Polarization measurement of Λ- and $\bar{\Lambda}$-hyperons formed by the interaction of K^--, π^--mesons with nuclei at the SPASCHARM facility at the U-70 accelerator

V. V. Abramov, V. V. Moiseev
on behalf of the SPASCHARM collaboration

NRC ≪Kurchatov Institute≫ - IHEP
Protvino, Russia

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Introduction

The transverse polarization in the inclusive production of Λ-hyperons was discovered in 1976 in the interaction of unpolarized 300 GeV protons with a fixed beryllium target [1]. Contrary to expectations, the polarization turned out to be significant.

The polarization of antihyperons has been studied to a much lesser extent, due to smaller production cross sections and a higher background level. The transverse polarization of inclusive $\bar{\Lambda}$-hyperon production has been measured in only one experiment on a copper target at $\sqrt{s} = 20.8$ GeV [2].

A number of phenomenological models have been developed that explain individual details of polarization data [3–8].

$\Lambda/\bar{\Lambda}$-hyperon decay

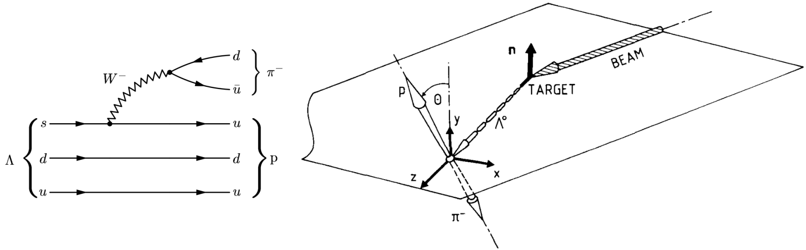
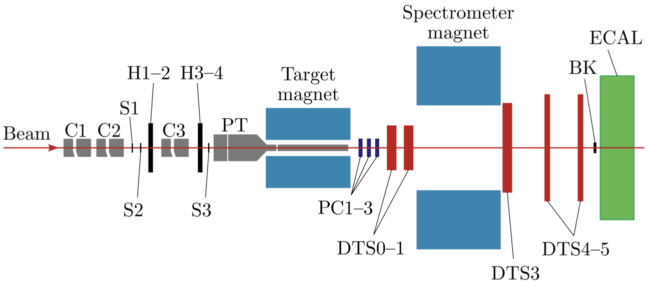


Figure: Scheme of reaction and decay kinematics (right), $\vec{n} = \frac{\vec{p}_{beam} \times \vec{p}_{\Lambda/\bar{\Lambda}}}{|\vec{p}_{beam} \times \vec{p}_{\Lambda/\bar{\Lambda}}|}$ (scattering plane normal vector) [9].

In the decay of the $\Lambda/\bar{\Lambda}$-hyperon with transverse polarization P into π^-/π^+-meson and $p/\bar{p}$, the probability of $p/\bar{p}$ emission at the angle Θ to the hyperon polarization vector $\vec{P}$ has the form $\frac{dN}{d\Omega} = \frac{1+\vec{P}\cdot\vec{e}_P}{4\pi} = \frac{1+\alpha_{\Lambda/\bar{\Lambda}} P cos\Theta}{4\pi}$, where $\vec{e}_P$ is the unit vector in the $p/\bar{p}$ motion direction in the $\Lambda/\bar{\Lambda}$ rest frame, vector $\vec{P}$ is directed along $\vec{n}$ ($\alpha_\Lambda = 0.732 \pm 0.014$, $\alpha_{\bar{\Lambda}} = -\alpha_\Lambda$ [10]).

Experimental setup SPASCHARM



Negatively charged particles π^-($\approx$ 98.0 %), K^-($\approx$ 1.75 %), $\bar{p}$ ($\approx$ 0.15 %) are extracted into the beam channel (26.5 GeV/c). Beam tracks by hodoscopes H1-4, identification by threshold Cherenkov counters C1-3. Target magnet (0 T·m), hollow cryostat of a polarized target (PT), external nuclear targets - at its output. Tracking system: PC1-3 - proportional chambers, DTS0-5 - drift tube stations, spectrometer magnet with $\int Bdl \sim 0.7$ T·m.

