

Spin Transfer in Exclusive Λ Production from $\vec{p}p$ Collisions at 3.67 GeV/c

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(Received 6 November 1998)

We report the first polarization transfer measurements for exclusive hyperon production reactions. The normal spin transfer coefficient D_{NN} for $\vec{p}p \rightarrow pK^+\vec{\Lambda}$ is large and negative for forward Λ production at a beam momentum of 3.67 GeV/c, a result qualitatively consistent with expectations for a mechanism dominated by kaon exchange and rescattering. The sign of D_{NN} is opposite to that observed in the fragmentation regime for inclusive Λ production at much higher energies.

PACS numbers: 13.88.+e, 13.75.Cs, 14.20.Jn

One of the primary challenges in the study of hadronic interactions is the identification of the most effective degrees of freedom for their theoretical description: In what regimes is it essential to consider explicitly the interactions of the underlying quarks and gluons, where is meson exchange an efficient alternative, and what (possibly hybrid) descriptions can be used in the transition between these two regimes? One may hope to elucidate such a transition by examining the evolution of a given class of reactions over a very broad energy range.

A promising case study is offered by polarization measurements in the production of hyperons in proton-proton collisions. Here, a large body of existing data [1] for inclusive reactions appears to span the transition regime: Over a wide c.m. energy range ($5 < \sqrt{s} < 60$ GeV) and at transverse momentum transfers $p_T \approx 1$ to 3 GeV/c, they reveal stable polarization effects that are too large to be understood in a partonic framework based on perturbative quantum chromodynamics. These results have been interpreted in a variety of simple *ad hoc* models, based on diagrams involving either constituent quarks [1–3] or Reggeized meson exchange [4]. However, data at higher and lower energies are needed to anchor the existing interpretations in regions where the relevant degrees of freedom ought to be more clear.

We report here the first hyperon polarization results at energies closer to threshold, needed to determine the viability of meson-exchange approaches where they have worked successfully in reproducing cross section measurements [5]. The present experiment is the first to combine

polarized beam with *exclusive* hyperon production kinematics. The exclusivity (achieved without polarized beam in [6]) removes significant ambiguities as to whether observed Λ 's result from direct production or from heavier hyperon decay [7]. Our measurement has sufficient resolution to separate the $\vec{p}p \rightarrow pK^+\Lambda$, $pK^+\Sigma^0(1192)$, and $pK^+\Sigma^*(1385)$ reactions.

Polarized beam allows measurements of the reaction polarization [$P_N(Y)$ for hyperon Y] to be supplemented by the analyzing power (A_N) and the spin transfer coefficient (D_{NN}). The subscripts N label quantization axes normal to the production plane formed by the beam proton and the hyperon momentum vectors. D_{NN} measures the fraction of the normal beam polarization component transferred to the hyperon. We concentrate here on the D_{NN} results because they are sizable and subject to simple interpretation within either meson exchange or constituent quark reaction models [3,8].

Figure 1 shows a schematic view of the experimental setup [9] which was installed at the Laboratoire National Saturne at Saclay. A polarized proton beam of 3.67 GeV/c was scattered from a liquid hydrogen target placed at the center of a large gap (40 cm) dipole magnet. Multiple charged reaction products were detected in counters arranged in two arms mounted symmetrically on both sides of the curving beam trajectory. The particles were tracked with scintillating fiber (SF) detectors and multi-wire proportional chambers (MWPC's), each composed of three stereo planes with elements aligned vertically (x) or horizontally (y), and at $\pm 45^\circ$ (u, v) to the vertical.

Particle multiplicities, energy loss, and flight times were measured with a plastic scintillator hodoscope comprising six horizontal and ten vertical elements per arm. Particle velocities (for $\beta > 0.75$) were determined with an array of twelve water Čerenkov counters mounted vertically at the rear of each arm. In the laboratory frame, the detectors covered an angular range from $\approx 2^\circ$ to $\approx 48^\circ$ horizontally, on both sides of the beam, and $\pm 15.5^\circ$ vertically. The large acceptance improves sensitivity in determining the polarization of the Λ particles from the parity-violating asymmetry in their weak decay to $p\pi^-$.

