flip processes induced by the condensate. It should also be noted that $|M|^2$ is independent of $\boldsymbol{p}_T^2$, the transverse gluon or quark momentum. This means that the integral $\int \mathrm{d}\boldsymbol{p}_T^2(1/\boldsymbol{p}_T^2)|M|^2$ needed for calculating branching probabilities is infrared divergent and has to be regulated by imposing a cut-off, presumably depending on the inverse of hadron size. In any case, the purpose of the above remarks was merely to highlight the non-perturbative character of spin transfer. A first-principles calculation of quark polarised distributions is no more possible than one of unpolarised distributions. However, better models could, and should, be constructed.

To conclude, it was shown in the context of a particular partonic model that gluonic excess in nuclei could lead to a downward shift in individual nucleon axial coupling strengths. Numerically, this turns out to be a roughly 5% effect for medium nuclei. This also amounts to a manifestation of an 'EMC effect' for quark spin distributions and suggests that if polarised-lepton–polarised-nucleus experiments could be made feasible then very interesting non-additive effects would be seen.

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