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**Λ^0 POLARIZATION IN HADRON-NUCLEON, HADRON-NUCLEUS
AND NUCLEUS-NUCLEUS INTERACTIONS**

Apostolos D. Panagiotou

CERN, Geneva, Switzerland

and

University of Athens, Physics Department,
Nuclear & Particle Physics Division,
Panepistimiopolis, Ilisia, Athens, Greece

ABSTRACT

We discuss the experimental systematic characteristics of the Λ^0 polarization observed in hadron-nucleon, hadron-nucleus, and nucleus-nucleus interactions. The current theoretical framework is reviewed and compared with the experimental data. We also discuss the effects of QCD deconfinement on the transverse and longitudinal polarization in nucleus-nucleus interactions and the possibility of using these effects as signals of quark matter formation.

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CONTENTS

1. INTRODUCTION
2. THEORETICAL CONSIDERATIONS
 - 2.1 Lund model
 - 2.2 DeGrand-Miettinen model
 - 2.3 s-quark scattering model
 - 2.4 SU(6) quark model
3. EXPERIMENTAL TECHNIQUES
 - 3.1 Detector systems
 - 3.1.1 *Electronic tracking detectors*
 - 3.1.2 *Hybrid detectors*
 - 3.2 Analysis methods
4. EXPERIMENTAL RESULTS
 - 4.1 Hadron-nucleon interaction
 - 4.1.1 *K^- -p interaction*
 - 4.1.2 *K^+ -p interaction*
 - 4.1.3 *π^- -p interactions*
 - 4.1.4 *π^+ -p interaction*
 - 4.1.5 *Nucleon-nucleon interaction*
 - 4.2 Hadron-nucleus interaction
 - 4.2.1 *π^- -nucleus interaction*
 - 4.2.2 *Nucleon-nucleus interaction*
 - 4.2.3 *Summary of nucleon-nucleus results*
 - 4.3 Nucleus-nucleus interaction
 - 4.4 Global systematics and summary
5. Λ^0 POLARIZATION AS A SIGNAL OF QUARK MATTER
IN NUCLEUS-NUCLEUS INTERACTIONS
 - 5.1 Transverse polarization
 - 5.2 Longitudinal polarization

6. CONCLUSIONS

REFERENCES

1. INTRODUCTION

The discovery of parity non-conservation and large asymmetry in the weak decay of $\Lambda^0 \rightarrow p + \pi^-$ [Cr57, Ei57], and the subsequent measurement of a substantial transverse polarization of the Λ^0 hyperon in inclusive hadron-nucleon [Pe67], nucleon-nucleon [Aa78], and nucleon-nucleus [Bu76] interactions, stimulated much theoretical and experimental work, aiming at understanding the nature of the polarization and verifying these results in every conceivable case: from e^+e^- , ν -p, and e-p, to nucleus-nucleus interactions.

Parity violation in the weak Λ^0 decay permits a mixture of S and P waves in the final state. This has, as a result, an asymmetry in the decay [Le57]. The angular distribution of the decay nucleon from a completely polarized Λ^0 hyperon is given by

$$dN/d\Omega = (1/4\pi)[1 + \alpha \cos \theta],$$

where θ is the angle between the nucleon momentum and the hyperon's polarization axis, and α is the decay asymmetry parameter.

It had been generally believed that certain two-body spin effects in hadronic interactions should play a minor role at high energies, since hard-scattering processes, when calculated in perturbative QCD, do not give rise to large polarization effects [Ka78]. The intuitive picture was that particle production at high energies involves a large number of final states and thus no coherent interference of amplitudes would be possible [Pa76].

It is interesting that lowest-order QCD predicts no polarization for Λ^0 with transverse momenta greater than about 5 GeV/c [Ka78]. To date, there is no measurement of Λ^0 polarization above 3.2 GeV/c [Lu82]. However, the large polarization found at lower transverse momenta shows no indication of a diminishing trend with increasing transverse momentum. If the polarization persists at high values for larger transverse momenta, then some assumptions of QCD (e.g. that the strong coupling constant α_s could be larger than expected at the corresponding value of momentum transfer) must be false, or there are still serious problems with the theory [Ka78].