Two additional vertical scintillator slabs were added beyond the angular range of the hodoscope to detect recoil protons as part of a $\bar{p}p$ elastic scattering coincidence event stream used for on-line monitoring of the beam polarization (P_b). The asymmetries, $\epsilon = P_b A_N \sim 0.1$, measured with this polarimeter were stable over time and determined with a statistical precision $\sim \pm 0.001$ during a typical two-week running period. The polarimeter A_N was taken from the systematics of existing $\bar{p}p$ elastic scattering data [10]. The magnitude of the (vertical) beam polarization, averaged over all production runs, is 0.73 ± 0.05 , where the error reflects the normalization uncertainties in A_N data in the 2–3 GeV energy range. The beam spin direction was flipped on alternate beam bursts to minimize time-dependent instrumental asymmetries.

The hyperon production trigger [9] required at least three charged tracks in the final state, based on the multiplicity of fired hodoscope elements and scintillating fibers. The beam intensity ($\sim 10^8$ protons/burst) and trigger conditions were adjusted to limit the total data acquisition dead time typically to 12%.

Position information from the SF's, MWPC's, and hodoscopes was used to reconstruct curved tracks through the magnetic field and locate their intersection points. Pulse height information from the hodoscope and Čerenkov counters, together with reconstructed momenta for each

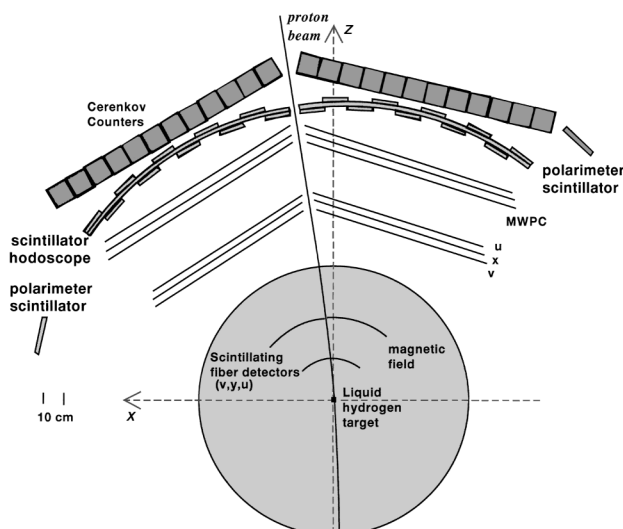


FIG. 1. Schematic view of DISTO detector elements.

track, were used for particle identification. Hyperon production candidates were selected from events with four reconstructed tracks, consistent with identification as p and K^+ from a primary vertex within the target volume and p and π^- from a decay vertex displaced by ≥ 1 cm. The spectra presented here have been subjected only to loose kinematic cuts, designed to yield minimal loss of good hyperon production events.

Exclusive Λ production events were identified as those with both the invariant mass of the $p\pi^-$ pair ($M_{p\pi^-}$) and the missing mass (ΔM_{pK}) reconstructed from the pK^+ pair equal, within resolution, to the Λ mass. The Λ peak is seen clearly in both mass spectra in Fig. 2. Two types of background under the Λ missing mass peak must be removed to isolate the exclusive production: (1) combinatoric background (p and π^- not from Λ decay) [11]; (2) feedthrough from the adjacent peak due to Σ^0 production and decay to $\Lambda\gamma$. All other Λ production channels, such as $pp \rightarrow pK^+\Sigma^*(1385)$, $pK^+\Lambda\pi^0$, or $pK^0\Lambda\pi^+$ (the latter contributing only via $\pi^+ - K^+$ misidentification), are too far removed in missing mass to contribute appreciably under the direct Λ peak.

