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Prompt photon production with a polarized deuteron target

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Predictions are presented of the polarization asymmetry in prompt photon production at large transverse momentum in the scattering of longitudinally polarized protons from longitudinally polarized deuteron targets. Data would provide important constraints on the polarization asymmetry of the gluon density in a nucleon. The experiments could take advantage of recent advances in the technology of polarized ^{6}LiD.

Recent data on the polarization asymmetry in deep-inelastic scattering of polarized muons on polarized protons have renewed interest in the relationship of the proton's spin to that of its parton constituents (quarks and gluons).[1,2] Of particular interest to us is the spin carried by the gluons. The deep-inelastic measurements have been interpreted in terms of a large positive polarization asymmetry of the gluons.[3] This interpretation is subject to ambiguity[4] because the gluon contribution enters formally as a higher-order contribution in quantum chromodynamics. More direct access to the polarized gluon density is provided by processes in which the gluons contribute in the lowest order of perturbation theory. A prime example is prompt photon production at large transverse momentum in nucleon-nucleon interactions.[5]

In this paper we provide predictions for the production of prompt photons in interactions of longitudinally polarized proton beams with longitudinally polarized deuteron targets. Our attention was drawn to deuteron targets by recent developments in the technology of polarized-target materials.[6] The material ^{6}LiD has significant advantages over conventional materials. The ^{6}Li nucleus, which may be viewed as an αd system, can be significantly polarized. Thus, polarized ^{6}LiD is essentially an α particle plus two polarized deuterons, meaning that 50% of the target nucleons are polarized in this material. By contrast, conventional polarized-proton-target materials contain less than 20% free hydrogen by weight, and the contribution of all target nucleons to the net polarization is usually also comparably small.

We will regard the deep-inelastic structure function of a polarized deuteron as a sum of the structure functions of a polarized proton and a polarized neutron. This assumption should be fairly good since the deuteron's d-state probability is small. The assumption is also made in calculations of unpolarized processes where it is presumed valid except in the region of large fractional Bjorken momentum x ($x > 0.8$) where coherent effects and Fermi smearing may be significant.

One important difference from the unpolarized case which does require care is that the spin-dependent structure function of the nucleon need not be positive. In particular, in many models,[7] the spin-dependent structure function of the neutron is expected to be negative in interesting regions of the fractional momentum x. Cancellations in these regions between the proton and neutron contributions will result in reduced overall cross sections and small event rates for experiments done with deuteron targets. We will show explicitly that this potential problem is *not* likely to be concern for prompt-photon-production studies at energies accessible in fixed-target experiments at Fermilab energies. In the region of $x \gtrsim 0.2$ which could be explored in such studies, the polarized-deuteron-structure function is expected to be strongly positive, as shown in Fig. 1. Thus, the practical advantage offered by the ^{6}LiD technology is not offset, and a program of studies with polarized deuteron targets would seem fully justified.

The asymmetry measured in deep-inelastic lepton scattering determines the spin-dependent structure function of the proton $g_1^p(x,Q^2)$.[8] Here x is the usual Bjorken scaling variable, and Q^2 is the square of the four-momentum transfer. In perturbative quantum chromodynamics, the structure function $g_1^p(x,Q^2)$ may be expressed as a sum of terms representing the spin-dependent quark, antiquark, and gluon densities of the proton, denoted respectively by $\Delta q_f(x,Q^2)$, $\Delta \bar{q}_f(x,Q^2)$, and $\Delta G(x,Q^2)$.

