Polarizations and Cross Sections of Λ Hyperons Produced at Backward Angles in the Reaction $\pi + {}^{12}C \rightarrow \Lambda + X$ at 4 GeV/c

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(Received 5 December 1988)

We have measured the polarizations and the differential cross sections at the Λ's produced at backward angles ($70° < \theta_{lab} < 145°$) using a large-aperture spectrometer. The angular range is kinematically not accessible in interactions of the incident pions with free nucleons. The calculated polarizations in terms of a superposition of elementary processes incorporating Fermi motion of nucleons in the nucleus are opposite in sign to the observed ones, while a quark-parton model of Λ production with a Thomas precession effect reproduces both the polarizations and the cross sections well.

PACS numbers: 25.80.Ls, 24.70.+s

A hyperon is a baryon which contains one or more strange quarks as its constituents. Since no strange quark exists in usual matter, a strange quark in matter behaves like an impurity in a solid. About ten years ago a striking polarization was found in inclusive production of Λ hyperons in high-energy *pp* collisions.[1] Although the appearance of such a polarization was a puzzle in perturbative QCD, it was clearly understood in terms of the phenomenology of soft hadronic processes, i.e., a quark-recombination model incorporated with a Thomas precession effect.[2] On the basis of this successful phenomenology, the production of a Λ hyperon in the nucleus is associated with the creation of a strange-quark–strange-antiquark pair inside the nucleus, which is followed by the recombination of the strange quark with a spin-singlet *ud*-diquark spectator. In this picture, the spin of the Λ hyperon should be tightly correlated with the values of its kinematical variables. This correlation can thus reveal the quark dynamics underlying in the hadron-nucleus reaction. A bubble-chamber experiment in Dubna yielded surprisingly large polarizations ($\sim -100\%$) in the reaction $\pi^- + {}^{12}C \rightarrow \Lambda + X$ at backward angles in the laboratory system.[3] The polarizations were substantially different from those of the elementary process[4] $\pi^- + p \rightarrow \Lambda + X$. The difference might suggest nontrivial nuclear effects, i.e., a many-nucleon effect. However, no definite conclusion can be obtained because of the low statistics in the bubble-chamber experiment. Therefore a counter experiment with higher statistics is essential in order to gain insight into a possible new nuclear effect in polarization.

In hadron-nucleus reactions, to study particle productions in the backward angular region where production is kinematically forbidden on a free nucleon at rest has a special meaning, because this is expected to reveal the possible existence of "something heavier than a nucleon" or various many-particle correlations in nuclear matter, such as a "flucton,"[5] a "multi-quark state,"[6] a "coherent tube,"[7] etc. The backward-particle production needs essentially some kind of anomalous kinematics which produces a particle with an energy beyond that expected by the quasifree hadron-nucleon interaction. So far, experiments[8,9] for backward-particle production have mainly measured cross sections at several fixed angles; measurements over a wide angular range have rarely been performed due to the problem of having a large solid angle. A few experiments measuring Λ polarizations at backward angles have been carried out by using bubble chambers with poor statistics.[3,10] The present work is the first counter experiment measuring Λ polarizations over a wide angular range by using a large-aperture spectrometer system.

We have measured the differential cross sections and the polarizations of Λ hyperons produced by the reaction $\pi + {}^{12}C \rightarrow \Lambda + X$ at 4 GeV/c in the backward angular region ($70° < \theta_{lab} < 145°$), where the production of Λ hyperons by the reaction of the pions with free nucleons at rest was forbidden kinematically. The experiment was done by using a large-aperture multiparticle spectrometer, FANCY,[11] in conjunction with a newly developed vertex detection system of target chambers[12] (TC) and a vertex chamber[13] (VC) (Fig. 1). The spectrometer system was placed on the $\pi 2$ beam line of the 12-GeV proton synchrotron (PS) at KEK. Secondary pion beams from an internal nuclear target inside the 12-GeV PS were guided to a carbon target (11 mm thick × 32 mm in diameter) mounted in FANCY. The intensity of the beam particles was a few × 10^4 π/pulse. Plastic scintillators S0 and S3 and threshold-type gas Cherenkov counters GC1 and GC2 were used for particle identification of incident beam particles. The target chambers (TC1 to TC4) and beam chambers (BC1 to

