MEASUREMENT OF THE RATIO OF Σ^0/Λ INCLUSIVE PRODUCTION AND THE Σ^0 AND Λ POLARIZATIONS BY 28.5 GEV/C PROTONS ON BERYLLIUM

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ABSTRACT

The ratio of the cross section for Σ^0 inclusive production to the cross section for Λ inclusive production has been measured with 28.5 GeV/c protons incident on a beryllium target. The ratio does not depend strongly on the momentum of the produced particle between 10 and 24 GeV/c and is $0.278 \pm 0.011 \pm 0.050$, where the uncertainties are statistical and systematic in that order. The polarization of the Σ^0 has been measured with the same data and is found to be opposite to that of the Λ. The polarization of the Λ has also been measured in the transverse momentum range $0.64 < p_T < 1.14$ GeV/c and is consistent with previous results.

INTRODUCTION

Since the discovery of large polarization in inclusive Λ production at 300 GeV in 1976[1] further experimental effort has been directed toward: determining the energy dependence of the effect; exploring the phenomenon in other inclusively produced hyperons; and expanding our knowledge of the kinematic dependence of the polarization. Much progress has been made. Far from being a trait unique to the Λ, polarization appears to be an almost universal property of hyperon production — all of the hyperons examined (which until this experiment was all excepting the Σ^0), have been found to be polarized in inclusive production from protons. We report here on the first measurements of the polarization of inclusively produced Σ^0 hyperons.[2]

The polarization of the Λ has been investigated most extensively, but despite the large amount of effort expended in understanding its polarization, none of the experiments have addressed a fundamental experimental question: determining the contamination in their Λ data from Λ's resulting from the decay of other particles or resonances. This contamination could be large and is presumably dominated by Λ's from Σ^0 decay: $\Sigma^0 \to \Lambda + \gamma$. Since the Λ and Σ^0 have the same quark content, one might naively expect that the number of Λ's from Σ^0 decay and the number of directly produced Λ's to be equal. If that were the case the direct Λ polarization would be 20% to 50% larger than the measured Λ polarization, depending on the Σ^0 polarization magnitude and direction (Λ's from Σ^0 decay retain on average $-1/3$ of the Σ^0 polarization). We report here on the first measurement of the ratio Σ^0/Λ in inclusive production.[3]

THE APPARATUS

The experiment was done at the B5 beam line of the AGS at Brookhaven National Laboratory. Since it is known that inclusive polarization is not strongly dependent on energy, we chose to do the experiment at an energy where the photons from Σ^0 decay are emitted at large enough angles to facilitate their detection. Details of the apparatus are given in references 3, 4, and 5. Fig. 1 shows a plan view of the apparatus. A 28.5 GeV/c proton beam was incident on a beryllium target followed by a collimator embedded in a 3.71 Tm dipole (sweeper) magnet which performed the dual task of sweeping away unwanted charged particles and precessing the Λ polarization. The axis of the collimator, defining the z axis of the spectrometer coordinate system, was at a 4^0 angle to the incident proton beam in the horizontal plane. The y axis lay in the vertical direction and the x axis at beam left. A two dipole magnetic spectrometer followed a He filled decay region and measured the proton and pion momenta in the decay $\Lambda \rightarrow p+\pi^-$. The gamma from the Σ^0 decay was detected using a lead-glass calorimeter. The calorimeter was an array of 84 $6.35\times 6.35\times 58.4$ cm^3 SF-2 lead-glass blocks covering 84% of the 3.1 msrad solid angle made available by the collimator aperture. Each block was calibrated before and after the data taking in an electron test beam. By placing the calorimeter out of the production plane, Σ^0 decays in which a large fraction of the Σ^0 polarization is transferred to the Λ were selected.