Polarization has been observed also in other hyperons when they occur as proton fragmentation products [He85]. The Σ^- , Σ^0 , and Σ^+ are all found to have polarization of approximately equal magnitude but opposite in sign to that of the Λ^0 . The Ξ^- , Ξ^0 are found to have polarization similar to that of the Λ^0 , whilst the Ω^- is also found to exhibit polarization [Lu83].

From the wealth of experimental data, which we shall discuss in detail, the following outstanding qualitative features for the Λ^0 polarization could be summarized:

- 'Leading' Λ^0 exhibits polarization that is perpendicular to the reaction plane, defined by the vector $\mathbf{n} = (\mathbf{p}_b \times \mathbf{p}_{\Lambda^0})/|\mathbf{p}_b \times \mathbf{p}_{\Lambda^0}|$, where $\mathbf{p}_b$ denotes the momentum of the incident beam. It is the result of the elementary binary hadron-hadron interaction.
- It depends strongly on the Λ^0 's transverse momentum and, in certain cases, on the Feynman x .
- It is independent of the beam energy and depends weakly on the target mass.
- Non-leading Λ^0 possesses no polarization.

In terms of the simple quark model, the spin of the Λ^0 hyperon is that of the s-quark, since the ud-diquark is in a spin-isospin singlet state. Therefore, the presence of the polarization implies that the produced s-quark is polarized. Several models provide mechanisms for the s-quark polarization. We summarize the main suggestions in order to get a feeling of the possible different interpretations:

- In a semiclassical approach [An79] the $s\bar{s}$ pair is produced by a tunnelling soft process in the colour field, thereby acquiring the polarization.
- In the parton recombination model with SU(6) symmetry [De81], the polarization is produced by a Thomas precession effect in the quark recombination process.

- In another approach [Sz81], which does not require a new model of particle production, the polarization of a slow s-quark arises through its scattering in the external gluonic field.
- In the gluon bremsstrahlung mechanism and in the framework of the standard SU(6) quark model, a quark in the projectile radiates a polarized gluon, which creates an $s\bar{s}$ pair. The s-quark, assumed to be polarized in analogy to the electromagnetic bremsstrahlung process, combines with the spectator ud-diquark forming a polarized Λ^0 [He77].
- The polarization arises from interference between the one-gluon and two-gluon s-channel exchange terms in a quark-parton hard scattering [Ef78].

The upsurge of experimental and theoretical work produced also several controversies regarding the sign or magnitude of the Λ^0 polarization in certain interactions, the ‘universality’ of its nature, and the interpretation of the results. As the convention determining the sign of the polarization differs among the quoted references, care must be taken when comparing the experimental data of different authors. To date, there are still a few such basic disputes, which we shall try to point out and evaluate.

In the following, we shall discuss in detail the main theoretical models and their predictive power with regard to the experimental results. We shall then examine the experimental and analysis methods for measuring the Λ^0 polarization with the various detector systems employed. The results of these measurements for several interactions will be examined in detail and compared on the basis of a common polarization convention. They will also be compared with predictions of the various theoretical models. Finally, we shall discuss the effects of quark deconfinement in a quark-gluon plasma on the polarization of the emitted — upon hadronization — Λ^0 , and the possibility of using the predicted change of state of the polarization as a signature for the formation of quark matter in ultrarelativistic nucleus–nucleus interactions.

2. THEORETICAL CONSIDERATIONS

The interest in the Λ^0 hyperon has been outstanding, owing in part to its particularly simple description within the static quark model and to its s-quark content. In this model the u- and d-quarks in the Λ^0 are coupled to an $S = 0$, $I = 0$ diquark, thereby requiring that the spin of the hyperon be that of the s-quark. A spin-transfer experiment [Bo88], using polarized protons on a Be target in order to study the polarization of the Λ^0 , has shown that the Λ^0 does take into account the spin orientation of the incoming proton. This experimental fact clearly demonstrates that the spin is carried by the created s-quark and is not related to the diquark, which is left over from the projectile.