To infer the shape and magnitude of the combinatoric background in the ΔM_{pK} spectrum we have selected, within each analyzed kinematic bin, the event sample with $1150 \leq M_{p\pi^-} \leq 1180$ MeV/ c^2 . (As shown by the dashed spectrum in Fig. 2(a), the $M_{p\pi^-}$ background above the Λ peak is quite flat when examined within a gate on the Λ missing mass peak.) This sample is dominated by the abundant $pp\pi^+\pi^-$ events, which occasionally satisfy our loose hyperon production cuts for π^+ momenta ≥ 1 GeV/ c (where $\pi - K$ particle discrimination is limited). As indicated by the dashed curve in Fig. 2(b), this sample reproduces very well the nonphysical “hyperon” events below 950 MeV/ c^2 , and accounts for a fraction $f_{\text{comb}} = 0.12$ to 0.31 (depending on kinematic bin) of the area under the Λ peak.

After subtracting the combinatoric background in each kinematic bin, we have fitted the Λ - Σ^0 region with a sum of two Lorentzian peaks. This peak shape reproduces

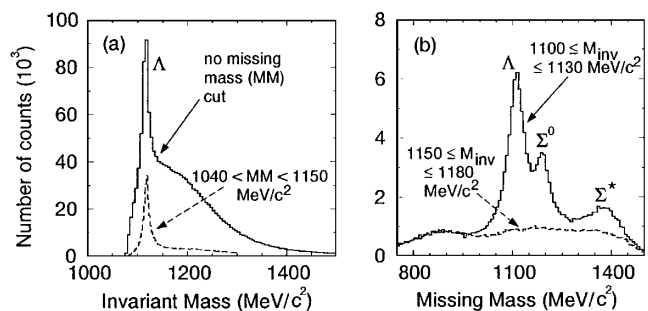


FIG. 2. (a) Spectrum of $p\pi^-$ invariant mass at the decay vertex (measured with resolution $\sigma \approx 5$ MeV/ c^2) with (dashed) and without (solid) a cut on the Λ missing mass. (b) Missing mass spectrum ($\sigma \approx 25$ MeV/ c^2) from primary pK^+ pairs for $p\pi^-$ invariant mass in the range 1100–1130 MeV/ c^2 (solid line) and 1150–1180 MeV/ c^2 (dashed line).

well the simulated spectra for pure Λ or pure Σ^0 production when these are analyzed with the same event reconstruction software as the real data. The fits determine the relative enrichments [$f_{\Lambda,\Sigma}^i$, where $f_{\Lambda}^i + f_{\Sigma}^i = 1$] in Λ vs Σ^0 production of two event samples, within ΔM_{pK} gates around the Λ ($i = 1, 1040\text{--}1150 \text{ MeV}/c^2$) and Σ^0 ($i = 2, 1165\text{--}1240 \text{ MeV}/c^2$) peaks. For example, f_{Σ}^1 varies from 0.01 to 0.17 over the bins analyzed.

The polarization of the Λ 's is manifested by a fore-aft (pseudoscalar) asymmetry of the angular distribution of the daughter proton in the Λ rest frame, measured with respect to a spin quantization axis parallel to the momentum vector product $\mathbf{k}_{\text{beam}} \times \mathbf{k}_{\Lambda}$. By analyzing separately the event samples acquired with beam spin up vs down, and with \mathbf{k}_{Λ} to the left vs right of \mathbf{k}_{beam} , one can separate the Λ polarization into a component independent of the beam spin (arising from the reaction polarization P_N) and a component that reverses sign when the beam spin is flipped (corresponding to D_{NN}) [12]. The subtracted combinatoric background is always statistically consistent with symmetry in the "decay" angular distribution, hence with $P_N = D_{NN} = 0$, as expected for the parity-conserving background processes.

For each ΔM_{pK} gate D_{NN}^i is a linear combination,

$$D_{NN}^i = f_{\Lambda}^i D_{NN}(\Lambda) + f_{\Sigma}^i D_{NN}(\Sigma^0 \rightarrow \Lambda), \quad i = 1, 2,$$

from which we extract the pure direct Λ and $\Sigma^0 \rightarrow \Lambda$ results separately, using the fitted enrichments $f_{\Lambda,\Sigma}^i$. Here, $D_{NN}(\Sigma^0 \rightarrow \Lambda)$ represents the product of the polarization transfers in the $\vec{p}p \rightarrow pK^+\vec{\Sigma}^0$ production and the $\vec{\Sigma}^0 \rightarrow \vec{\Lambda}\gamma$ decay. The latter factor is typically $-1/3$. The extracted $D_{NN}(\Lambda)$ values are always within ± 0.04 of the measured D_{NN}^1 , and are stable with respect to small shifts in the bounds of gates 1 and 2.