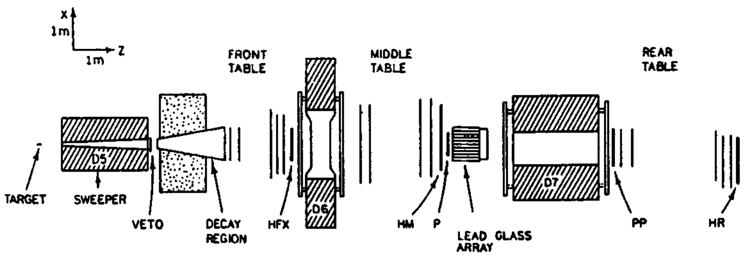

Fig. 1. Plan view of the apparatus.

The event trigger was the logical OR of a Λ (prescaled by 64) and a Σ^0 trigger. The Λ trigger required a high momentum positively charged particle passing through both spectrometer magnets in coincidence with a second charged particle passing through the upstream spectrometer magnet only, both particles coming from a neutral parent. The Σ^0 trigger was a Λ trigger in coincidence with a minimum of 0.5 GeV energy in the calorimeter. Two tapes of approximately 30,000 events each required about four hours after which the sweeper magnet polarity was reversed and the process repeated. Approximately 5×10^6 Σ^0 triggers and 1.3×10^6 Λ triggers were recorded on magnetic tape.

THE PRODUCTION RATIO

The data were first processed with the goal of finding all events reconstructing a Λ. Good Λ events were selected by requiring two charged particle tracks of opposite sign emanating from a common vertex within the decay region, their summed vector momentum pointing back to the target, and their invariant mass within 5σ, or ± 10 MeV/c^2 of the Λ mass. Σ^0 events were identified by reconstructing the $\Lambda\gamma$ invariant mass for those events with a good Λ. The gamma energy was determined by finding the lead-glass block with the maximum amount of energy in the array and summing its energy with that of the surrounding eight blocks. Showers with maxima in an edge block were discarded as were showers out of time with the Λ trigger. To track the variations in the lead-glass calibration constants, run by run calibrations were done by constraining well defined Σ^0 topologies to the Σ^0 mass. The average energy resolution was 12% (rms) for photon energies between 0.8 and 3.8 GeV. The $\Lambda\gamma$ invariant mass is shown in Fig. 2.

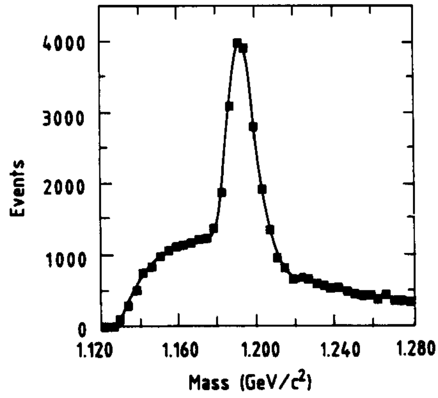

Fig. 2. The $\Lambda\gamma$ invariant mass.

The production ratio R_1 of the cross section for Σ^0 inclusive production to the cross section for Λ inclusive production was calculated in each bin using

$$R_1 = (N_\Sigma/N_\Lambda) \times (A_\Lambda/A_\Sigma) \times (1/64)$$

where N_Σ and N_Λ are the number of Σ^0 and Λ events observed in each bin and A_Λ/A_Σ is the ratio of the acceptance of the apparatus for Λ and Σ^0's. The number 64 is the prescale factor. The number of Σ^0 and Λ events were found by counting the number of events passing all the cuts minus the background under the respective invariant mass peaks. The background under the Λ peak was small, typically 1.5%. The background under the Σ^0 peak was larger and found by fitting a gaussian signal plus an exponential background to the $\Lambda\gamma$ invariant mass histogram. Several non&hyppen.negligible systematic corrections were applied to N_Σ. These included an estimate of the number of photons lost due to conversion before the calorimeter (13 ± 1)%; lifetime corrections for the Σ^0 trigger (<1%); and effects due to photon reconstruction and the energy calibration procedure (<3%).