In the last ten years a number of theoretical attempts have been made to understand and explain the ‘unexpected’ and puzzling data on the hyperon transverse polarization. In perturbative QCD, one simply expects single spin symmetries to be strongly suppressed because of the helicity conservation [Cr83]. Owing to the vectorial coupling of the gluon, we should expect the hyperon polarization to go to zero in the high- $p_{\perp} \rightarrow 0$ [Ka78].

Several QCD-inspired models have been proposed to describe the general systematics of hyperon polarization. These models may be grouped into two classes: the first is based on semiclassical considerations [An79, De81] and the second, which is valid in particular for the $K^{\pm}$ -p interactions, assumes a scattering of the s($\bar{s}$)-quark in a static colour field [Sz81, Dh86, Ga87]. We shall discuss these models in some detail below.

2.1 Lund model

In this semiclassical model [An79, An83] the mechanism that produces the Λ^0 polarization is basically a soft process, where sea $s\bar{s}$ pairs are produced by a tunnelling process through a classically forbidden region in the colour field before entering the outgoing hyperon’s wave function, and where perturbative QCD is not applicable. The main assumptions of the model are the following:

- A colour dipole field is stretched between the diquark ($S = 0, I = 0$) of the incoming proton and the central collision region, and an $s\bar{s}$ pair is produced in this field.
- The transverse momentum is locally conserved in the string force-field. This field has no (excited) transverse degrees of freedom. Thus the $s\bar{s}$ pair is produced in a state with equal but opposite transverse momenta: $\mathbf{k}_\perp(s) = -\mathbf{k}_\perp(\bar{s})$.

The total transverse momentum of the Λ^0 , $\mathbf{p}_\perp(\Lambda^0)$, with respect to the beam direction, is made up of two contributions: the $\mathbf{q}_\perp(u\bar{d})$, which determines the direction of the force-field string, and the $\mathbf{k}_\perp(s)$, which is measured with respect to the string direction (Fig. 1). Since the s-quarks have mass, the s and $\bar{s}$ must be produced at a certain distance from each other in order to conserve momentum and energy. Thus the energy in the force field in between them can be transformed into the transverse mass of the pair. This causes the appearance of an orbital angular momentum perpendicular to the string. The assumption of the model is that this orbital angular momentum ($L \leq 1$) is compensated by the spin of the $s\bar{s}$ pair.

The mechanism that makes the Λ^0 polarized may be thought of as a kind of a bias effect: in a Λ^0 sample, with a definite transverse momentum $\mathbf{p}_\perp(\Lambda^0)$, an enhanced number of events is obtained where $\mathbf{k}_\perp(s)$ is in the same direction as $\mathbf{p}_\perp(\Lambda^0)$. Thus the correlation between the transverse momentum and the spin of the s-quark will cause the s-quark, and hence the Λ^0 , to become polarized.

The main predictions of the semiclassical Lund model for the hyperon polarization—assuming direct hyperon production and small scattering angle ($x_F \approx 1$)—can be summarized as follows:

- The Λ^0 polarization is perpendicular to the plane defined by the incident beam and Λ^0 momentum vectors.
- It increases (absolutely) with the transverse momentum of the hyperon. However, for $p_\perp > 4 \text{ GeV}/c$ it becomes weaker.
- The polarization of the Σ^0 is in the opposite sense and is equal to 1/3 of the Λ^0 polarization. This result is obtained by considering the spin-flavour wave functions of the hyperons. However, it is not in agreement with measurements, which give a similar (in magnitude) polarization for both hyperons.

For smaller values of x_F , additional mechanisms contribute to the Λ^0 production, and the polarization decreases with decreasing x_F for a constant $p_\perp$ of the Λ^0 . The comparison between the predictions of this model and experimental data will be made in the corresponding sections.

A limitation of this model is the non-inclusion of the contribution of a (polarized) leading parton to the polarization asymmetry of the hyperon. Thus the positive polarization in the projectile hemisphere, observed in the $K^- \rightarrow \Lambda^0$ and $K^+ \rightarrow \bar{\Lambda}^0$ processes as the result of the polarized leading parton, cannot be explained by this model. A new version of the Lund model, in which leading quark polarization effects are also included, has been given recently by Skold [Sk84].

