Polarized Λ-Baryon Production in pp Collisions

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We study the production of longitudinally polarized Λ baryons in single-spin $p\vec{p}$ collisions at BNL RHIC and DESY HERA-$\vec{N}$ as a means of determining the spin-dependent Λ fragmentation functions. It is shown that a measurement of the rapidity distribution of the Λ's would provide an excellent way of clearly discriminating between various recently suggested sets of polarized Λ fragmentation functions that are all compatible with present e^+e^- data. We also address the main theoretical uncertainties, which appear to be well under control. [S0031-9007(98)06651-4]

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The understanding of spin-dependent deep-inelastic scattering (DIS) processes in terms of QCD-evolved polarized parton distributions $\Delta f(x, Q^2)$ $(f = q, \bar{q}, g)$ is still far from being satisfactory, despite significant experimental and theoretical progress over the past few years. In particular, the angular momentum component of the proton's spin and the polarized gluon density $\Delta g(x, Q^2)$ remain almost completely unknown for the time being, and more experimental results are required.

Studies of spin-transfer reactions could provide further invaluable and completely new insight into the field of "spin physics" and, in addition, might also yield a better understanding of the hadronization process. Such cross sections can be expressed as convolutions of perturbatively calculable partonic spin-transfer cross sections with certain sets of parton distributions and fragmentation functions, whose scale dependence is completely predicted by QCD once a suitable nonperturbative input at some reference scale has been determined by data. To obtain a nonvanishing twist-2 spin-transfer asymmetry, the measurement of the polarization of one outgoing particle is obviously required, in addition to having a polarized beam or target. This certainly provides a great experimental challenge. Λ-baryons are particularly suited for such studies due to the self-analyzing properties of their dominant weak decay $\Lambda \to p\pi^-$, and recent results on Λ production reported from large electron-positron collider (LEP) [1] have demonstrated the experimental feasibility of successfully reconstructing the Λ spin.

In [2] a first attempt was made to determine the spin-dependent Λ fragmentation functions by analyzing these LEP data [1] in leading and next-to-leading order QCD, using the results of a preceding study of unpolarized Λ fragmentation functions. Unfortunately it turned out, however, that the available LEP data, all obtained on the Z resonance and, hence, sensitive only to the flavor nonsinglet part of the cross section, cannot even sufficiently constrain the valence fragmentation functions for all flavors. Rather different, but all physically conceivable, scenarios adopted for the input valence distributions appear to describe the data equally well, and for the "unfavored" sea quark and gluon fragmentation functions one has to fully rely on mere assumptions. Clearly, further measurements of other helicity transfer processes are required to test the models proposed in [2].

With the advent of RHIC [3], spin transfer reactions can be studied for the first time also in pp scattering at center of mass system (c.m.s.) energies of up to $\sqrt{s} = 500$ GeV. In the following we will demonstrate that such measurements would provide a particularly clean way of discriminating between the various conceivable sets of spin-dependent Λ fragmentation functions presented in [2], and are almost unaffected by theoretical uncertainties. For this purpose, only *one* polarized beam at RHIC would be needed. It should be noted here that similar (and almost equally useful) measurements could be performed also in a possibly forthcoming experiment at DESY, HERA-$\vec{N}$ [4], utilizing the existing polarized "fixed" gas target of HERMES and the *un*polarized HERA proton beam.

The process we are interested in is $p\vec{p} \to \vec{\Lambda}X$ (the arrows denoting a longitudinally polarized particle) at large transverse momentum p_T of the Λ, where perturbative QCD can be safely applied. For the time being, the required partonic helicity transfer cross sections, i.e., $q\vec{q} \to q\vec{q}, \ldots, g\vec{g} \to g\vec{g}$, are calculated only to leading order (LO) accuracy and can be found, for example, in [5]. Hence, we have to restrict our analysis to LO, implying the use of LO-evolved Λ fragmentation functions, contrary to the case of $e^+\vec{e}^- \to \vec{\Lambda}X$ or SIDIS ($e\vec{p} \to \vec{\Lambda}X$, $\vec{e}p \to \vec{\Lambda}X$) where all relevant coefficient functions are now available at next-to-leading order (NLO) [2,6–8]. In various analyses of processes sensitive to polarized parton distributions it has turned out to be particularly useful to study distributions differential in the rapidity of a produced particle [9], on which we will therefore focus also in the present analysis.