The acceptance ratio N_Λ/N_Σ was calculated using a Monte Carlo program. Generated events were passed through the same reconstruction and analysis procedure as used for the data. The Λ Monte Carlo events were generated with a polarization taken from ref. 6 and the Σ^0 events were generated with equal and opposite polarization. The acceptances were not very sensitive to the polarization of the particle, although in the highest p and p_T bins the acceptance changed by 15% with the addition of polarization. The acceptance ratio A_Λ/A_Σ decreased with increasing momentum with an average value of about 50.

The ratio R_1 is shown as a function of p and p_T in Fig. 3. R_1 does not depend strongly on either p or p_T in the range observed. The weighted average for R_1 is $0.278 \pm 0.011 \pm 0.05$, where the first uncertainty is statistical and the second is systematic. It should be emphasized that these results include all sources of Σ^0 and Λ production including, for example, Λ's from Σ^0 decay in the Λ sample. Decays of other strange particles which lead to Λ or $\Lambda\gamma$ final states, such as the Ξ^0, were found to have negligible contributions due to their small production cross sections or acceptances. We remark that our value for the Σ^0/Λ ratio is consistent with the value determined with incident kaons[7] at a much lower energy (0.30 at 8.25 GeV/c) and with exclusive measurements[8] in pp interactions at 6 GeV/c (0.33).

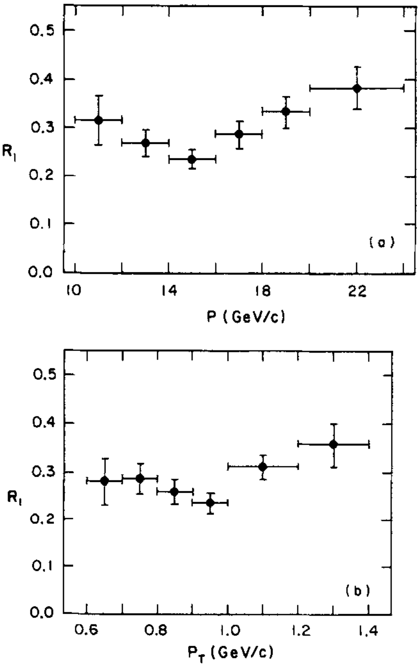

Fig. 3. R_1, the ratio of Σ^0 inclusive production to Λ inclusive production.

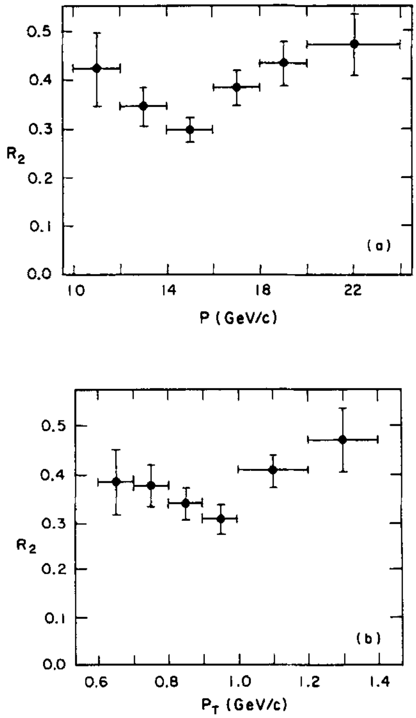

Fig. 4. R_2, the ratio of Σ^0 inclusive production to directly produced Λ's.

Assuming that only prompt Λ's and Λ's from Σ^0 decay contribute to the Λ production observed in this experiment allows R_2, the ratio of the cross section for Σ^0 inclusive production to the cross section for inclusively produced prompt Λ's to be measured. To do this first the ratio r of the number of Σ^0 decay Λ's to the total Λ production was measured by searching the Λ data sample for events with showers in the calorimeter which reconstruct to a good Σ^0 mass. R_2 is obtained using the relation $R_2 = R_1/(1-r)$ and is plotted in Fig.4 versus p and p_T. The average value is approximately 36%.

