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On the possible measurement of gluon asymmetry in a spinning nucleus

Mohammad Ali Yusuf and Pervez Hoodbhoy
Department of Physics, Quaid-i-Azam University, Islamabad, Pakistan

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Abstract. The quadrupole gluon distribution, which exists only for hadrons with spin $\geqslant 1$, is investigated for a typical light nucleus using the convolution model and a QCD inspired parton recombination model. The effects of an exotic quadrupole gluon component upon asymmetries in prompt photon production and J/ψ lepton production are estimated.

The gluon asymmetry in a polarized proton has become the focus of considerable interest following the EMC measurements [1] of polarization asymmetry in the deep inelastic scattering of polarized muons off polarized protons. For transverse gluons in a longitudinally polarized $J=\frac{1}{2}$ hadron target, there is only one gluon asymmetry, $\Delta G(x, Q^2) = G_\uparrow^{1/2} - G_\downarrow^{1/2}$ where $_{\uparrow,\downarrow}$ denote gluon helicities and $\frac{1}{2}$ indicates positive helicity of the target. However, in view of recent discussions [2, 3] of deep inelastic scattering from polarized $J \geqslant 1$ targets, it is worthwhile to ask what additional gluon asymmetries exist for higher spins and whether their measurement would be interesting and possible. From parity invariance we have $G_\uparrow^H = G_\downarrow^{-H}$ with $-J \leqslant H \leqslant J$. For $J=1$ there are two independent asymmetries which can be chosen as $\Delta G = G_\uparrow^1 - G_\downarrow^1$ and $\Delta G = \frac{1}{2}(G_\uparrow^1 + G_\uparrow^{-1} - 2G_\uparrow^0)$. The latter 'quadrupole' asymmetry is interesting; it can be measured with an unpolarized probe (see below) and, paraphrasing the discussion for the quark distribution in [2], it can be easily seen to vanish for two independent nucleons in a relative s state. For p, d, f ... states it is small, of order $\langle P^2/M^2 \rangle$. Thus it is a good indicator of 'exotic' gluons in a nucleus—i.e. the extent to which the nuclear gluon distribution is non-additive. For $J=\frac{3}{2}$, the corresponding gluon asymmetry of interest is $\Delta G = \frac{1}{2}(G_\uparrow^{3/2} - G_\uparrow^{1/2} - G_\uparrow^{-1/2} + G_\uparrow^{-3/2})$ or equivalently, $\Delta G = G^{3/2} - G^{1/2}$ where $G^H = \frac{1}{2}(G_\uparrow^H + G_\downarrow^H)$.

Because gluons carry no electric charge, gluon distributions are only indirectly measurable in lepton–hadron scattering. A more direct probe is provided by prompt photon production [4], which is dominated by the quark–gluon Compton scattering diagrams of figure 1(a), with contamination only at the few per cent level from quark–antiquark fusion as in figure 1(b). Since our investigations are exploratory, radiative corrections are not considered. The specific situation considered here is an unpolarized proton beam striking a nuclear target with definite helicity H. According to the usual hard scattering model,

$$E_\gamma \frac{\mathrm{d}\sigma_H(s, x_F, P_T)}{\mathrm{d}^3P_\gamma} = \sum_{a,b} \int \mathrm{d}x_a \, \mathrm{d}x_b \, P^a(x_a) P_H^b(x_b) E_\gamma \frac{\mathrm{d}\hat{\sigma}_{ab}(\hat{s}, x_F, P_T)}{\mathrm{d}^3P_\gamma} \qquad (1)$$

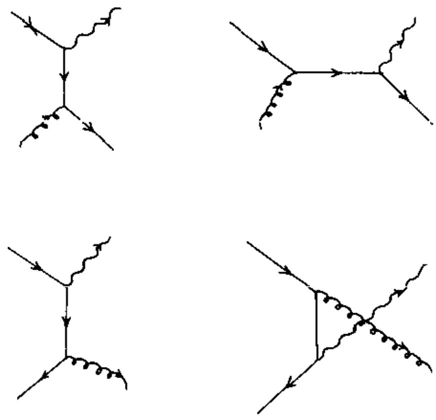

Figure 1. Lowest order Feynmann diagrams contributing to the process $pp \to \gamma X$: (a) Compton subprocess, (b) annihilation subprocess.