Sessions 2021-2022

Polarization measurements were performed using data from the 2021 and 2022 sessions. In the 2021 session, the main trigger - $S1 \cdot S2 \cdot S3 \cdot \overline{BK}$, in 2022 - $S1 \cdot S2 \cdot S3 \cdot \overline{BK} \cdot \overline{C1} \cdot \overline{C2}$ (enrichment of K^--mesons by suppressing π^-). Nuclear targets were used: C, Al, Cu, Si, Sn, Pb, W ($\langle$A$\rangle = 62$), also pentanol ($C_5H_{12}O$), its carbon equivalent and the "empty" target.

Total trigger number in two sessions on all targets - 1.2×10^9.

2×10^9 minimum bias events were generated in Pythia, all generated particles were passed through the setup using Geant. The final number of reconstructed Λ- and $\bar{\Lambda}$-hyperons is an order of magnitude greater than their number in the real data, which makes their contribution to the statistical error of the measured polarization negligibly small.

$\Lambda/\bar{\Lambda}$-hyperon selection criteria I

- One track in beam hodoscopes.
- Beam particle type determination (π^-, K^-, $\bar{p}$).
- Two or more tracks in the spectrometer.
- Distance between two secondary tracks with opposite charges, which are decay products of the $\Lambda/\bar{\Lambda}$-hyperon, < 0.4 cm.
- Distance between the beam track and the "trajectory" of $\Lambda/\bar{\Lambda}$-hyperon candidate (pair $p/\bar{p} + \pi^-/\pi^+$) < 0.4 cm.
- Distance along Z coordinate between primary and secondary vertex > 18 cm. *This is the main criterion that suppresses the combinatorial background*.

$\Lambda/\bar{\Lambda}$-hyperon selection criteria II

- Distance from primary vertex to target axis < 1.6 cm.
- The coordinate of the secondary vertex is within 35 - 110 cm from the origin (polarized target center).
- Using the Armenteros-Podolyanski plot [11], pairs with $\alpha_{AP} > 0$ for Λ and $\alpha_{AP} < 0$ for $\bar{\Lambda}$ were selected, where α_{AP} is the asymmetry between the longitudinal momenta of positively and negatively charged particles (decay products) relative to the direction of the $\Lambda/\bar{\Lambda}$-hyperon.
- By assigning the masses of $\pi^{\pm}$-mesons to the particles of the selected pair, pairs with mass K_S^0 are excluded (0.468 - 0.525 GeV/c^2).

Signal and background extraction of the Λ-hyperon

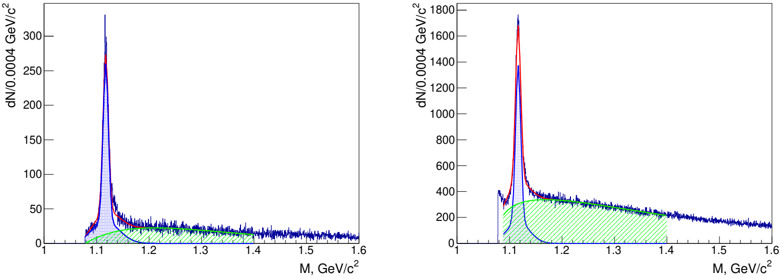


Figure: Λ-hyperon invariant mass distributions for the K^--beam (left: $S = 8318 \pm 94$, $S/B = 13.28 \pm 0.55$) and π^--beam (right: $S = 43800 \pm 242$, $S/B = 2.90 \pm 0.03$) in sessions 2021-2022.

The "signal" distribution is approximated by two Gaussian distributions (two variances), "background" by function $N(M - M_{p+\pi})^k exp[-b(M - M_{p+\pi})]$.
Pairs in the mass range of 1.105 - 1.125 GeV/c^2 are selected as a signal (S), and pairs in the mass ranges of 1.077 - 1.1 and 1.14 - 1.16 GeV/c^2 - as a background (B).

