Spin-Parameter Measurements in Inclusive Σ^0 Production

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(Received 12 December 1988)

We have measured the polarization P, the analyzing power A, and the polarization transfer D of Σ^0's produced inclusively by a polarized proton beam at 18.5 GeV/c. Our data cover a region of moderate p_T (average 1 GeV/c) and Feynman x up to 0.75. We find agreement with a previous measurement of the Σ^0 polarization P. We observe nonzero values for A and D, but they are significantly smaller than predictions based on a simple parton-recombination model. We have extended this model to include finite transversity spin flips, which improves agreement with the data considerably.

PACS numbers: 13.88.+e, 13.85.Ni

Many experiments have shown that inclusively produced hyperons emerge from p-A collisions polarized.[1] However, very little is known about the spin dynamics of the production processes. This can be investigated using a polarized beam and looking at the spin-dependent asymmetry of the cross section (analyzing power A) and at the polarization transfer D in the reaction. We recently reported the first measurements of this type for the case of Λ production.[2,3] Deviations from the predictions of simple models[4] of the process were evident from our data. A possible explanation for the disagreement was the significant contribution to our sample of Λ's from the decay $\Sigma^0 \to \Lambda\gamma$. It was, therefore, of interest to measure A, P, and D for the case of Σ^0 production.

The 18.5-GeV/c polarized proton beam at the Brookhaven Alternating Gradient Synchrotron (AGS) was used to produce Σ^0's from a beryllium target. The Σ^0's were reconstructed from the dominant decay chain $\Sigma^0 \to \Lambda\gamma$ and $\Lambda \to p\pi^-$. A plan view of the experimental setup is shown in Fig. 1. The charged particles were tracked in the multiparticle spectrometer[5] MPS-II, placed on the left side of the incoming beam, and a lead-glass calorimeter detected the γ's arising from the Σ^0 decay. The Σ^0 polarization was deduced from the measured polarization of the daughter Λ. The acceptance was optimized for events with transverse decays, where the polarization transfer from Σ^0 to Λ is greatest,[6] by offsetting the calorimeter vertically with respect to the spectrometer axis. The lead-glass array had been calibrated using electrons with momenta of 1 and 2 GeV/c,[7] a range which matches the γ energies in the Σ^0 decay.

The incident polarized proton beam was defined by scintillator S2 and a hole scintillator S3. The Σ^0 trigger consisted of a Λ trigger together with a minimum-energy-deposition requirement in the lead-glass. The most powerful element was the requirement $\bar{S}4 \cdot S5(\geq 2)$, which signified a neutral transversing scintillator S4

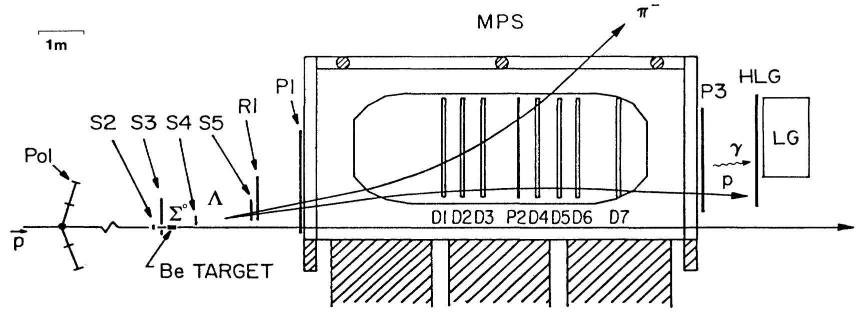

FIG. 1. Plan view of the experimental setup, explained in the text.

which then decayed into two charged particles before scintillator S5. The cluster-multiplicity readouts of the proportional chambers P1–P3 were used to enhance the acceptance of a fast proton and to suppress γ showers produced inside the spectrometer. The whole downstream aperture of the MPS-II was covered by a segmented scintillator hodoscope located in front of the lead-glass array; appropriate elements were placed in anticoincidence with the corresponding rows of lead-glass to suppress showers induced by charged hadrons. Events in which a fast proton traversed all the chambers were favored by requiring at least one charged-particle hit in the hodoscope. Each row of lead-glass was timed with a time-to-digital converter (TDC) to suppress accidentals.

The spectrometer consisted of 49 drift planes clustered into seven chambers (D1–D7), and four proportional chambers R1(x,u,v) and P1(x)–P3(x). Charged particles were tracked inside the 0.5-T magnetic field and then extrapolated into the upstream field-free region through the proportional chambers P1(x) and R1(x,u,v) for the reconstruction of the neutral decay vertex.