where $E_\gamma d\hat{\sigma}_{ab}/d^3P_\gamma$ is the subprocess $ab \to \gamma x$ cross section, $P^a(x_a)$ is the spin-averaged density of parton a ($a = \mathrm{q}, \bar{\mathrm{q}}, \mathrm{G}$) in an unpolarized proton, $P_H^b(x_b)$ is the spin-averaged density of parton b ($b = \mathrm{q}, \bar{\mathrm{q}}, \mathrm{G}$) in the nuclear target with polarization H, and the subprocess invariants $\hat{s}$, $\hat{t}$, $\hat{u}$ are related to the usual observables s, t, u by $\hat{s} = x_a x_b s$, $\hat{t} = x_a t$, and $\hat{u} = x_b u$. The matrix elements for the two basic subprocesses are readily computed,

$$|M_{\mathrm{qg}\to\gamma\mathrm{q}}|^2 = -\tfrac{1}{3}\frac{\hat{s}^2 + \hat{t}^2}{\hat{s}\hat{t}} \tag{2a}$$

$$|M_{\mathrm{q}\bar{\mathrm{q}}\to\gamma\mathrm{q}}|^2 = \tfrac{8}{9}\frac{\hat{t}^2 + \hat{u}^2}{\hat{t}\hat{u}}. \tag{2b}$$

The parton level cross sections are expressible in terms of these as

$$E_\gamma \frac{d\hat{\sigma}}{d^3P_\gamma}(\hat{s}, x_F, P_T) = \alpha_{\mathrm{em}}\,\alpha_s \frac{1}{\hat{s}} |M|^2\, \delta(\hat{s} + \hat{t} + \hat{u}). \tag{3}$$

Further details of reaction kinematics may be found, for example, in [4].

Although one could use a polarized deuterium target to explore the second gluon asymmetry discussed earlier, the low density of the deuteron makes a significant exotic gluon component unlikely. A more appealing possibility is ^{7}Li, which has $J = \frac{3}{2}$. In the shell model, it consists of a single nucleon in the $1P_{3/2}$ level outside a closed spherical core. This ignores core polarization effects, but is adequate as a first approximation. The single nucleon thus carries all the spin of the nucleus. Our aim is to estimate the influence of the 'quadrupole' gluon asymmetry, $\Delta G = G^{3/2} - G^{1/2}$, upon the prompt photon cross section asymmetry. This entails making reasonable models for the parton asymmetries in the ^{7}Li target.

As our first model, we shall assume that the parton asymmetries in ^{7}Li can be obtained from the single nucleon by convolution,

$$P_\uparrow^{JH}(x) = \iint dy\, dz \sum_{s=\pm 1/2} f_s^{JH}(y) P_\uparrow^{1/2s}(z)\, \delta(x - yz). \tag{4}$$

In the above, $P = \mathrm{q}, \bar{\mathrm{q}}$ or G, and f_s^{JH} is the light-cone probability distribution for a nucleon with helicity $s = \pm\frac{1}{2}$ in a nucleus with helicity H, $-J \leqslant H \leqslant J$. For the gluon asymmetry, for example, we have

$$\Delta G = G^{3/2}(x) - G^{1/2}(x)$$
$$= \int \mathrm{d}y\, \mathrm{d}z\, [f^{3/2\,3/2}(y) - f^{3/2\,1/2}(y)] G(z)\, \delta(x - yz) \tag{5}$$

where $f^{3/2\,3/2} = f^{3/2\,3/2}_{1/2} + f^{3/2\,3/2}_{-1/2}$, etc. Note that only the spin-averaged gluon distribution in a nucleon enters in (5); this quantity is better known than the gluon asymmetry. The convolution model, with the Dirac nature of the nucleon taken into account properly [5, 2, 3], gives a definite prescription for $f^{3/2\,3/2}$, etc, in terms of the nuclear wavefunction.

$$f^{JH}(y) = \frac{1}{2\pi} \int \mathrm{d}\xi^- \, \mathrm{e}^{-\mathrm{i}ym\xi^-/\sqrt{2}} \langle JH \mid \bar{\psi}(\xi^-)\gamma^+ \psi(0) \mid JH \rangle$$
$$= \int \mathrm{d}^3 P |\phi^{JH}(P)|^2 \left(1 + \frac{P^3}{M} + \frac{P^2}{4M^2}\right) \delta\left(y - \frac{P^0 + P^3}{M}\right). \tag{6}$$

The above approximately includes binding of the nucleon since $P^0 = M - \varepsilon$, as well as leading order relativistic effects. Since $P^0 + P^3$ is quite close to M, the distribution peaks at around $y = 1$. This allows for a rapidly convergent series in the delta function and its derivatives,

$$f^{3/2\,3/2}(y) - f^{3/2\,1/2}(y) = -\frac{2}{15}\left\langle \frac{P^2}{M^2} \right\rangle [-2\delta'(y-1) + \delta''(y-1)] \tag{7}$$

where

$$\left\langle \frac{P^2}{M^2} \right\rangle = \int_0^\infty \mathrm{d}p \, \frac{P^4}{M^2} |\phi(P)|^2 \simeq 0.04. \tag{8}$$

The various quadrupole asymmetries are readily computed from the above,

$$\Delta G(x) = -\frac{2}{15} \left\langle \frac{P^2}{M^2} \right\rangle \left(2 \frac{\mathrm{d}}{\mathrm{d}y} \frac{G(x/y)}{y} \bigg|_{y=1} + \frac{\mathrm{d}^2}{\mathrm{d}y^2} \frac{G(x/y)}{y} \bigg|_{y=1} \right). \tag{9}$$

The quark and antiquark distributions are obtained similarly.