Signal and background extraction of the $\bar{\Lambda}$-hyperon

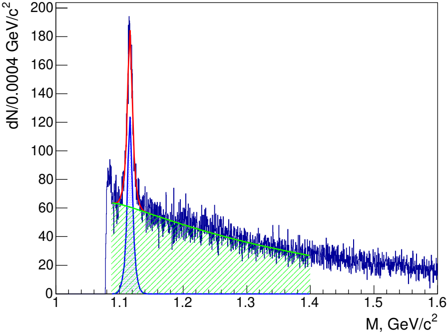


Figure: $\bar{\Lambda}$-hyperon invariant mass distribution for the π^--beam in session 2021 at $0.14 < x_F < 0.25$ ($S = 3163 \pm 78$, $S/B = 1.04 \pm 0.03$).

For S pairs are selected in the mass range of 1.105 - 1.125 GeV$/c^2$, B - in the mass ranges of 1.090 - 1.1 and 1.14 - 1.15 GeV$/c^2$.

Λ-hyperons polarization in the K^-- and π^--beams

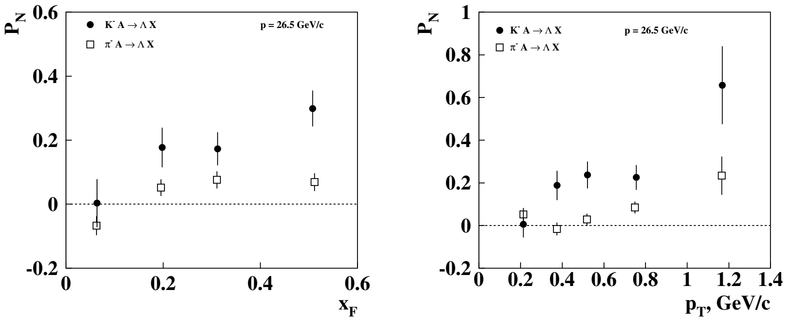


Figure: Graphs of $P_N(x_F)$ (left) and $P_N(p_T)$ (right) in reactions $K^-A \to \Lambda X$ and $\pi^-A \to \Lambda X$.

The P_N value in the π^--beam does not exceed several percent, with the exception of the region $p_T > 1$ GeV/c - (23 ± 9) %. For the K^- beam in the region $p_T > 0.3$ GeV/c the average polarization (23.6 ± 3.6) %, which is 6.5 sigma effect.

$\bar{\Lambda}$-hyperons polarization in the π^--beam

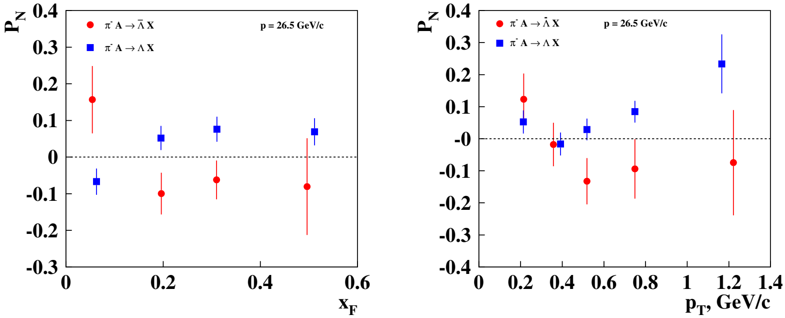


Figure: Graphs of $P_N(x_F)$ (left) and $P_N(p_T)$ (right) in the reaction $\pi^- A \to \bar{\Lambda} X$ compared to $\pi^- A \to \Lambda X$.

The P_N value of $\bar{\Lambda}$-hyperons in the π^--beam is small, negative and almost does not change, for Λ - positive and increases monotonically (p_T).