Figure 3 shows the D_{NN} results for the exclusive Λ production as a function of both (a) the transverse momentum transfer p_T (from \vec{p} to $\vec{\Lambda}$) and (b) the Λ 's longitudinal momentum, expressed as a fraction (x_F) of its maximum kinematically allowed value. Exclusive results are extracted only for $x_F > 0.1$ (the range included in Fig. 2), since at smaller x_F the rising p and K^+ momenta cause the missing mass resolution to deteriorate. D_{NN} is large and negative (≈ -0.4) over most of the kinematic region. The negative sign signifies that the component of the Λ polarization that is correlated with the beam spin is oriented *opposite* to the beam spin.

The error bars in Fig. 3 include statistical, but not systematic, uncertainties from the background subtraction and the Λ - Σ^0 peak fitting. We estimate the associated systematic errors to be $\leq \pm 0.02$ and ± 0.04 , respectively, allowing, very conservatively, for shape changes that scale f_{comb} by $\pm 20\%$ and f_{Σ}^1 by $\pm 75\%$. The latter error is consistent with the observed $D_{NN}(\Lambda) - D_{NN}^1$ differences. Instrumental asymmetries in detection efficiency do not change when the beam spin is reversed, hence contribute errors $< \pm 0.01$. Overall scale uncertainties in D_{NN} arise

from the present uncertainties in the beam polarimeter calibration ($\pm 7\%$) and in the Λ decay asymmetry ($\pm 2\%$ [15]). The systematic errors do not affect the striking qualitative behavior observed for D_{NN} or the conclusions drawn below.

The D_{NN} parameter is especially sensitive to the hyperon production mechanism [8]. For example, in a meson-exchange framework, D_{NN} distinguishes clearly between π - and K -exchange contributions. This is illustrated in Fig. 4 by theoretical calculations employing the model of Ref. [5]. At large positive x_F , D_{NN} is maximally different for the two dominant contributions indicated in the figure. The difference arises from the different spin coupling at the vertices joining the polarized proton to the hyperon. To conserve angular momentum and parity, kaon emission at this vertex (bottom right diagram, Fig. 4) causes a spin flip, yielding $D_{NN} = -1$.

In contrast, the second mechanism (depicted in the top-right diagram of Fig. 4), where a virtual pion undergoes a strangeness-changing rescattering at the polarized proton vertex, has a spin structure ($\frac{1}{2}^+ + 0^- \rightarrow \frac{1}{2}^+ + 0^-$) for which angular momentum and parity conservation require $D_{NN} = +1$. (The latter holds rigorously for the on-shell $\pi\vec{p} \rightarrow K\vec{\Lambda}$ process, but only approximately in this case, where the rescattering can have an out-of-plane component of momentum transfer.) The predicted D_{NN} tends toward zero for both mechanisms at the more negative x_F , since the hyperon is then connected preferentially to the *unpolarized* (target) proton.