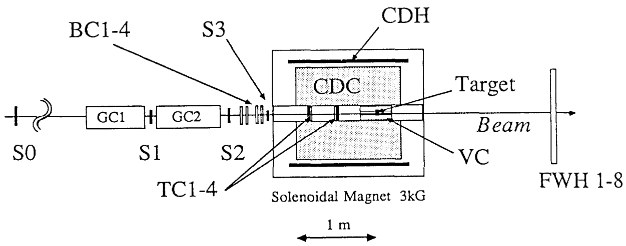

FIG. 1. Schematic diagram of the experimental setup.

BC4), which are multiwire proportional chambers (MWPC's) of wire spacing 1 and 2 mm, respectively, measured the positions of beam particles on the target within an accuracy of 0.5 mm. The FANCY spectrometer consists of three parts; a solenoidal magnet with a 3-kG magnetic-field excitation, a cylindrical drift chamber (CDC), and a cylindrical hodoscope (CDH). The spectrometer covers a large solid angle of about 60% of 4π. The CDH which surrounds the CDC consists of 24 plastic scintillation counters providing time-of-flight signals for the outgoing particles and serving as a trigger counter for the detection system. The CDC is a jet-chamber-type cylindrical drift chamber for measuring the momentum and trajectory of outgoing particles with a momentum resolution of $\delta p/p \sim 10\%\ p$ (p in GeV/c). The VC is a high-wire-density drift chamber surrounding the target and is used for detecting Λ's decay vertices within an accuracy of 1.5 mm. We acquired the events under the condition that the CDH-hit multiplicity was more than 2 in coincidence with the beam.

The Λ particles were identified as events of the decay $\Lambda \to p\pi^-$ under the following criteria: (1) The distance between the reaction point, determined as the position of beam particles on the target, and the decay vertex point was more than 5 mm. (2) The angle between the vector from the reaction point to the decay vertex point and that calculated by the sum of the momenta $\mathbf{p}_{\pi^-}$ and $\mathbf{p}_p$ was within 40°. (3) The opening angle Φ between the momenta $\mathbf{p}_{\pi^-}$ and $\mathbf{p}_p$ was between 30° and 150° because the vertex position resolution becomes much worse for $\Phi < 30°$ and $\Phi > 150°$. (4) The invariant mass calculated from $[(E_{\pi^-}+E_p)^2-(\mathbf{p}_{\pi^-}+\mathbf{p}_p)^2]^{1/2}$ was between 1105 and 1120 MeV/c^2. Figure 2(a) shows the invariant-mass spectrum of Λ's obtained under the selection criteria (1)-(3).

The polarization P of the produced Λ hyperons was calculated from the up-down asymmetry of the decay protons in the Λ rest frame. Owing to the parity violation of weak decay $\Lambda \to \pi^- p$, the protons show an asymmetric angular distribution $dW/d\Omega = (1/4\pi)(1+\alpha P \times \cos\theta^*)$, where $\alpha = 0.642 \pm 0.013$ and the angle θ^* is the proton emission angle with respect to the Λ spin direction. The unit vector normal to the reaction plane $\mathbf{n} = \mathbf{p}_{\rm in} \times \mathbf{p}_\Lambda / |\mathbf{p}_{\rm in} \times \mathbf{p}_\Lambda|$ gives the axis of the Λ polarization, where $\mathbf{p}_{\rm in}$ and $\mathbf{p}_\Lambda$ are the momentum vectors of the incident π and produced Λ, respectively. Actually we