To numerically estimate the prompt photon cross section asymmetry, we have used the Duke–Owens [6] set 1 of parton densities. As a check of their suitability and our tree-level computations, the p–p spin-averaged cross section has been plotted in figure 2. The asymmetry is plotted in figures 3 and 4 for two different beam energies. As was stated at the outset, we do not expect these to be large—the contributions come from Fermi motion at the $\langle P^2/M^2 \rangle$ level. Binding effects cancel out in the differences at this level of approximation.

Non-additive nuclear parton distributions could alter the above results. Non-additivity can be obtained in numerous ways; here we shall follow the parton recombination model developed by Close, Qiu and Roberts [7], which is based upon the arguments of Mueller and Qui [8] and which has been explored further in [9]. Briefly, when viewed in the infinite momentum frame the nucleus is Lorentz contracted in the $\hat{z}$ direction and has a longitudinal size $\Delta z_A 2R/\gamma \simeq 2mR/P$, where m and P are the nucleon mass and momentum respectively. On the other hand, the longitudinal size of a sea parton (whether quark or gluon) is $\Delta z \simeq 1/xP$, where x is

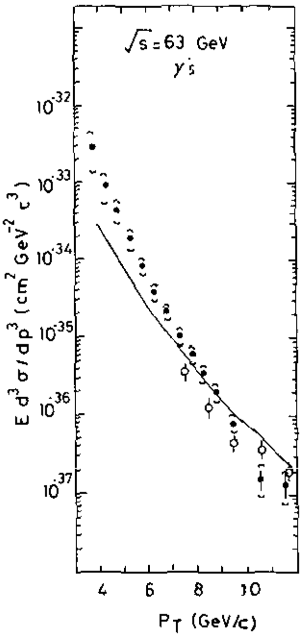

Figure 2. The invariant inclusive cross section for prompt photon production in pp collisions at $\sqrt{s} = 63$ GeV near 90° in the centre of mass [11, 12]. The full curve shows our fit to the cross section.

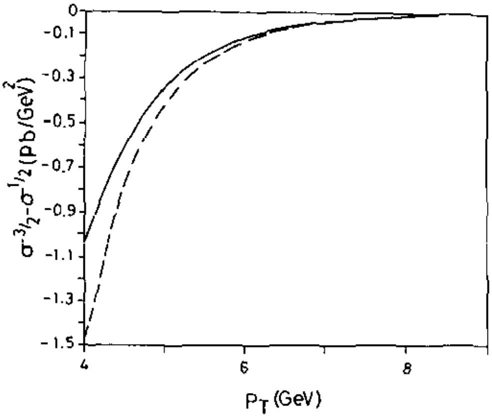

Figure 3. Prompt photoproduction asymmetry of $P_{\text{beam}} = 400$ GeV. The full curve shows pure convolution model results, the broken curve shows results including fusion diagrams.

the fraction of the nucleon's momentum carried by the parton. For small x, Δz exceeds the size of the nucleus and shadowing occurs for $x \leqslant \frac{1}{2}mR$, i.e. the nuclear parton distribution is no longer A times the nucleon parton distribution, $q^A \neq Aq^N$. For sufficiently small x the sea quarks and gluons from a given nucleon extend along the entire length of the nucleus in the $\hat{z}$ direction. In the QCD parton recombination model of [7] a parton from one nucleon leaks into a neighbouring nucleon and fuses with partons of the latter.

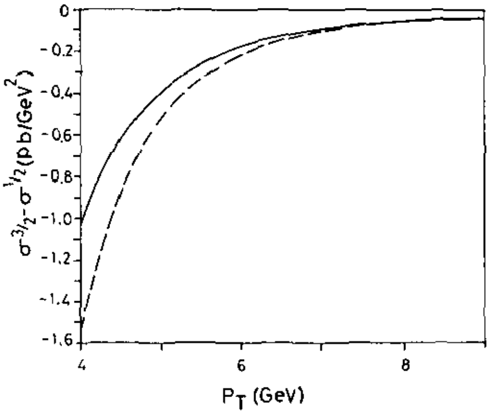

Figure 4. Same as figure at $P_{\text{beam}} = 2000$ GeV

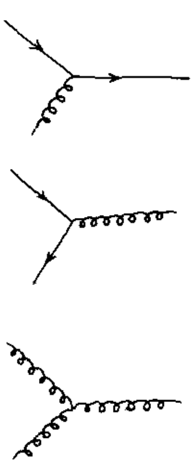

Figure 5. The basic subprocesses contributing to $\delta x P(x)$

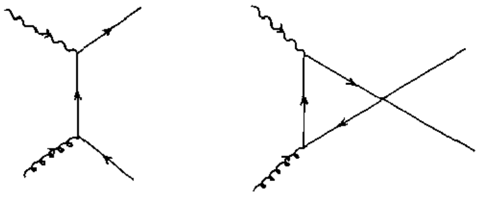

Figure 6. Lowest order Feynman diagrams contributing to the process $ep \to J/\psi + X$.