Here we focus on independent determinations of the magnitude, sign, and x dependence of the polarized gluon density $\Delta G(x,Q^2)$. Knowledge of $\Delta G(x,Q^2)$ will be of value in its own right and is necessary for extracting the

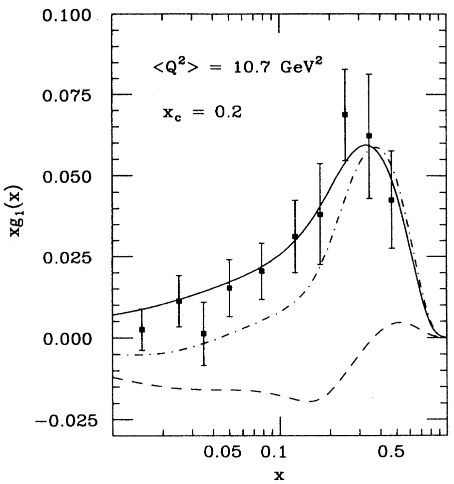

FIG. 1. The solid, dashed, and dashed-dotted lines show our prediction for the polarized structure functions of the proton $xg_1^p(x,Q^2)$, neutron $xg_1^n(x,Q^2)$, and deuteron $xg_1^d(x,Q^2)$, respectively, as the functions of x for $Q^2=10.7$ GeV^2. The data on $xg_1^p(x,Q^2)$ are from the European Muon Collaboration, Ref. 1.

true spin-dependent quark and antiquark distributions from the deep-inelastic lepton-scattering data.

In the case of unpolarized pp or pn scattering, direct photon production at fixed-target energies is known to be dominated by the "Compton" subprocess $qg \rightarrow \gamma q$.[9] Here q and g stand for quark and gluon constituents. Data therefore allow a direct determination of the (spin-averaged) gluon distribution $G(x,Q^2)$ in a hadron. Similarly, when both the beam and target nucleons are polarized, the cross section for prompt photon production is dominated by the $qg \rightarrow \gamma q$ subprocess, and it can be expressed in terms of the polarized gluon distribution $\Delta G(x,Q^2)$.[5,10] Inclusive direct photon production at large transverse momentum in proton-proton interactions with longitudinally polarized beam and target is an incisive probe of the polarized gluon distribution in a proton. In order to help motivate experiments with deuteron targets, we extend our earlier work to provide predictions of the polarization asymmetry of large-p_T direct photon production in proton-deuteron interactions with longitudinally polarized beam and target.

We now briefly outline our parametrizations of polarized parton distributions.[5] We parametrize the x dependences of $\Delta G(x,Q^2)$, $\Delta q_f(x,Q^2)$, and $\Delta \bar{q}_f(x,Q^2)$ at an arbitrary reference value $Q^2=Q_0^2$, and then we use the spin-dependent Altarelli-Parisi evolution equations[11] to obtain the polarized parton distributions for all $Q^2>Q_0^2$. The parameters in these distributions are chosen to fit the data on $g_1^p(x,Q^2)$ and to satisfy the Bjorken sum rule.[12]

We select a simple one-parameter function which satisfies both the large- and small-x constraints for $\Delta G(x,Q_0^2)$:

$$\Delta G(x,Q_0^2)=\begin{cases} G(x,Q_0^2), & x_c \le x \le 1, \\ \dfrac{x}{x_c}G(x,Q_0^2), & 0 \le x < x_c. \end{cases} \quad (1)$$

This parametrization satisfies the requirement $\Delta G(x,Q^2) \le G(x,Q^2)$ for all x, as well as the constraints $\Delta G(x,Q^2)/G(x,Q^2) \rightarrow 1$ as $x \rightarrow 1$ (Ref. 13) and $\Delta G(x,Q^2)/G(x,Q^2) \rightarrow 0$ as $x \rightarrow 0$ (Ref. 10). $G(x,Q^2)$ is the standard spin-averaged gluon distribution. For experiments sensitive to values of $x > x_c$, our polarized gluon distribution is as large as it could be. In this sense, our predictions provide *upper* bounds on polarization asymmetries. The single parameter x_c determines the value of the integral $\langle \Delta G \rangle = \int_0^1 dx\, \Delta G(x)$.

