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Spin structure functions and gluon exchange

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Two-quark correlations due to gluon exchange give corrections to both the proton and neutron spin-dependent structure functions in the Bjorken sum rule. They are found to be as large as the pionic corrections in the cloudy bag model of the nucleon. While still not enough to explain the result published recently by the European Muon Collaboration, it is compatible with the reanalysis of the data by Close and Roberts.

In a recent paper Høgaasen and Myhrer[1] reported a calculation of gluon-exchange corrections to some low-energy hadronic properties using the MIT bag model.[2] This work,[1] which confirmed earlier studies by Ushio and Konashi[3] and Ushio,[4] explained the measured[5] ratio $\Sigma^- \to ne\bar{\nu}/\Lambda \to pe\bar{\nu}$ as well as why the magnetic moment of Ξ^- is more negative that that of the Λ ($\mu_{\Xi^-} < \mu_\Lambda = -0.61\mu_N$, where μ_N is the nuclear magneton).[5] In addition it restored the nucleons' magnetic-moment ratio $\mu_p/\mu_n \cong -\frac{3}{2}$ which presents difficulties for chiral bag models.[6] We examine the effect of these same corrections on the integrated spin distribution functions of the proton and neutron in the Bjorken sum rule.[7] This is of particular interest at the present time due to the recent results from the European Muon Collaboration[8] (EMC).

For a given nucleon (N) target the usual quark commutation relations imply that

$$\int_0^1 dx\, g_1^N(x) = \tfrac{1}{2}\langle N\uparrow|\bar{\psi}\gamma_Z\gamma_5 Q^2\psi|N\uparrow\rangle , \qquad (1)$$

where ψ is the quark field operator, Q is the quark charge, and $|N\uparrow\rangle$ denotes a spin-up nucleon state. The Bjorken sum rule which says that

$$\int_0^1 dx[g_1^p(x) - g_1^n(x)] = \frac{1}{6}\frac{g_A}{g_V} \qquad (2)$$

is then easily obtained. We stress the beauty of Eqs. (1) and (2), which relate deep-inelastic-scattering (DIS) results at high energy and momentum transfer to low-energy matrix elements. The latter can be examined in any conventional model of nucleon structure.

If we assume the standard spin-flavor **56** representation of SU(6) for the nucleon, the right-hand side of Eq. (1) vanishes for the neutron in either the nonrelativistic quark model (NRQM) or in the MIT bag model. However, we shall show that this is no longer the case when the exchange-current corrections associated with the chromomagnetic interaction are taken into account. The processes we shall calculate are illustrated in Fig. 1 where we specify the possible intermediate excited quark and antiquark states (with total angular momentum $j = \frac{1}{2}$ or $\frac{3}{2}$), denoted by M below. For the axial-vector current of Ref. 1 the operator $O(l)$ for quark l is $\sigma_Z(l)\tau(l)$, where the flavor operator τ changes a d quark into a u quark ($\Delta S = 0$ decay). Here we need the quark operator of Eq. (1)

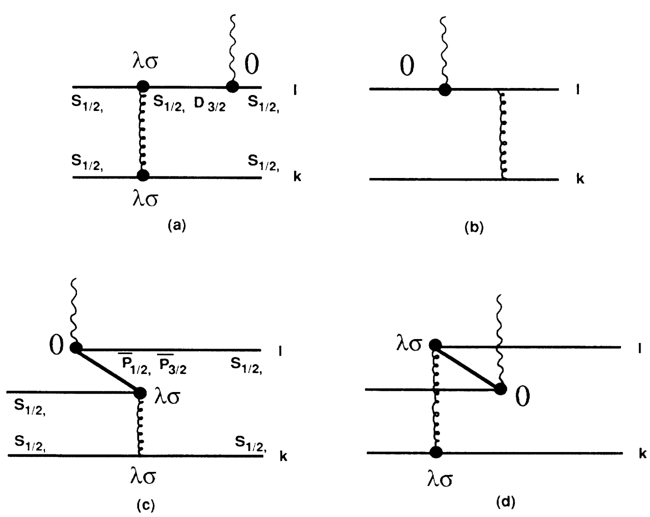

FIG. 1. Illustration of the different Feynman tree diagrams which contribute to the chromomagnetic exchange currents. Diagrams (c) and (d) contain intermediate four-quark–one-antiquark states.

$O(l)=\sigma_Z(l)Q^2(l)$ together with the color-magnetic gluon exchange between quarks k and l where quark l goes from a $j=\frac{1}{2}$ to a $j=p$ state ($p=\frac{1}{2}$ or $\frac{3}{2}$)

$$H(k,l)=b_{kl}\lambda^a(k)\lambda^a(l)\sigma(k)\cdot\sigma^{[1/2,p]}(l)\,, \qquad (3)$$

and $k\neq l$ since we work in the tree approximation. The coefficients b_{kl} are model dependent because they are functions of the quark masses and include the spatial integration of products of quark wave functions. The spin matrices $\sigma^{[1/2,p]}(l)$ are transition matrices in spin space[9] corresponding to the transition from a quark state of angular momentum $\frac{1}{2}$ to angular momentum p. As illustrated in Fig. 1 we have both $j=\frac{1}{2}$ and $j=\frac{3}{2}$ intermediate states. The general correction to $\int_0^1 dx\, g_1^N(x)$ will have the form

$$\sum_M \Delta g_A(M)\,\tfrac{1}{2}\langle N\uparrow|\sum_{k\neq l}\sigma_Z(k)Q^2(l)|N\uparrow\rangle\,. \qquad (4)$$