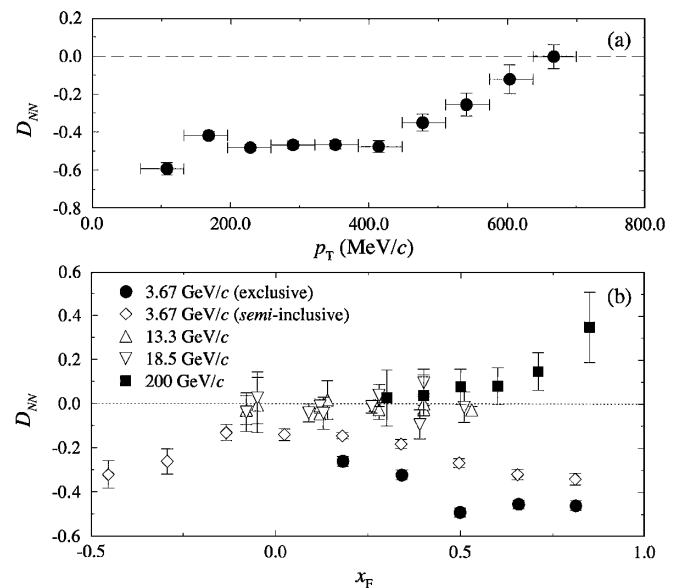


FIG. 3. (a) Measured D_{NN} values vs transverse momentum transfer for the exclusive $\vec{p}p \rightarrow pK^+\vec{\Lambda}$ reaction. The horizontal error bars reflect the width of the p_T bins analyzed. The vertical error bars reflect statistical uncertainties only. (b) D_{NN} as a function of x_F for the present exclusive Λ production and for inclusive Λ production at various higher incident momenta from Refs. [13,14]. Also shown for comparison are the semi-inclusive results from the present data.

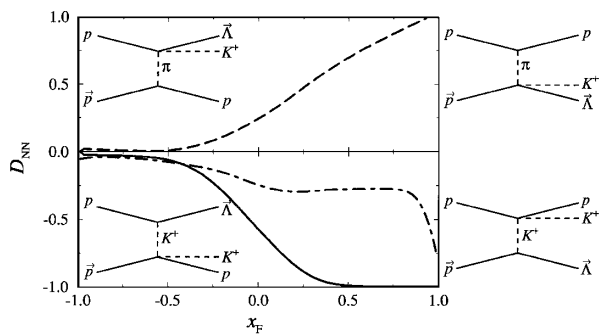


FIG. 4. Theoretical calculation [5] of D_{NN} for various *exclusive* Λ production mechanisms: kaon exchange (solid curve), pion exchange (dashed), or both combined with a Λ - p final state interaction (dotted-dashed). The Feynman diagrams indicate the dominant exchange contributions for positive vs negative x_F . The calculations are integrated over *all* phase space in other kinematic variables.

Quark-line diagrams lead to still different expectations for D_{NN} [8].

The large negative values observed for D_{NN} at $x_F > 0$ in Fig. 3(b) and comparison with Fig. 4 can thus be interpreted in a meson-exchange framework to suggest kaon-exchange dominance. The full theoretical calculation (dotted-dashed curve in Fig. 4, not yet folded with the experimental acceptance) is qualitatively similar to the measurements.

How do the present results compare to polarization transfers measured previously [13,14] for *inclusive* Λ production at higher energies? To facilitate this comparison, we include in Fig. 3(b) the D_{NN} results for the *semi-inclusive* sample obtained by summing the present data (after subtracting combinatoric background) over all missing masses above 1000 MeV/ c^2 . Inclusion of the Σ^0 and $\Sigma^*(1385)$ yields makes D_{NN} only slightly less negative than our exclusive Λ results at $x_F > 0$. The present data clearly differ in sign from inclusive D_{NN} results obtained at 200 GeV/ c for large x_F .

Although these different data sets encompass quite different ranges of p_T , the dominant sign of D_{NN} does not change with p_T at either the present or the highest energies. The signs of the polarization observables, including D_{NN} and P_N , for inclusive Λ production at 200 GeV/ c [14] have been successfully interpreted in a simple constituent quark model in Ref. [3]. The present results are not naturally explained within this quark model.

In summary, we have reported the first polarization transfer measurements for an exclusive hyperon production reaction, $\bar{p}p \rightarrow pK^+\bar{\Lambda}$. The large negative values observed for D_{NN} at positive x_F represent a robust qualitative behavior that suggests a production mechanism dominated by kaon exchange, and that differs markedly from high-energy observations for inclusive hyperon production. Detailed comparison of meson exchange [5] and other model calculations with the data will be important for a more refined understanding. The addition of the

present results to the existing database for hyperon production affords an opportunity to track the evolution with energy in the relevant degrees of freedom.

This work has been supported in part by the following agencies: CEA-DSM, CNRS-IN2P3, GSI, INFN, KBN (2 P03B 117 10 and 2 P03B 115 15) and NSF. We thank J.-M. Laget for making his calculation available and for useful discussions. We acknowledge the excellent support provided by the SATURNE II accelerator and technical staff in completing this program.

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