A few meters before the target, the transverse components of the beam polarization P_B were monitored with a polarimeter consisting of a polyethylene target viewed by four scintillator telescopes. Its analyzing power was periodically checked against an absolute polarimeter[8] located in another beam line. We checked that P_B was rotated from the vertical in a direction transverse to the beam momentum by $29° \pm 1°$ in the azimuthal angle Φ, in agreement with the calculated value due to the spin precession in the magnets of the extracted proton beam line.[9] The beam polarization was $44.3\% \pm 1.4\%$, and its direction was reversed after each AGS pulse. The average beam intensity on target was 3×10^6 per 500-ms AGS pulse.

In the event reconstruction, the neutral decay vertex was required to fall inside the field-free region between S4 and S5 and the neutral-particle momentum had to extrapolate back to the target. We required one positive- and one negative-charged-particle track reconstructing, under the $p\pi^-$ hypothesis, to an effective mass within 2σ ($1\sigma = 2.9$ MeV/c^2) of the Λ mass value. All the charged-particle tracks were extrapolated to the lead-glass position, and energy deposition clusters closer than 13 cm to any track were rejected. This was done to suppress showers induced by charged hadrons hitting the lead-glass. Accidental showers were eliminated by applying TDC cuts. For all the events that satisfied the cuts above, we calculated a $\Lambda\gamma$ invariant mass.

A total of 17×10^4 reconstructed events contained a Λ and 10^4 among them reconstructed to Σ^0's. The Σ^0 mass peak (see Fig. 2) rests on background due to events in which a Λ was produced together with an uncorrelated γ. In determining the spin observables for Σ^0 production, the background under the peak was taken into account, and the results for P, A, and D were corrected according to the known contributions[3] from Λ production. The kinematic region covered by our data extends between 0.0 and 0.75 in x_F and 0.5 and 2.0 GeV/c in p_T. Only events with $x_F > 0.2$ were considered in the determination of A and D; the events have an average Feynman x of 0.36 and an average transverse momentum of 1.22 GeV/c.

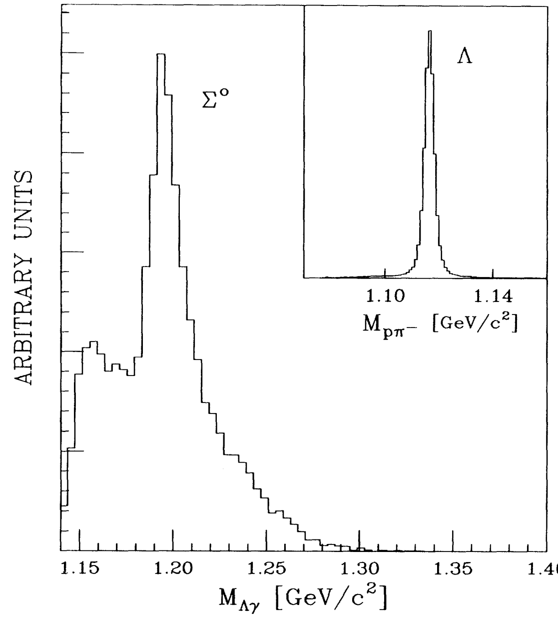

FIG. 2. Effective-mass distribution for Σ^0 and Λ (inset) events.

The Λ polarization P_Λ is extracted from the parity-nonconserving angular distribution of decay protons in the Λ rest frame:

$$dN/d\cos\theta^* = N_0(1+\alpha P_\Lambda \cos\theta^*)\,, \tag{1}$$

where the analyzing power[10] $\alpha = 0.645 \pm 0.017$, and θ^* is the angle of the decay-proton momentum with respect to the Λ polarization vector in the Λ rest frame. The Σ^0 polarization P_{Σ^0} can be determined from the decay-Λ polarization through the complete reconstruction of the decay kinematics, since in the Σ^0 rest frame[6]

$$\mathbf{P}_\Lambda = -(\mathbf{P}_{\Sigma^0}\cdot\hat{\mathbf{p}}_\Lambda)\hat{\mathbf{p}}_\Lambda\,, \tag{2}$$

where $\hat{\mathbf{p}}_\Lambda$ is a unit vector in the direction of the Λ momentum in the Σ^0 rest frame. The acceptance of our setup for Λ decay products, which is relevant for the polarization determination, was not homogeneous, due to the up-down asymmetry introduced by the lead-glass and hodoscope detectors. To determine the acceptance function we used the fraction of our data consisting of events where a Λ is produced together with uncorrelated γ's. From our previous experiment[3] we know the polarization values over the whole kinematic range and thus, the angular distributions of the decay protons and pions. This enables the extraction of the acceptance function for each phase-space element. The Σ^0 polarization value we obtain, $P = 0.23 \pm 0.13$, is in good agreement with the measurement of Ref. 11. The error we quote is largely statistical; a systematic uncertainty of 0.04, mainly due to background corrections, is included.