For the polarized valence-quark distributions at starting value Q_0^2, we adopt those proposed by Carlitz and Kaur,[14] $\Delta u_v(x,Q_0^2)$ and $\Delta d_v(x,Q_0^2)$. We assume the sea-quark distributions are unpolarized at $Q^2=Q_0^2$. By themselves, these distributions do not fit the recent data, providing too great a value of $g_1^p(x,Q^2)$ in the small-x region.[1] We model the full input quark and antiquark distributions of flavor f as

$$\Delta q_f'(x,Q_0^2) \equiv \Delta q_f(x,Q_0^2) - \frac{\alpha_s(Q^2)}{4\pi}\int_x^1 \frac{dy}{y}\hat{\gamma}\left(\frac{x}{y}\right)\Delta G(y,Q_0^2), \quad (2)$$

where the kernel $\hat{\gamma}$ is

$$\hat{\gamma}(x)=(1-2x)\left[\ln\frac{1}{x^2}-2+K\right]. \quad (3)$$

The constant K in the kernel and x_c in $\Delta G(x,Q_0^2)$ are fixed[5] by fitting data on $g_1^p(x,Q^2)$ and using the Bjorken sum rule. The function $g_1(x,Q^2)$ is obtained from

$$2g_1(x,Q^2)=\sum_f e_f^2[\Delta q_f'(x,Q^2)+\Delta \bar{q}_f'(x,Q^2)]. \quad (4)$$

For convenience we adopt the Duke-Owens set 1 distributions[15] as our unpolarized parton distributions, with the reference scale $Q_0^2=4$ GeV^2 and $\Lambda=200$ MeV. In Fig. 1, we plot our spin-dependent structure functions $g_1^p(x,Q^2)$, $g_1^n(x,Q^2)$, $g_1^d(x,Q^2)$, along with data, for the specific choice $x_c=0.2$ and $K=0.5$. As one can see from Fig. 1, our structure function $g_1^p(x,Q^2)$ fits data reasonably well. For prompt photon production in the fixed-target momentum interval $200 < p_{\rm lab} < 800$ GeV/c, and $p_T \gtrsim 4$ GeV/c, we will be interested in the structure functions for $x \gtrsim 0.2$ and the scale $Q^2 \simeq 4-100$ GeV^2 (Q^2 is typically equal to $\frac{1}{2}p_T^2$ or p_T^2).

Once the parton distributions are determined it is straightforward to calculate the cross sections and asymmetries.[5] We evaluate predictions for the choice of the scale $Q^2=p_T^2/2$, which is known to approximately minimize the size of the higher-order contributions in unpolarized pp collisions at fixed-target energies. Our predictions of direct photon-production rates in proton-deuteron scattering are plotted as a function of the photon's transverse momentum p_T in Fig. 2, for incoming beam momentum equal to 200, 400, and 800 GeV, respectively. The solid lines represent the rates in unpolarized pd interactions. The dashed lines represent the rates in polarized $\vec{p}\vec{d}$ interactions with parameter $x_c=1.0$ for the polarized-input gluon distribution, and the dashed-dotted lines for $x_c=0.2$. We define the polarized cross sections to be the difference $\Delta\sigma_{pd} \equiv \frac{1}{2}(\sigma_{++}-\sigma_{+-})$ where the + symbol