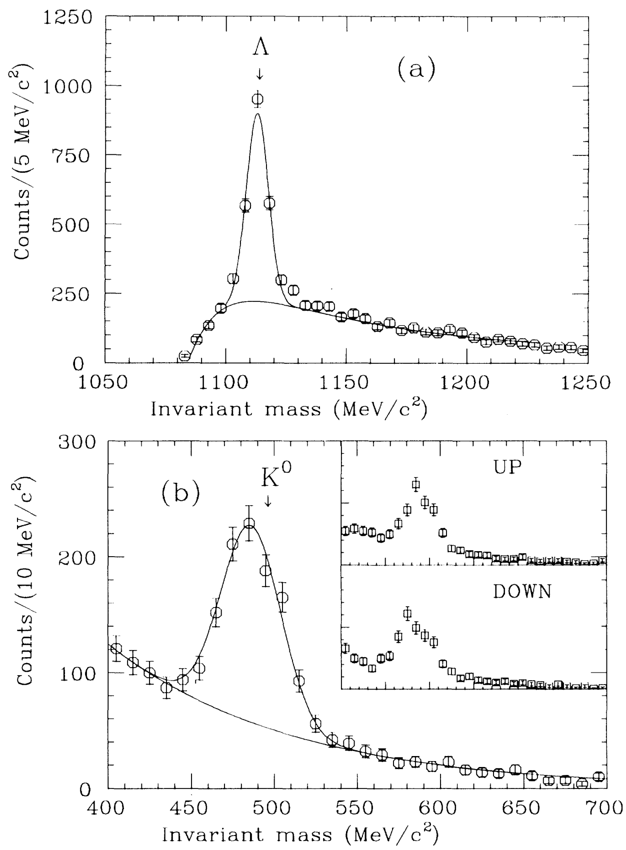

FIG. 2. (a) The invariant-mass spectra of a pair of π^- and p and (b) that of π^- and π^+. Solid curves are fitted results by the least-squares method. Inset: up and down spectra of a pair of π^- and π^+.

calculated the polarization of Λ particles as $P = (\eta/\alpha) \times (N_{\rm up} - N_{\rm down})/(N_{\rm up} + N_{\rm down})$, where $N_{\rm up}$ ($N_{\rm down}$) was the number of the events in which the proton is emitted upward (downward) relative to the reaction plane. The factor η is the acceptance-correction parameter, which should be 2.0 if all the Λ particles are detected. Our detector system is cylindrical and thus possesses a symmetry axis, which coincides essentially with the incident beam direction. Therefore there exists a good up-down geometrical symmetry of the detector system with respect to the reaction plane on which the symmetry axis lies. We calculated the factor η by a Monte Carlo simulation and then compared the result with the experimental data.[14] The discrepancy was found at most within 4% and it was added to the errors of the Λ polarizations.

In order to estimate systematic errors in the observed polarizations, we made the following investigations: (1) We measured the asymmetry of the background events in the invariant-mass spectra of a pair of π^- and p. The result at each emission angle is shown in Fig. 3. The integrated asymmetry over all emission angles after making the all selection cut was $(+5.9 \pm 3.2)\%$. (2) We measured the "polarization" asymmetry of K_S^0 particles,

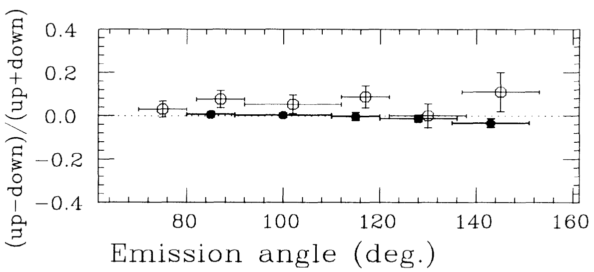

FIG. 3. Asymmetry of the background yield in the Λ spectrum greater than 1130 MeV/c^2 [cf. Fig. 2(a)] vs Λ emission angles. Filled and open circles correspond to the background asymmetry before and after Λ event selection cut, respectively.

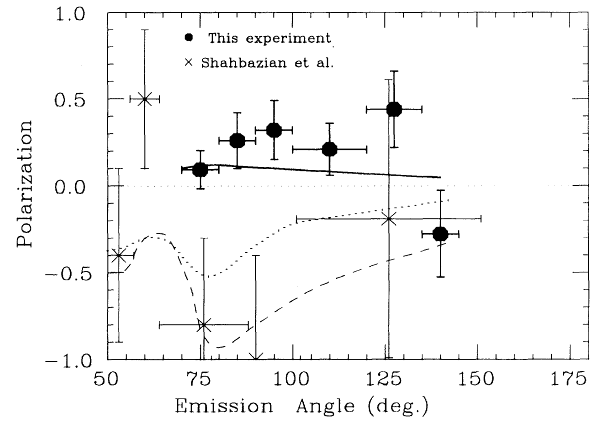

FIG. 4. The Λ polarization vs Λ emission angles in the reaction $\pi + {}^{12}C \rightarrow \Lambda + X$ at 4 GeV/c. Dotted and dashed curves are calculated by superposition of an elementary process incorporating the Fermi motion of nucleons of 250 and 500 MeV/c, respectively. The solid curve is from the quark-recombination model with the Thomas precession effect.