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The relevant differential polarized cross section can be schematically written as (the subscripts "+", "−" below denote helicities)

$$\frac{d\Delta\sigma^{p\vec{p}\to\vec{\Lambda}X}}{d\eta} \equiv \frac{d\sigma^{pp_+\to\Lambda_+X}}{d\eta} - \frac{d\sigma^{pp_-\to\Lambda_+X}}{d\eta} = \int_{p_T^{\min}} dp_T \sum_{ff'\to iX} \int dx_1\, dx_2\, dz\, f^p(x_1,\mu^2)\Delta f'^p(x_2,\mu^2)\Delta D_i^\Lambda(z,\mu^2)\,\frac{d\Delta\sigma^{f\vec{f}'\to\vec{i}X}}{d\eta}\,, \tag{1}$$

the sum running over all possible LO subprocesses, and where we have integrated over p_T, with $p_T^{\min}$ denoting some suitable lower cutoff to be specified below. The Δf^p (f^p) are the usual (un)polarized parton distributions of the proton, and

$$\Delta D_i^\Lambda(z,\mu^2) \equiv D_{i(+)}^{\Lambda(+)}(z,\mu^2) - D_{i(+)}^{\Lambda(-)}(z,\mu^2) \tag{2}$$

describes the fragmentation of a longitudinally polarized parton i into a longitudinally polarized Λ, where $D_{i(+)}^{\Lambda(+)}(z,\mu^2)$ [$D_{i(+)}^{\Lambda(-)}(z,\mu^2)$] is the probability for finding a Λ at a mass scale μ with positive (negative) helicity in a parton i with positive helicity, carrying a fraction z of the parent parton's momentum.

The directly observable quantity will be not the cross section in (1) itself but the corresponding spin asymmetry, defined as usual by

$$A^\Lambda \equiv \frac{d\Delta\sigma^{p\vec{p}\to\vec{\Lambda}X}/d\eta}{d\sigma^{pp\to\Lambda X}/d\eta}\,, \tag{3}$$

where the unpolarized cross section $d\sigma^{pp\to\Lambda X}/d\eta$ is given by an expression similar to the one in (1), with all Δ's removed.

To study the sensitivity of (3) to the poorly known Λ fragmentation functions ΔD_i^Λ, we use the three LO sets obtained in [2]. For the discussion below, the idea behind these very different models for spin-dependent Λ fragmentation should be briefly recalled here.

Scenario 1.—is based on expectations from the nonrelativistic naive quark model, where only strange quarks can contribute to the fragmentation processes that eventually yield a polarized Λ.

Scenario 2.—is inspired by estimates of Burkardt and Jaffe [10,11] for a fictitious DIS structure function g_1^Λ, taking into account a similar breaking of the Gourdin-Ellis-Jaffe sum rule [12] for Λ's as is observed for nucleons. Assuming the same features also for the ΔD_i^Λ, a sizable negative contribution from u and d quarks to Λ fragmentation is predicted here.

Scenario 3.—is the most extreme counterpart of scenario 1 since all of the polarized fragmentation functions are assumed to be equal here, which might be realistic if, for instance, a sizable contribution to the production of polarized Λ's results from decays of heavier hyperons who have inherited the polarization of u and d quarks produced originally.

For the unpolarized parton distributions of the proton, f^p, appearing in (1) and (3) we use the LO set of Ref. [13] throughout our calculations (using other recent LO sets would not lead to any sizable differences here). Unless otherwise stated we use for the corresponding polarized densities Δf^p the LO Glück-Reya-Stratmann-Vogelsang (GRSV) "standard" scenario [14]. For the unpolarized Λ fragmentation functions D_i^Λ needed for calculating $d\sigma^{pp\to\Lambda X}/d\eta$ we use the LO set presented in [2], which provides an excellent description of all available, rather precise e^+e^- data. It should be emphasized, however, that there are still sizable uncertainties for the D_i^Λ, mainly related to possible $SU(3)_f$ breaking effects not discernible from the presently available data. We note that, in contrast to this, the assumption of $SU(2)_f$ symmetry ($D_u^\Lambda = D_d^\Lambda$) appears to have a far more solid foundation. Clearly, further measurements of the D_i^Λ are required here. Nevertheless, the uncertainty in the D_i^Λ resulting from $SU(3)_f$ breaking does not really affect our conclusions to be drawn below, since the contribution from strange quark fragmentation to the unpolarized cross section is only about 5%.