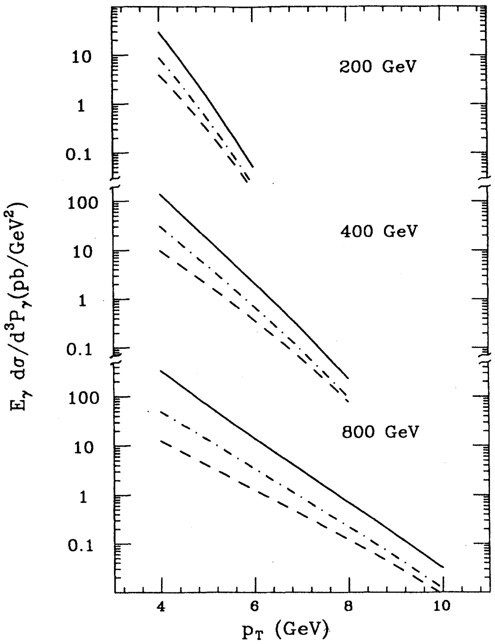

FIG. 2. Predicted invariant inclusive yield of prompt photons as a function of p_T for center-of-mass longitudinal-momentum fraction $x_F = 0$ in pd interactions at $p_{\rm lab} = 200$, 400, and 800 GeV/c, respectively. The solid curves show the predicted rates in unpolarized pd interaction, whereas the dashed and dot-dashed curves show two possible results for the polarized cross sections corresponding to parameter choices $x_c = 1.0$ and 0.2, respectively.

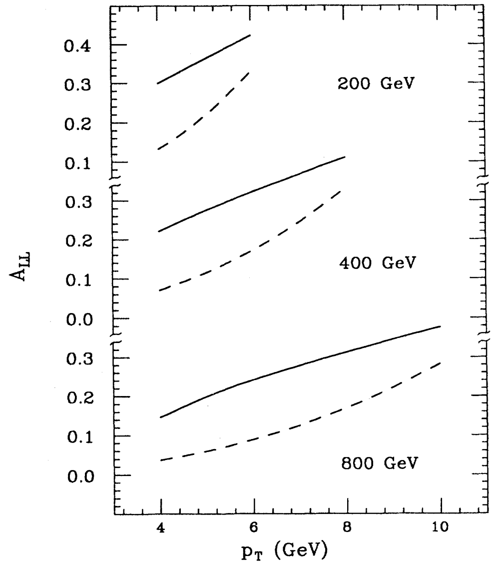

FIG. 3. Predicted asymmetry A_{LL} as a function of p_T for center-of-mass longitudinal-momentum fraction $x_F = 0$ in pd interactions at $p_{\rm lab} = 200$, 400, and 800 GeV/c. The solid and dashed curves correspond to parameter choices $x_c = 0.2$ and 1.0, respectively.

indicates that the spin direction is along the momentum direction. For values of parameter $x_c < 0.2$, the predictions are about the same as those with $x_c = 0.2$, because 0.2 is about the smallest value of the parton momentum fraction to which large-p_T single-photon production is sensitive at those beam energies. Because of the single-parameter form of $\Delta G(x)$ that we use, the dashed-dotted curves in Fig. 2 represent the largest values of the polarized cross sections which could be reasonably expected. In Fig. 3, we plot the values of the asymmetry A_{LL} at $x_F = 0$ as a function of the photon's transverse momentum p_T, for incoming beam momenta equal to 200, 400, and 800 GeV. The solid lines represent the values of the asymmetry with parameters $x_c = 0.2$ for the polarized input gluon distribution, and the dashed lines for $x_c = 1.0$. The asymmetry A_{LL} increases as x_F increases; for example, with $x_c = 0.2$ at $p_T = 4$ GeV and $p_{\rm lab} = 200$ GeV/c, it rises from $\simeq 30\%$ at $x_F = 0$ to 80% at $x_F = 0.6$.

We now turn to the question of sensitivity of our predictions to a different choice of polarized quark distributions. In leading order, the rate for large-p_T prompt photon production is determined by the quark-gluon Compton-scattering and quark-antiquark annihilation subprocesses. In the energy region of present fixed-target experiments, the Compton-scattering subprocess is dominant for $\vec{p}\vec{p}$, but it might not be dominant for $\vec{p}\vec{n}$, because $g_1^n(x,Q^2)$ is expected to be small and even negative at certain values of x.[7] Nevertheless, the Compton-scattering subprocess is still dominant for $\vec{p}\vec{d}$ at the energy scale of the present experiments. To show this is true, we write the cross section for prompt photon production in $\vec{p}\vec{d}$ in the approximate form