The nuclear quark and gluon densities can be written as $P_A(x) = xP(x) + \delta xP(x)$, where the first part corresponds to the convolution model. Three basic subprocesses illustrated in figure 5, gives rise to changes in $\delta xP(x)$: quark-gluon fusion, quark-antiquark fusion, and gluon-gluon fusion. Using old-fashioned perturbation theory in the infinite momemtum frame, all parton-parton fusion functions are readily calculated [7]. The numerical evaluation of the fusion corrections to the prompt photo production asymmetry is illustrated in figures 3 and 4, from which the difference relative to pure convolution is apparent. The evaluation uses as input gluon and quark asymmetries, which requires a plausible model of nucleon structure [9]. We choose the ^{7}Li core density to be $\sim\exp(-r^2/R_0^2)$ with $R_0^2 = 3.8\,\mathrm{fm}^2$, and the valence proton to be in the $1P_{3/2}$ state whose radial part is $\sim r\exp(-\frac{1}{2}r^2/r_0^2)$ with $r^0 = 1.44\,\mathrm{fm}$. The extent to which the core affects the nuclear parton asymmetries is determined by the dimensionless quantity K,

$$K = \frac{g^2}{Q_0^2} \int \mathrm{d}^3R\, \mathrm{d}^3r \rho_{\mathrm{core}}(\boldsymbol{R}) \rho_n(\boldsymbol{r}) \delta^2(\boldsymbol{B} - \boldsymbol{b}). \tag{10}$$

In the above, the delta function restricts the impact parameters of the nucleons in the core and the valence nucleon to be equal. We have taken $Q_0^2 \simeq P_T^2/4$ although this choice is open to the same criticism as in the original formulation [7] of the fusion model. The results, however, should be qualitatively correct. As can be seen from figures 3 and 4, the difference in the prompt photon cross sections due to fusion are substantial although the cross sections themselves are small.

A second useful probe of gluon distributions is the lepton production of heavy mesons [10]. The dominant (tree level) mechanism for this is $\gamma^* G \to Q\bar{Q}$, and is illustrated in figure 6. The outgoing heavy quarks are assumed to form through soft

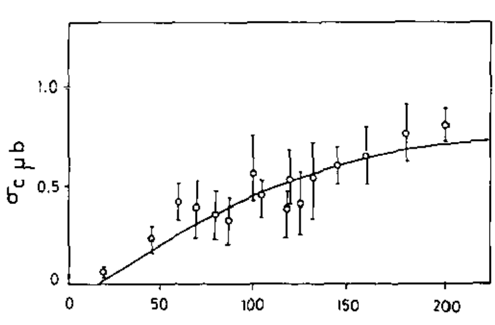

Figure 7. Charm production results from NA14' [10]. The full curve shows our fit to the cross section.

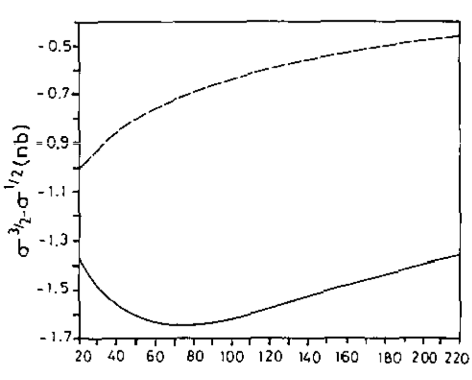

Figure 8. J/ψ production asymmetry at $Q^2 = -10\,\mathrm{GeV}^2$. The full curve shows pure convolution model results, the broken curve shows results including fusion diagrams.

gluon interactions into the appropriate flavour meson with unit probability independent of the momenta. As a test of the distributions we have used, a comparison with the data [10] for spin-averaged lepton production of $c\bar{c}$ mesons from a proton target is shown in figure 7. Using the quadrupole gluon distributions in the convolution and fusion models discussed earlier, we have plotted in figure 8 the cross section asymmetries for J/ψ production in the two models. Although both asymmetries are rather small as compared with the spin-averaged cross section, it is encouraging to note that they differ substantially —in fact appreciably more than the prompt photon asymmetry. This raises the hope that exotic gluon components of the nuclear wavefunction may be eventually measurable in high-flux fixed target polarization experiments.

Acknowledgments

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