Here the sum over the intermediate quark states M converges rapidly as shown[1] and we have used the fact that for the $j=\frac{1}{2}$ intermediate states $\sigma^{[1/2,1/2]}=\sigma$ and

$$[\sigma(k)\cdot\sigma(l),\sigma_Z(l)]_+=2\sigma_Z(k)\,, \qquad (5a)$$

while for the $j=\frac{3}{2}$ intermediate states

$$[\sigma(k)\cdot\sigma^{[1/2,3/2]}(l),\sigma_Z^{[3/2,1/2]}(l)]_+=\tfrac{4}{3}\sigma_Z(k)\,. \qquad (5b)$$

The quantities $\Delta g_A(M)$ involve spatial integrals over quark wave functions and propagators and are all given in Ref. 1 with the result $C''=\sum_M\Delta g_A(M)=-0.056$. We are left with calculating the spin-flavor matrix element of the *two-body* operator $\sum_{k\neq l}\sigma_Z(k)Q^2(l)$. Using the **56** spin-flavor nucleon wave function we find this matrix element to be $\frac{2}{9}$ for the neutron and $\frac{4}{9}$ for the proton.

The effect of this exchange-current correction on the sum rule for the spin structure functions is twofold. First, it modifies the value of g_A (for the model):

$$g_A=g_A^0+\delta g_A\,, \qquad (6a)$$

where

$$\delta g_A=C''_{FS}\langle p\uparrow|\sum_{l\neq k}\sigma_Z(k)\tau(l)|n\uparrow\rangle_{FS} = -\tfrac{2}{3}C''\,, \qquad (6b)$$

where C'' is negative[1] and proportional to α_s and the subscript FS denotes the flavor-spin **56** states only. This value of g_A appears in the Bjorken sum rule. However, this correction δg_A is not of direct concern to us since the parameters of a model could be arranged to yield the experimentally observed value of g_A after δg_A is included. Second, and more important, the exchange current gives a negative contribution to $\int_0^1 dx\, g_1^n(x)$ and reduces the standard theoretical values of $\int_0^1 dx\, g_1^p(x)$. We find

$$\int_0^1 dx\, g_1^p(x)=\tfrac{1}{6}g_A^0+\tfrac{1}{2}\tfrac{4}{9}C''=\tfrac{1}{6}g_A+\tfrac{1}{3}C'' \qquad (7)$$

and

$$\int_0^1 dx\, g_1^n(x)=\tfrac{1}{2}\times\tfrac{2}{3}C'' \qquad (8)$$

so that the Bjorken sum rule for the difference of proton and neutron is preserved:

$$\int_0^1 dx[g_1^p(x)-g_1^n(x)]=\tfrac{1}{6}g_A \qquad (9)$$

as before. Numerically $C''=-0.056$, which means these gluon-exchange currents are of the same order and have the same signs as the pionic corrections of Schreiber and Thomas in their cloudy-bag-model calculation.[10] Since we discuss here the spin content of the nucleons it is very relevant to require quark helicity conservation at the bag surface and chiral or cloudy bag models are postulated to do just that.[6,10] Thereby chiral symmetry, a symmetry of the QCD Lagrangian, is restored in the MIT bag model.

If we were to take the maximum pionic correction for the neutron, of -0.017, and our result for gluon exchange, we would find a value for

$$\int_0^1 dx\, g_1^n(x)=-0.036\left(1-\frac{\alpha_s}{\pi}\right)\cong-0.033\,. \qquad (10)$$

Depending on one's interpretation of the errors this might be considered incompatible with the EMC result $-0.078\pm0.012\pm0.026$. On the other hand it is in reasonable agreement with one reanalysis of the data by Close and Roberts:[11] namely, $-0.043\pm0.012\pm0.026$. [This number, the number on the far right in Eq. (10), and the EMC result quoted above include the QCD correction at $Q^2\cong 20$ GeV^2 to the structure function.] Of course it is not strictly legitimate to add the pion and gluon-exchange contributions in this way. The reason for this is that the value of $C''=-0.056$ is found using $\alpha_s=2.2$ of the original MIT model.[2] We know this value of α_s is too large since the pionic corrections of chiral bag models will give sizable contributions to the Δ-N mass splitting.[6] Nevertheless, it seems likely that for any bag radius these two corrections together should contribute at least -0.03 contributions to the neutron sum rule.

There have been a number of suggestions for the EMC result which are far more exciting than ours.[12,13] However, we feel that our work demonstrates the extreme sensitivity of spin polarization to relatively small effects. It may be premature to throw away[8,13] the old quark models which have been so successful over the past two decades.

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