The analyzing power A is given by[3,12]

$$A=\frac{1}{P_B\cos\phi}\,\frac{N_\uparrow(\phi)-N_\downarrow(\phi)}{N_\uparrow(\phi)+N_\downarrow(\phi)}\,, \tag{3}$$

where ϕ is the mean angle between the beam polarization direction and the normal to the production plane, defined as $\hat{\mathbf{p}}_p\times\hat{\mathbf{p}}_\Lambda$, where $\hat{\mathbf{p}}_p$ is a unit vector in the direction of the laboratory momentum of the beam. The number of particles produced for up (down) beam polarization is denoted by $N_{\uparrow(\downarrow)}$. The average analyzing power we obtain in Σ^0 production is $A=0.02\pm0.03$, where both statistical and systematic errors due to the background correction are contained in the quoted uncertainty. The results for both Σ^0 and Λ production, obtained from the uncorrelated $\Lambda\gamma$ events, are shown in Fig. 3. In an earlier experiment,[3] we carefully investigated the p_T and x_F dependence of the Λ analyzing power and found that

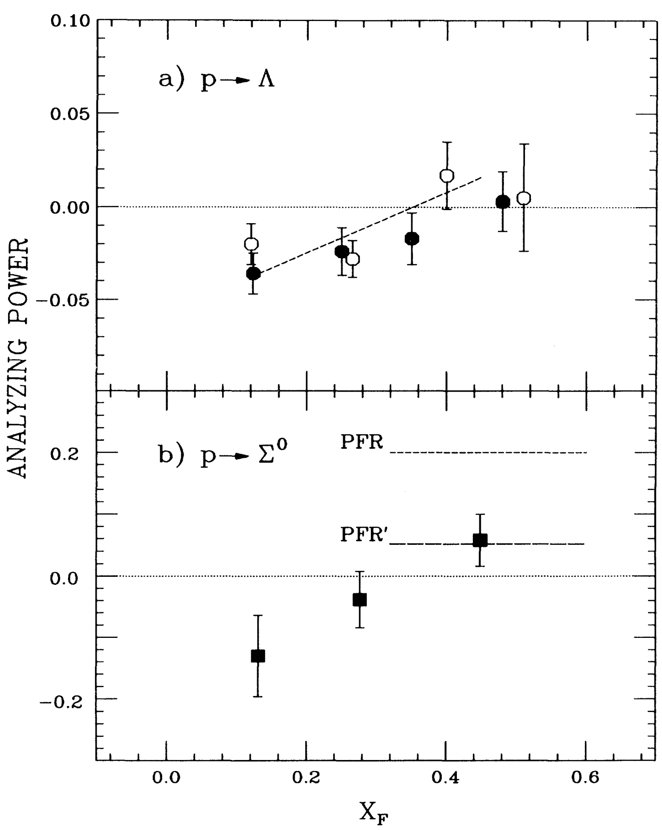

FIG. 3. (a) Analyzing power for Λ production. The results are from this experiment (solid circles) and from Ref. 3 (open circles). The dashed line is the contribution due to Λ production through Σ^0 decays. (b) Analyzing power for Σ^0 production. The dotted lines show the predictions of the parton fragmentation and recombination model (PFR) and from an extension of the model to allow a nonzero spin-flip probability (PFR′).

$A=0$ within a few percent, with no energy or other kinematic dependence. Recall that in Λ production we do not distinguish between directly produced Λ's and those arising from Σ^0 decay. The contribution to the Λ analyzing power due to indirect production can be determined by using the measured values for the Σ^0 analyzing power [dashed line in Fig. 3(a)]. We observe that the results are compatible with a vanishing effect for direct Λ production, as predicted by a naive parton-recombination model,[4] where a (u,d) diquark of spin 0 is transmitted from the proton to the Λ during the reaction.