2.2 DeGrand–Miettinen model

In this semiclassical model [De81] the hyperon polarization is due to a Thomas precession effect during the quark-recombination process. Considering the $p \rightarrow \Lambda^0$ transition, the fundamental observation underlying the model is that the s-quark, combining with a ud -diquark to form the Λ^0 , resides in the sea of the incoming proton (with momentum $\mathbf{p}_p$) and carries a very small fraction (≈ 0.1) of its momentum. After the combination, it becomes a valence quark in the Λ^0 and, therefore, carries a large fraction ($\approx 1/3$) of the Λ^0 's momentum. Since the Λ^0 carries a large fraction (x_F) of the proton's momentum, the combination process induces a strong increase in the longitudinal momentum of the s-quark, from about $0.1p_p$ to $1/3x_F p_p$, while simultaneously it causes a deceleration of the leading partons (u, d -quarks) from $2/3p_p$ to $2/3x_F p_p$.

At the same time, the s-quark carries, on the average, a transverse momentum $p_\perp(s)$ (in proton) $\approx p_\perp(s)$ (in Λ^0) $\approx 1/2p_\perp(\Lambda^0)$. Therefore, the velocity vector of the s-quark is not parallel to the change

in momentum induced by the combination (Fig. 2). In this case, the s-quark's spin will feel the effects of the Thomas precession [Th27], and an additional term will appear in the effective Hamiltonian, which describes the combination process:

$$U = \mathbf{s} \cdot \boldsymbol{\omega}_T \quad (2.1)$$

with the Thomas frequency:

$$\boldsymbol{\omega}_T = \frac{\gamma}{(\gamma + 1)} \frac{\mathbf{F} \times \mathbf{v}}{m_s}, \quad (2.2)$$

where $\mathbf{v}$ is the s-quark's velocity, $\mathbf{F}$ is the force, m_s the s-quark's mass, and $\gamma = (1 - v^2)^{-1/2}$. In the infinite momentum frame, $\gamma/(1 + \gamma) \simeq 1$. The s-quark, accelerated in the confining field by the force $\mathbf{F}$ along the direction of the incident proton, acquires a negative polarization. This polarization is the result of the spin-orbit interaction term (2.1) in the Hamiltonian. The Thomas precession vector $\boldsymbol{\omega}_T$ is directed parallel or antiparallel to the normal, $\mathbf{n}$, to the reaction plane depending on whether the s-quark is decelerated or accelerated.

In this model, a polarization asymmetry arises as the result of strong momentum ordering in the proton's wave function, assumed to be the minimal three-quark SU(6) wave functions, where the s-quark is slow and the u,d-quarks are fast. This ordering does not happen when recombination involves only sea (s,u,d)-quarks, all of whose wave functions are roughly equal, as in the case of antihyperon production from baryon interactions. Here the average value of $\boldsymbol{\omega}_T$ vanishes and a zero polarization asymmetry is predicted.

A recent comment on the DeGrand-Miettinen semiclassical approach [Fu87] notes that this model breaks down if the spin-orbit interaction for the s-quark inside the hyperon is treated properly. The polarization obtained in such a treatment, using an analytic solution of the massless Dirac equation with a scalar linear-confining potential, is completely different from the semiclassical approach and cannot explain the observed polarization. The arguments presented in [Fu87] are also valid for a massive Dirac equation, although the polarization cannot be presented in terms of analytic expressions for the solution.

The predictions for the Λ^0 polarization of the DeGrand-Miettinen model, for several beam particles in their fragmentation hemisphere and with respect to the axis perpendicular to the scattering plane, defined by the beam and the Λ^0 momenta, are summarized in Table 1. The comparison of these predictions with experimental data will be made in the corresponding sections.