Estimation of the systematic polarization error $\Lambda/\bar{\Lambda}$

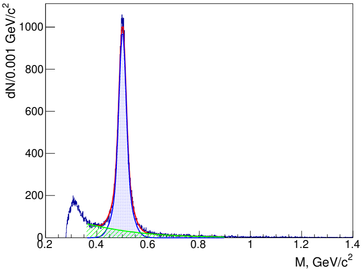


Figure: K_S^0 mass distribution for π^--beam in session 2021 at $0.61 < p_T < 1.00$ GeV/c ($S = 44408 \pm 221$, $S/B = 9.23 \pm 0.14$).

To estimate the systematic error in polarization measuring of $\Lambda/\bar{\Lambda}$-hyperons in the π^--beam, the "polarization" of spinless (pseudoscalar) K_S^0-mesons was determined.

The absolute value of the "polarization" of K_S^0-mesons does not exceed 0.036, which is lower than the statistical error of Λ and $\bar{\Lambda}$ polarization.

Summary

The first results on the polarization of inclusively produced $\Lambda/\bar{\Lambda}$-hyperons in the K^-- and π^--beams with a momentum 26.5 GeV/c were obtained at the SPASCHARM facility at the U-70 accelerator complex in Protvino.

The π^--beam data indicate a negligible transverse polarization of $\Lambda/\bar{\Lambda}$-hyperons, except of the region $p_T > 1$ GeV/c, where the measured Λ-hyperons polarization reaches $\boxed{(23 \pm 9)\ \%}$.

Polarization of Λ-hyperons in the K^--beam (which contains valence s-quarks) has a noticeable positive value, in the region $p_T > 0.3$ GeV/c the average P_N $\boxed{(23.6 \pm 3.6)\ \%}$, *which is* $\boxed{\text{6.5 sigma effect}}$, *in the region $p_T > 1$ GeV/c the P_N is* $\boxed{(66 \pm 18)\ \%}$.

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Armenteros-Podolyanski plot

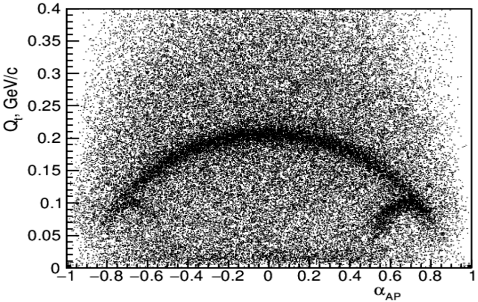

Figure: Armenteros-Podolyanski plot of $p + \pi^-$ pairs over Q_t and α_{AP} for the π^--beam in the 2021 session.

Signal and background extraction of the $\Lambda/\bar{\Lambda}$-hyperon for Monte Carlo events

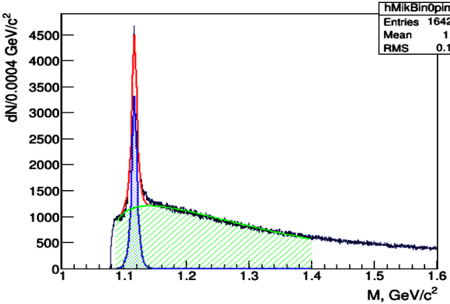

Figure: $\bar{\Lambda}$-hyperon invariant mass distribution for the π^- beam in the Monte Carlo simulation ($S = 87007 \pm 381$, $S/B = 1.50 \pm 0.01$).

The same S and B extraction conditions of $\Lambda/\bar{\Lambda}$-hyperon were used for Monte Carlo events.

Polarization determination of $\Lambda/\bar{\Lambda}$-hyperons

The uncorrected distribution of $p/\bar{p}$ over $cos\Theta$ in the $\Lambda/\bar{\Lambda}$ rest frame has the form $\frac{dN}{d(cos\Theta)} = 0.5 \cdot A(cos\Theta) \cdot (1 + \alpha_{\Lambda/\bar{\Lambda}} P_N cos\Theta)$, where $A(cos\Theta)$ is the reconstruction efficiency ("acceptance").