Figure 1(a) shows our predictions for the spin asymmetry A^Λ as a function of rapidity, calculated according to Eqs. (3) and (1) for $\sqrt{s} = 500$ GeV and $p_T^{\min} = 13$ GeV. Note that we have counted positive rapidity in the forward region of the *polarized* proton. We have used the three

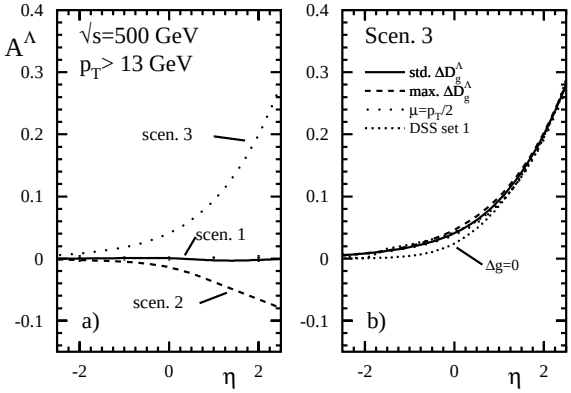

FIG. 1. (a) The asymmetry A^Λ as defined in Eq. (3) as a function of rapidity of the Λ at RHIC energies for the various sets of spin-dependent fragmentation functions. The error bars have been calculated according to (4) and as discussed in the text. (b) same as for scenario 3 in (a), but using the "maximal" ΔD_g^Λ (see text), a hard scale $\mu = p_T/2$, $\Delta g = 0$, or the spin-dependent parton distributions of the proton of set 1 of [15]. For comparison the solid line repeats the original result for scenario 3 of (a).

different scenarios for the ΔD_i^Λ discussed above, employing the hard scale $\mu = p_T$. The "error bars" should give an impression of the achievable statistical accuracy for such a measurement at RHIC. They have been estimated via

$$\delta A^\Lambda \simeq \frac{1}{P} \frac{1}{\sqrt{b_\Lambda \epsilon_\Lambda \mathcal{L}\, \sigma^{pp\to\Lambda X}}}, \qquad (4)$$

assuming a polarization P of the proton beam of about 70%, a branching ratio $b_\Lambda \equiv B(\Lambda \to p\pi) \simeq 0.64$, a conservative value for the Λ detection efficiency of $\epsilon_\Lambda = 0.1$, and an integrated luminosity of $\mathcal{L} = 800\ \mathrm{pb}^{-1}$ [3]. The cross section $\sigma^{pp\to\Lambda X}$ is the unpolarized one, integrated over suitable bins of η. A typical value for the bin $-0.5 \le \eta \le 0.5$ is $\sigma^{pp\to\Lambda X}(p_T > 13\ \mathrm{GeV}) \approx 3$ nb. It should be mentioned that results almost identical to the ones in Fig. 1(a) can be obtained also for a lower c.m.s. energy of $\sqrt{s} = 200$ GeV and a correspondingly lowered $p_T^{\min}$ and luminosity of 8 GeV and 240 pb^{-1}, respectively. Figure 2(a) shows our results for a conceivable future measurement at HERA-$\vec{N}$ at a much lower energy $\sqrt{s} = 40$ GeV and for $p_T^{\min} = 4$ GeV and $\mathcal{L} = 240\ \mathrm{pb}^{-1}$ [4]. Here, one finds $\sigma^{pp\to\Lambda X}(p_T > 4\ \mathrm{GeV}) \approx 1.8$ nb for the bin $-0.5 \le \eta \le 0.5$. It should be stressed that the p_T cuts we have introduced do not only guarantee the applicability of perturbative QCD [the hard scale μ in (1) should be $\mathcal{O}(p_T)$], but also ensure that finite-mass corrections to the cross section, which would become increasingly important for $z \le 0.05$, remain small [2]. Furthermore, small values of z also have to be excluded in order to make sure that there are no unreasonably large NLO contributions: as was noticed for the DIS case in [2], the (unpolarized) NLO kernels for the evolution of the fragmentation functions have an extremely singular behavior at small z, which eventually must lead to a complete breakdown of the "perturbative" formalism we use.

The behavior of A^Λ in Figs. 1(a) and 2(a) for the different sets of polarized Λ fragmentation functions can be easily understood from the fact that the process, in this particular kinematical region, is dominated by contributions from u and d quarks, so that the differences between the predictions in Figs. 1(a) and 2(a) are driven by the differences in the corresponding ΔD_u^Λ and ΔD_d^Λ. This immediately implies that the asymmetry has to be close to zero for scenario 1, negative for scenario 2, and positive and larger for scenario 3. The η dependence is also readily understood: At negative η, the parton densities of the polarized proton are probed at small values of x_2 (i.e., in the "sea region"), where the ratio $\Delta q(x_2)/q(x_2)$ is also small. On the contrary, at large positive η, typical values of x_2 correspond to the valence region where the quarks are polarized much more strongly, resulting in an asymmetry that increases with η.