POLARIZATION MEASUREMENTS

We now turn away from the production ratio and discuss the polarization measurements. Measurement of the polarization of the Λ data sample, besides being of intrinsic interest, also provided an excellent check of systematic effects as it has previously been measured at this energy. The initial direction of the Λ polarization was constrained by parity conservation to lie perpendicular to the production plane or along the y axis. The magnetic field of the sweeper then precessed the polarization by $\Omega = 41.6^0 \pm 0.5^0$ in the yz plane, the direction depending on the field polarity. Hence the z component of the polarization vector changed sign with change in sweeper polarity. The data were divided into two sets according to the sweeper magnet polarity and each was analyzed separately. The polarization in each set was found through the measurement of the asymmetry in the proton $\cos\theta$ distribution in the Λ rest frame along the z axis:

$$dN/d(\cos\theta_Z) = A(\cos\theta_Z)(1 + \alpha_\Lambda P_{\Lambda Z}\cos\theta_Z)/2$$

where θ_Z is the angle the proton makes with respect to the z axis, $A(\cos\theta_Z)$ is the apparatus acceptance, and $\alpha_\Lambda = +0.642 \pm 0.013$.[9] The acceptance was determined using a Monte Carlo hybrid technique[10] in which all the kinematic parameters of the simulated Λ and its decay, except $\cos\theta_Z$ of the proton, are taken from the real events being analyzed. The measured asymmetry along the z axis is the sum of a term reversing sign with polarity change, $\alpha_\Lambda P\sin\Omega$, and a term incorporating apparatus induced biases. The biases were eliminated by subtracting the opposing polarity z asymmetries. The polarization of 53,000 events is plotted in Fig. 5. The errors are statistical. Our results agree with those of Raychaudhuri et al.[6], which was done at the same energy using similar apparatus as well as other results at different energies. Note that we use the standard convention of positive polarization being in the $\hat{p}_{beam} \times \hat{p}_{hyperon}$ direction.

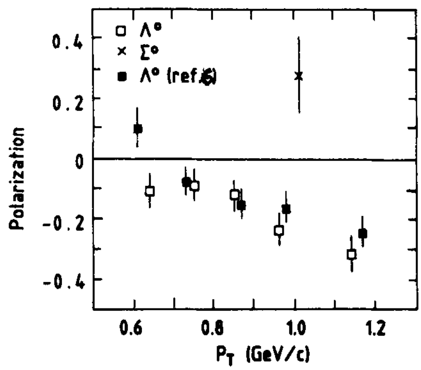

Fig. 5. The polarization results. Shown for comparison are the Λ polarization results of ref. 6, from a subset of their data using a Be target and 28.5 GeV/c incident protons.

The Σ^0 polarization was measured through its daughter Λ polarization (its electromagnetic decay conserves parity). Like the Λ, the Σ^0 polarization is initially produced along the y axis. It decays before any precession, transferring a fraction of its polarization to the Λ:[11]

$$\vec{P}_\Lambda = -(\vec{P}_\Sigma \cdot \hat{p}_\Lambda)\hat{p}_\Lambda.$$

Here $\hat{p}_\Lambda$ is the Λ momentum direction in the Σ^0 rest frame. Note that the Λ is initially in a helicity state. The sweeper magnet precessed the Λ polarization by $\Omega = 41.6^0 \sin\delta$, where δ is the angle the Λ polarization makes with the sweeper magnetic field. The precessed Λ polarization is

$$P_{\Lambda x} = -(P_\Sigma p_{\Lambda y})p_{\Lambda x},$$

$$P_{\Lambda y} = -(P_\Sigma p_{\Lambda y})(p_{\Lambda y}\cos\Omega \pm p_{\Lambda z}\sin\Omega),$$

$$P_{\Lambda z} = -(P_\Sigma p_{\Lambda y})(\mp p_{\Lambda y}\sin\Omega + p_{\Lambda z}\cos\Omega).$$

Each component of the Λ polarization depends on the Σ^0 polarization diluted by a factor (analyzing power) dependent on the Λ momentum direction cosines in the Σ^0 rest frame as well as the precession angle.