- Calculation of the coefficient $W = N_S/N_B/(1 + S/B)$ (where N_S and N_B - entries number of S and B histograms), by which the B histogram must be multiplied for its correct subtraction from S to obtain the distribution over $cos\Theta$ for "pure" $\Lambda/\bar{\Lambda}$-hyperons.
- Dividing the histograms of real data by the Monte Carlo data yields an efficiency-corrected distribution over $cos\Theta$, which is used to find the desired P_N by approximation.

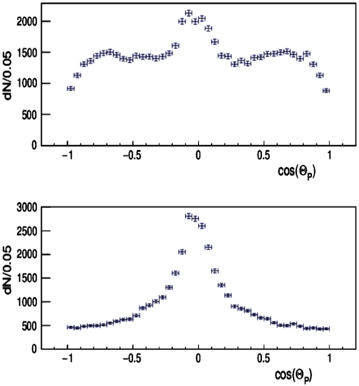

Figure: Distributions over $cos\Theta$ p for S (top) and B (bottom).

Λ-hyperons polarization on K^-- and π^--beams

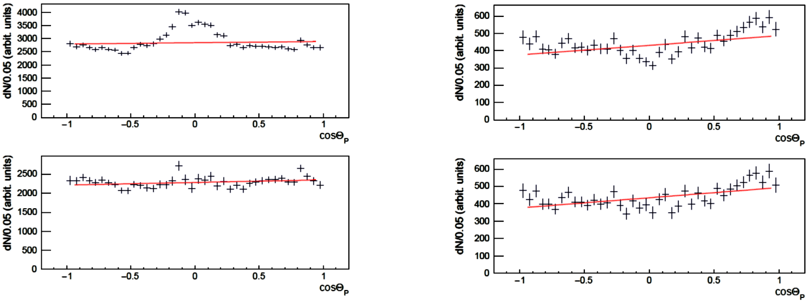

Figure: Distribution over $cos\Theta$ in the reaction $\pi^- A \to \Lambda X$ (left) and in the reaction $K^- A \to \Lambda X$ (right) in sessions 2021-2022. Top - before background subtraction, bottom - background subtracted. Approximation by the function $N(1 + \alpha_\Lambda P_N cos\Theta)$.

$\bar{\Lambda}$-hyperons polarization on π^--beam

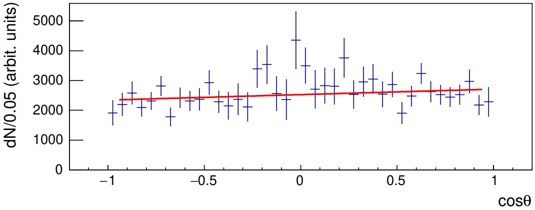

Figure: Distribution over $cos\Theta$ in the reaction $\pi^- A \to \bar{\Lambda} X$ in session 2021 at $0.14 < x_F < 0.25$. Approximation by the function $N(1 + \alpha_\Lambda P_N cos\Theta)$.

K_S^0-meson "polarization" on π^--beam

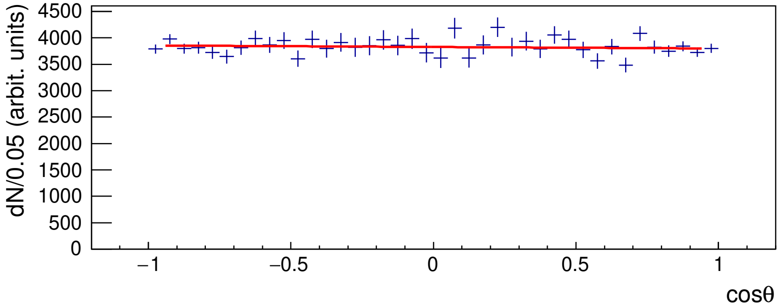

Figure: Distribution over $cos\Theta$ in the reaction $\pi^- A \to K_S^0 X$ in session 2021 at $0.61 < p_T < 1.00$ GeV$/c$.