which should be zero because of its zero spin, by measuring the $K_S^0 \rightarrow \pi^- \pi^+$ samples [$(+3.5 \pm 4.4)\%$]; see Fig. 2(b). Therefore we can conclude that the systematic zero-point errors of the observed Λ polarizations are less than 7%. This systematic bias is not included in the data.

Figure 4 shows the observed Λ polarizations as a function of the Λ emission angles together with theoretical curves. The contribution to the Λ polarizations from Σ^0 production can be neglected within the present experimental errors.[14,15] In comparison with the bubble-chamber data $\pi^- + {}^{12}C \rightarrow \Lambda + X$ at 4 GeV/c ($50° < \theta_{lab} < 180°$) by Shahbazian *et al.*,[10] we achieved better statistics by at least a factor of 10. The backward-polarization data of the reaction $\pi^- + (Xe/C) \rightarrow \Lambda + X$ at 2.9 GeV/c[3] are quite different from the present data; the former gave completely opposite polarizations. This fact suggests a strong dependence of the Λ polarizations on target mass number and/or incident energy. On the other hand, the present data for differential cross sections at $\theta_{lab} = 90°$ are very similar to those of the previous experiment on the reaction $\pi + {}^{12}C \rightarrow \Lambda + X$ at 3 GeV/c.[9] In comparison with the previous experiment on the reaction $\pi^- + (Xe/C) \rightarrow \Lambda + X$ at 2.9 GeV/c, there seems to be a strong dependence of differential cross sections on target-mass number. The invariant cross sections $E\, d^3\sigma/dp^3$ as a function of the kinetic energy of the Λ's in each Λ emission angle are given in Fig. 5 together with theoretical curves.

A calculation of Λ polarizations based on the superposition of Regge-pole amplitudes[16] of an elementary process $\pi + p \rightarrow \Lambda + K$ incorporating the Fermi motion of nucleons in the target nucleus has been done by Kubo *et al.*[17] They considered that the process $\pi^- + p \rightarrow \Lambda + K^0$ is enhanced in the reaction $\pi^- + C \rightarrow \Lambda + X$ at the backward angular region because this process has the lowest threshold energy and should be favored kinematically. However, the calculation cannot reproduce the polarization data at all; see dotted and broken curves in Fig. 4. Next, we made a hybrid calculation based on the following two models: (i) quark-parton model of nuclear production (coherent tube model[7]), and (ii) the quark recombination model for polarization asymmetry (Thomas precession model[2]). Both the polarizations and the cross sections are reproduced well by this calculation;[18] compare solid curves with the experimental data in Figs. 4 and 5. The good reproduction of the polarizations means that the recombination picture of an s quark with a diquark works quite well in this reaction process. The s quark (one of the sea quarks of the nucleons in the tar-

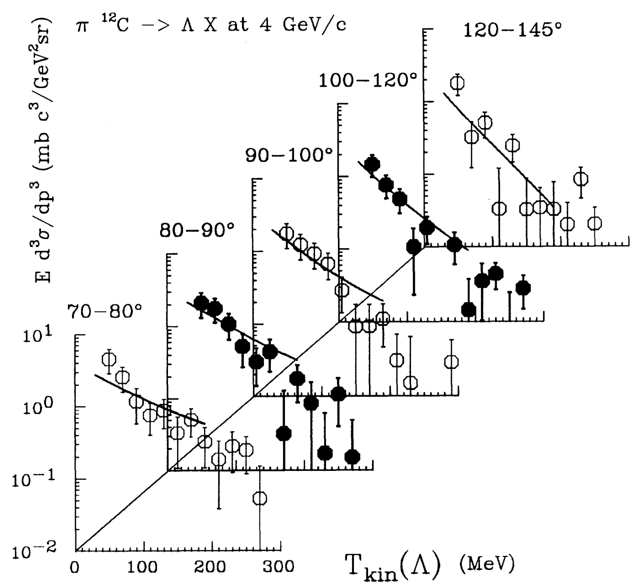

FIG. 5. Invariant cross section $E\, d^3\sigma/dp^3$ for the Λ production vs Λ kinetic energy in each Λ emission angle. Solid curves are calculated in terms of the quark-parton model.