$$
\begin{aligned}
E_\gamma \frac{d\Delta\sigma_{pd}}{d^3p_\gamma}(s,x_F,p_T) \approx \int dx_1\, dx_2 \Bigg[& 2g_1^p(x_1,Q^2)\Delta G^p(x_2,Q^2) E_\gamma \frac{d\Delta\hat{\sigma}_{qg}}{d^3p_\gamma}(\hat{s},x_F,p_T) \\
& + 2g_1^p(x_2,Q^2)\Delta G^p(x_1,Q^2) E_\gamma \frac{d\Delta\hat{\sigma}_{qg}}{d^3p_\gamma}(\hat{s},x_F,p_T) \\
& + 2g_1^p(x_1,Q^2)\Delta G^n(x_2,Q^2) E_\gamma \frac{d\Delta\hat{\sigma}_{qg}}{d^3p_\gamma}(\hat{s},x_F,p_T) \\
& + 2g_1^n(x_2,Q^2)\Delta G^p(x_1,Q^2) E_\gamma \frac{d\Delta\hat{\sigma}_{qg}}{d^3p_\gamma}(\hat{s},x_F,p_T) \Bigg] ,
\end{aligned} \tag{5}
$$

where $\Delta G^p(x,Q^2) = \Delta G^n(x,Q^2)$. Terms neglected on the right-hand side of Eq. (5) are the small quark-antiquark annihilation terms.

The first comment to be made about Eq. (5) is that the detailed forms of $\Delta q_f(x,Q^2)$ and $\Delta \bar{q}_f(x,Q^2)$ are not important. The functions of importance are $g_1^p(x,Q^2)$, $g_1^n(x,Q^2)$, and $\Delta G^p(x,Q^2)$. We will assume that $g_1^p(x,Q^2)$ is reasonably well determined from deep-inelastic scattering data. The "unknowns" are therefore $g_1^n(x,Q^2)$ and the function of principal interest to us here, $\Delta G(x,Q^2)$. The function $g_1^n(x,Q^2)$ enters only in the fourth term of Eq. (5).

The first three terms of Eq. (5) are all positive, and they are much larger than the neglected quark-antiquark annihilation terms. The fourth term is small or could be negative, because $g_1^n(x,Q^2)$ is smaller than $g_1^p(x,Q^2)$ at most x values and is negative in the small-x region. Since $g_1^n(x,Q^2)$ can be negative, as shown in Fig. 1, one might worry that in an extreme case, the fourth term would cancel the first three terms, or make the total contribution of the Comptom subprocess comparable with that of the quark-antiquark subprocess. If so, it would be almost impossible to extract information on the polarized gluon distribution from $\vec{p}\vec{d}$ scattering. Fortunately, this is not the case for two reasons. One is the Bjorken sum rule, and the other is the energy scale of the fixed-target experiments. Because of the Bjorken sum rule, the integral of $g_1^n(x,Q^2)$ over all x is a fixed number, provided $\int_0^1 dx\, g_1^p(x,Q^2)$ is well measured. If $g_1^n(x,Q^2)$ is made more negative in the small-x region, $g_1^n(x,Q^2)$ becomes more positive in the large-x region. The prompt-photon cross section is sensitive to $g_1^n(x,Q^2)$ over a region of x from 1 down to $x_{\min}$. The value of $x_{\min} \simeq 2p_{T_{\min}}/\sqrt{s}$ depends on the beam momentum of the experiments; $x_{\min}$ is above 0.2 for beam momenta currently available at fixed-target energies. Therefore, one should not expect the fourth term to be so negative that it would cancel the positive contribution from the first three terms. Indeed $g_1^n(x,Q^2)$ is likely to be positive, even if small, in the region $x > 0.2$.