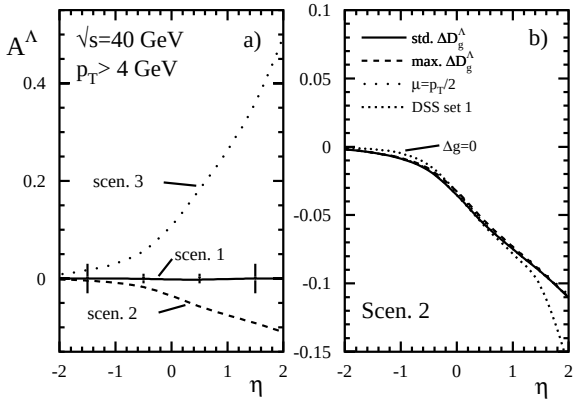

FIG. 2. (a) Same as Fig. 1(a), but for HERA-$\vec{N}$ kinematics. (b) Same as Fig. 1(b), but for HERA-$\vec{N}$ kinematics and scenario 2.

Information on the polarized Λ fragmentation functions is also expected to be revealed by the p_T dependence of the asymmetry A^Λ. From Figs. 1 and 2 one sees that the region $\eta \gtrsim 1$ should be considered here in order to discriminate between the scenarios. Indeed, we found that $A^\Lambda(p_T)$ also shows strong sensitivity to the ΔD_i^Λ, the asymmetries for the three scenarios actually becoming more and more different with rising p_T. However, the problem concerning the p_T dependence is the sharp decrease of the cross sections with p_T, resulting in a strong *in*crease in the size of the expected statistical error bars. For instance, while for the HERA-$\vec{N}$ situation the expected error on $A^\Lambda(p_T)$ for a bin around $p_T = 4$ GeV would be about 1%, it becomes bigger than 35% already at $p_T = 7$ GeV. It therefore seems much more promising to stick to the η dependence of A^Λ as we did in Figs. 1 and 2.

The results in Figs. 1(a) and 2(a) clearly demonstrate the usefulness of the proposed kind of measurements to determine the polarized Λ fragmentation functions more precisely. The expected statistical errors are much smaller than the differences in A^Λ induced by the various models. Thus an analysis of A^Λ would provide an excellent way of ruling out some of the presently allowed sets of spin-dependent Λ fragmentation functions, *provided* the observed differences in A^Λ are not obscured or washed out by the theoretical uncertainties inherent in this calculation. We will therefore finally address this important point in some detail to demonstrate that the uncertainties appear to be well under control for this particular process and do not impose any severe limitations.

There are three major sources of uncertainties: the dependence of A^Λ on variations of the hard scale μ in (1), which is of particular importance since we are limited to a LO calculation, our present inaccurate knowledge of the precise x shape and the flavor decomposition of the polarized densities Δf^p, especially of Δg, and our ignorance of ΔD_g^Λ which is not constrained at all by the presently available e^+e^- data [2]. Figure 1(b) gives an example of the scale dependence of A^Λ by changing the scale from $\mu = p_T$ to $\mu = p_T/2$ for scenario 3. The same is shown in Fig. 2(b) for the HERA-$\vec{N}$ situation

and scenario 2. Even though $d\Delta\sigma/d\eta$ and $d\sigma/d\eta$ individually change by as much as a factor 2 at certain values of η, the uncertainty almost cancels in the ratio A^{Λ}. This gives us some confidence that the (unknown) NLO corrections might also cancel to some extent in the asymmetry, a pattern observed for all available NLO corrections involving polarized particles. We also show in the same figures the changes in the predictions resulting from varying the polarized parton distributions, using the recent LO set 1 of Ref. [15], denoted by DSS, instead of the GRSV [14] one. As can be observed, the asymmetry remains practically unchanged, and differences can be found only at the end of phase space (at large values of η) where the cross section becomes small anyway. Also, as an extreme way of estimating the impact of the polarized gluon distribution, we have artificially set it to zero [$\Delta g(x, \mu^2) \equiv 0$]. The corresponding results are also included in Figs. 1(b) and 2(b). We find that changes in our predictions occur only in the region of negative η, but are small in the interesting region $\eta > 0$ where the asymmetries are larger.

Finally, in order to examine the role played by ΔD_g^{Λ} in our analysis, we have used two different approaches: the standard one for our polarized fragmentation functions, where the polarized gluon fragmentation function is assumed to be vanishing at the initial scale [2] and is then built up by evolution ("standard ΔD_g^{Λ}"), and a set corresponding to assuming $\Delta D_g^{\Lambda} \equiv D_g^{\Lambda}$ at the same initial scale of Ref. [2] ("maximal ΔD_g^{Λ}") while keeping the input quark fragmentation functions unchanged. As can be observed, the resulting differences are also negligible, again due to the fact that u and d fragmentation dominate.

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