The polarization transfer D in Λ production is given by

$$D=\frac{1}{2P_B\cos\phi}[P_{\Lambda\uparrow}(1+P_BA\cos\phi)-P_{\Lambda\downarrow}(1-P_BA\cos\phi)]\,, \tag{4}$$

where $P_{\Lambda\uparrow}$ $(P_{\Lambda\downarrow})$ is the measured Λ polarization for beam spin up (down). The polarization transfer can be determined in a fully acceptance-independent way[3] by subdividing the whole phase space into single elements of $d(\cos\theta^*)$, each one yielding a measurement of D. This method was not essential in our previous experiment on Λ production, where the measured distributions were not heavily affected by the detector acceptance,[3] but it is very important in this case, due to the inhomogeneities mentioned above. In the analysis of Σ^0 production data, the phase space was subdivided into single elements $d(\cos\psi_i)d(\cos\theta_j^*)$, where ψ is the angle between Σ^0 polarization and Λ direction in the Σ^0 rest frame. This parametrization was necessary because the spin transfer from the Σ^0 to the decay Λ is proportional to $\cos\psi$ [see Eq. (2)]. Due to the limited statistics of the Σ^0 data we have assumed that the polarization transfer is the same along any direction in space. For each phase-space element (i,j) a measurement D_{ij} was determined, and the result for $D(\Sigma^0)$ was calculated from the average over all D_{ij}, weighted with the individual statistical errors. The value so extracted is $D(\Sigma^0)=0.26\pm0.16$, with $(\chi^2/224)^{1/2}=0.98$.

In the absence of an *ab initio* calculation to explain the results in hyperon production, one is forced to seek understanding from simple models. The most effective approach up to now is the parametrization proposed by DeGrand and Miettinen,[4] which successfully reproduces the observed pattern of results in hyperon polarization measurements. Using their parton-recombination model, the predictions for Σ^0 production[3] are $A=0.20$ and $D=0.67$. This is in severe disagreement with the present data. An even greater failure of this model occurs in predicting the cross-section ratio between Λ and Σ^0 production. The experimental result[13] is 0.39 ± 0.04, whereas the predicted value[4] is $\frac{1}{9}$. It seems that Σ^0's are produced more easily than the assumptions of Ref. 4 would allow. Such an enhancement could occur if there were a finite transversity spin-flip probability for at least one of the valence quarks during the scattering and recombination process. We have extended the model in this sense by introducing two new recombination probabilities that couple quark or diquark states of different spin and transverse-spin-projection values, namely,

$$|\mathcal{B}^{f}_{\uparrow(\downarrow)}|^2=\tau_1\mathcal{B}'(1\pm\epsilon') \text{ and } |\mathcal{A}^{\xi}_{S,M}|^2=\tau_2\mathcal{A}(1+M\delta) \tag{5}$$

for a valence quark with final spin up (down) and for a diquark with final spin and transverse spin projection S and M, respectively. The notation we use is that of Ref. 4. $\mathcal{B}'$ and $\mathcal{A}$ are spin-dependent probabilities; ϵ' and δ are spin-orbit parameters. The parameters τ_1 and τ_2 are determined from the probability $\mathcal{P}$ of a single flip:

$$\tau_1=\frac{\mathcal{P}}{1-\mathcal{P}},\quad \tau_2=\frac{2\mathcal{P}(1-\mathcal{P})}{1-2\mathcal{P}(1-\mathcal{P})}. \tag{6}$$

The free parameter $\tau_2=0.38\pm0.04$ is determined by fitting the measured Σ^0-to-Λ production cross-section ratios[13]; this translates into a single transversity spin-flip probability $\mathcal{P}\simeq0.16$. The predicted values of the spin parameters for Σ^0 production then change dramatically to $P=0.23$, $A=0.05$, and $D=0.18$, coming into a 1σ agreement with the measured ones. We have verified that all the polarization predictions for the processes that have been investigated experimentally[1,3] ($p\rightarrow\Lambda,\Sigma^+,\Sigma^-,\Xi^-,\Xi^0$; $K\rightarrow\Lambda$, etc.) are unaffected by the introduction of this transversity spin-flip term, to within 10% of their values.[14] Significant changes occur, however, in the predictions of the analyzing power for meson production with a proton beam.[15] The predictions from the extended model are significantly closer to the measured values. The introduction of a finite probability for a transversity spin flip has the happy effect of improving the agreement between predictions and data for several observables in several different reactions.

We conclude that the data support the parton-recombination model[4] extended to include transversity flip. A higher-statistics measurement of D in Σ^0 production would allow a closer check of the proposed spin-spin coupling. Other measurements (e.g., $p\rightarrow\Sigma^+$) are also of great interest; they would provide independent results to better understand the mechanisms underlying particle production. The spin degree of freedom, long considered an annoying complication at high energies, is proving crucial to furthering our understanding of just how particles are produced.

This experiment was supported by the U.S. Department of Energy. We are grateful to Dr. L. Ratner and the entire staffs of the AGS Department, the MPS group, and the BNL Applied Mathematics Department.

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