In the calculations we have done, we find that the fourth term in Eq. (5) is always much smaller than the first three terms in the energy region of interest to us. This remark is evident from a glance at Fig. 1 where we see that $g_1^d(x,Q^2) \simeq g_1^p(x,Q^2)$ for $x \gtrsim 0.2$. The important quantities in Eq. (5) are therefore $g_1^p(x,Q^2)$ and $\Delta G(x,Q^2)$. Correspondingly, data on the polarization asymmetry in $\vec{p}\vec{d}$ scattering, coupled with knowledge of $g_1^p(x,Q^2)$, should suffice to yield valuable information on $\Delta G(x,Q^2)$. We emphasize that even determination of the *sign* of $\Delta G(x,Q^2)$ over a limited x region would be of significant interest.

We have provided predictions of the polarization asymmetry for large p_T prompt photon production in polarized $\vec{p}\vec{d}$ interactions at fixed-target energies. Equation (5) shows that the data should yield a direct determination of $\Delta G(x,Q^2)$ in the region $x > 0.2$. The cross sections are small but measurable. Results of such experiments would play a key role in establishing the relationship of the polarization of a nucleon to that of its constituents.

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[1]European Muon Collaboration, J. Asham *et al.*, Phys. Lett. B **206**, 364 (1988).

[2]M. J. Alguard *et al.*, Phys. Rev. Lett. **37**, 1258 (1976); **41**, 70 (1978); G. Baum *et al.*, *ibid.* **51**, 1153 (1983).

[3]A. V. Efremov and O. V. Teryaev, Dubna Report No. E2-88-287, 1988 (unpublished); G. Altarelli and G. G. Ross, Phys. Lett. B **212**, 391 (1988); R. D. Carlitz, J. C. Collins, and A. H. Mueller, *ibid.* **214**, 229 (1988).

[4]R. L. Jaffe and A. Manohar, MIT Report No. CTP 1706, 1989 (unpublished); G. T. Bodwin and J. Qiu, Argonne Report No. ANL-HEP-PR-89, 1989 (unpublished).

[5]E. L. Berger and J. Qiu, Phys. Rev. D **40**, 778 (1989).

[6]P. Chaumette, J. Deregal, G. Durand, and J. Fabre, in *Future Polarization Physics at Fermilab,* proceedings of the Symposium, Batavia, Illinois, 1988, edited by E. Berger, J. G. Morfin, A. L. Read, and A. Yokosawa (Fermilab, Batavia, 1988), p. 257.

[7]D. J. E. Callaway and S. D. Ellis, Phys. Rev. D **29**, 567 (1984); V. W. Hughes, in *Future Polarization Physics at Fermilab* (Ref. 6); J. Qiu, G. P. Ramsey, D. Richards, and D. Sivers, Phys. Rev. D (to be published).

[8]V. W. Hughes and J. Kuti, Annu. Rev. Nucl. Part. Sci. **33**, 611 (1983).

[9]E. L. Berger, E. Braaten, and R. D. Field, Nucl. Phys. **B239**, 52 (1984), and references therein; T. Ferbel and W. R. Molzon, Rev. Mod. Phys. **56**, 181 (1984); J. F. Owens, *ibid.* **59**, 465 (1987).

[10]N. S. Craigie, K. Hidaka, M. Jacob, and F. M. Renard, Phys. Rep. **99C**, 69 (1983); M. B. Einhorn and J. Soffer, Nucl. Phys. **B274**, 714 (1986).

[11]G. Altarelli and G. Parisi, Nucl. Phys. **B126**, 298 (1977).

[12]J. D. Bjorken, Phys. Rev. D **1**, 1376 (1970).

[13]G. R. Farrar and D. R. Jackson, Phys. Rev. Lett. **35**, 1416 (1975); F. Close and D. Sivers, *ibid.* **39**, 1116 (1977).

[14]R. Carlitz and J. Kaur, Phys. Rev. Lett. **38**, 673 (1977); J. Kaur, Nucl. Phys. **B128**, 219 (1977).

[15]D. W. Duke and J. F. Owens, Phys. Rev. D **30**, 49 (1984).