The background in the Σ^0 data sample was found to be Λ's with random gammas in the calorimeter. The consequences of the background are several. The most serious is in the boost of the Λ momentum into the Σ^0 rest frame needed for the determination of the analyzing power. As the very existence of a Σ^0 rest frame is meaningless for such events, the effect was difficult a priori to estimate. Hence the analyzing power was calculated using the Monte Carlo. This was compared to that calculated from the data – the difference between the two was less than 2%. The background also affects the measured asymmetry which is the sum of three terms: asymmetries due to: the Σ^0 polarization, background, and bias. Knowledge that the background consists of Λ events enabled the Λ polarization measurement to be used to determine the asymmetry due to the background. The bias was eliminated in a manner similar to that done for the Λ data. Due to the limited geometrical acceptance of the calorimeter – 9% of 4π – the initial Λ polarization was constrained to lie within a narrow cone on the yz plane at an angle of 41^0 to the y axis. On average this polarization precessed by 40^0 (for both sweeper polarities) resulting in a component perpendicular to the initial Λ polarization direction which changed sign with sweeper polarity change. It is from this component that the measurement of the polarization is made.

The Monte Carlo hybrid analysis method was used to measure the proton $\cos\theta$ acceptance. A total of 16,000 events, equally divided between the two sweeper polarities, were analyzed with a background of 31.5%. The polarization of this sample is $+0.28 \pm 0.13$ at an average $p_T = 1.01$ GeV/c and $x_f = 0.60$. Note that the polarization direction is opposite to that of the Λ polarization. The error is dominated by statistics, but includes errors in the determination of the background fraction and the measurement errors for the prompt Λ asymmetry. The background contribution to the measured asymmetry is less than one-third. The result is plotted in Fig. 5.

CONCLUSIONS

Although there is no convincing theoretical explanation of polarization in inclusive production, the data can be qualitatively explained by assuming that strange quarks produced from the sea with negative polarization combine with fragments of the proton projectile. This coupled with the static SU(6) quark model for hadron spin suffice to predict the direction of the spin for all of the hyperons. Our result for the Σ^0 is no exception. Whereas the spin of the Λ is entirely determined by the spin of the s quark, the Σ^0 has its spectator u and d quarks in a spin triplet state which can contribute along with the s quark to the overall spin. Assuming that the polarization of the Σ^0 is due solely to the polarization of the s quark, the Σ^0 should be produced with $-1/3$ the polarization of the Λ. Our result agrees with the sign, but is not sufficiently precise to say anything about the magnitude. In this model both the Σ^+ and Σ^- should also be found with polarization opposite to the Λ, and indeed are.[12,13]

There have been several attempts to calculate the Σ^0/Λ production ratio. DeGrand and Miettinen[14] have done this in a model which has had some success in predicting the hyperon polarizations in inclusive production. In their model both Σ^0 and Λ production involve fragments of the proton projectile combining with a strange quark from the quark sea with quark recombination occuring according to the coefficients of hadronic SU(6) wave functions. They find a ratio of 0.11 in contradiction to our results. Perhaps a more naive model is correct. Assuming that Σ^0 and Λ production are equal, since there are three Σ^0's, Σ^0/Λ should be roughly one-third.

Our results on the ratio of Σ^0 to Λ inclusive production and the Σ^0 polarization allow a re-examination of the Λ polarization data to determine the actual polarization of directly produced Λ's. Given our value for the production ratio, the direct Λ polarization is not very sensitive to the Σ^0 polarization result. Assuming that the Σ^0 polarization is equal and opposite to that of the Λ, results in a direct Λ polarization which is about 20% greater than the measured value. Assuming, as theory suggests, that the Σ^0 polarization is $-1/3$ that of the Λ results in a direct Λ polarization which is about 30% greater than the measured value. The direct Λ polarization is substantially greater than the already large values that have been measured.

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