get nucleus) is initially unpolarized. The quark-recombination mechanism generates a polarization asymmetry by enhancing recombination in one spin state over another as described in Ref. 2. The good agreement of the calculation with the differential cross sections indicates that the structure function of diquarks in the target nucleus is reasonable. The structure function is calculated by assuming formation of tubelike structure in the reaction. It should be noted, however, that the coherent tube model is not the only model which can provide this structure function.

In conclusion, we have studied the production of strange quarks from nuclear matter and their polarization. Actually we measured the polarizations and the differential cross sections at backward angles in the reaction $\pi + {}^{12}C \rightarrow \Lambda + X$ at 4 GeV/c with at least 10 times higher statistics than that of the previous experiments. The present work is the first counter experiment which has measured the polarizations of Λ hyperons produced in hadron-nucleus reactions over a wide range of backward angles. Both the polarizations and the cross sections are reproduced well in the calculations based on the quark-parton models.

We would like to thank Professor K. Nakai, Professor K.-I. Kubo, Professor T. Kohmura, and Professor F. Takagi for valuable discussions on the experiment and the calculations. Thanks are also due to Professor T. Nishikawa and the staff members of KEK for their support of the present work. This work was partially supported by a Grant-in-Aid for Scientific Research by the Ministry of Education, Culture and Science, Japan.

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[18]Cross section:

$$E\,d^3\sigma/dp^3 = E[\gamma^*(1-\beta^* p_L/E)/(\pi p^*_{\max})]\,d^2\sigma/dx_{DN}\,dp_T\,,$$

$$d\sigma = C^D_\Lambda \sigma_{\pi C} \sum_{i=1}^{A} P(i;A)[\tfrac{1}{3}\gamma_D(i) D_i(x_{Dt}) + \tfrac{2}{3}\gamma_D(i) D_i^1(x_{Dt})] \times f(p_T)\,2\pi\,dx_{DN}\,dp_T$$

[Eqs. (6.21) and (7.6b) in Ref. 7], where β^* and γ^* are the velocity and γ factor of the c.m. of πN in the laboratory system, p_L and p_T are the transverse and longitudinal Λ momenta in the laboratory system, $p^*_{\max}$ is the maximum momentum of Λ in the c.m. system of πN, $x_{DN} = p^*_L/p^*_{\max}$ is the Feynman scaling variable, p^*_L is the longitudinal momentum of Λ in the c.m. system of πN, x_{Dt} is the momentum fraction of the diquark in a tube, $C^D_\Lambda = 0.04$ is the recombination probability given on p. 1562 of Ref. 7, $\sigma_{\pi C} = 187$ mb, $P(i;A) = 2.21$ is the probability of finding a tube of i nucleons in the nucleus A, $\gamma_D(i) = (9/14i)[3-7(\frac{1}{3})^i + 4(\frac{2}{9})^i]$ is the attenuation factor, $D_i(x) = 6.20$ is the diquark distribution in the i nucleon tube, $D_i^1(x) = 6.22$ is the wounded diquark distribution in the tube, and $f(p_T) = 7.8$ is the p_T distribution. Polarization $P = (|A\uparrow|^2 - |A\downarrow|^2)/(|A\uparrow|^2 + |A\downarrow|^2)$, where the amplitudes were from Eqs. (3.4), (3.6), and (3.8) in Ref. 2. We used $m_D = 0.66$ GeV (mass of diquark), $m_s = 0.49$ GeV, $\langle p^2_{T\,D\,\mathrm{or}\,s}\rangle = \frac{1}{4} p^2_{T\Lambda} + \langle k_T\rangle^2$ (averaged squared transverse momentum of diquark or s quark), $\langle k_T\rangle^2 = 0.1$ GeV^2, $\Delta x_0 = 5$ GeV^{-1} (distance scale), $\xi = 0.1/x_{DN}$.