An advantageous feature of this model is the treatment of the leading partons that contribute to the polarization of the formed hyperon, as in the case of the $K^- \rightarrow \Lambda^0$ and $K^+ \rightarrow \bar{\Lambda}^0$ transitions. A recent version of this model treats quantitatively the effect of the polarization of the projectile (polarized leading parton) on the hyperon's polarization [De85].

2.3 s-quark scattering model

In a simple model proposed by Szwed [Sz81], the s-quark, originating from the incident proton sea, or produced during the collision in the subprocess $g \rightarrow s\bar{s}$, obtains the required transverse momentum by multiple scattering on quark-gluon matter. Because of its non-zero mass it becomes polarized in this process, just as in the case of scattering in a Coulomb field. Polarization appears already in the second order of the perturbation calculation (second-order diagrams) and it is qualitatively similar to the exact solution of the Dirac equation for Coulomb scattering:

$$P = \left(2C\alpha_s m_s \frac{k}{E^2} \right) \frac{\sin^3(\theta/2) \ln \sin(\theta/2)}{[1 - (k/E)^2 \sin^2(\theta/2)] \cos(\theta/2)}, \quad (2.3)$$

where C is the intensity of the colour field, α_s is the strong coupling constant, and m_s , k , E , and θ are the mass, the momentum, the energy, and the scattering angle of the s-quark. The main assumption

of this approach is that the s-quark is relatively slow, otherwise the polarization would be negligible. Its predictions—valid, in particular, for the Λ^0 polarization in K^- -p interactions—will be discussed in conjunction with the experimental data.

A similar approach is taken by Gago et al. [Ga87] for the Λ^0 polarization arising in the K^- -p interaction. They consider the scattering of the s-quark of the kaon in the colour field of the proton, and they take into account the confinement final-state interaction in determining the kinematical parameters of the scattered s-quark.

Since the s-quark of the kaon scatters from a constituent quark of the proton, they treat the scattering in the s-q centre-of-mass system, where the magnitude of the initial and final s-quark momenta is the same. This Lorentz transformation, along the proton momentum and taking into account the fractions of momentum carried by the s-quark in the initial K^- and final Λ^0 states, is unique and independent of the particular scattering mechanism. The fit of their predicted Λ^0 polarization to experimental data for the K^- -p interaction, in the incident momentum range between 8 and 176 GeV/c and for x_F between 0.3 and 0.9, will be discussed in the corresponding section. The main conclusion is that the qualitative features of the Λ^0 polarization seem to be compatible with their QCD model, at least for low transverse momenta, $p_\perp \approx 1$ GeV/c.

2.4 SU(6) quark model

Polarization requires coherence between at least two amplitudes and, therefore, it is sensitive to small spin-dependent terms. The observation of strong polarization in inclusive reactions suggests that only a few amplitudes contribute to the hyperon production process.

The SU(6) quark model is the simplest model, which gives an overall satisfactory description and prediction of the polarization phenomenon and of the relative polarization between hyperons [He78]. Within this model the Λ^0 is formed from u, d, and s valence quarks. The u,d-quarks combine to a spin-isospin singlet state, and hence the s-quark gives the spin (and polarization) to the Λ^0 . Hadron collisions are described in terms of the elementary interactions of constituent quarks, a process that becomes more relevant with increasing transverse momentum.

The mechanism that may produce polarized s-quarks is the gluon bremsstrahlung, shown schematically in Fig. 3 for the reaction $p-p \rightarrow \Lambda^0 + X$ [He78]. During the interaction, two of the proton's quarks (u,d) remain as spectators in a singlet state. The other u-quark is scattered by the target and radiates a gluon, which consequently fragments into an $s\bar{s}$ pair. The s-quark from this pair gives both the transverse momentum and the spin to the Λ^0 . If the gluon is polarized, then so is the $s\bar{s}$ pair, and this polarization is correlated with the transverse momentum direction of the Λ^0 .

The non-polarization of the $\bar{\Lambda}^0$ is explained within this model by the fact that $\bar{u}$ - and $\bar{d}$ -quarks must also be produced (incoherently) and combine with the $\bar{s}$ -quark. These quarks would now contribute to the $\bar{\Lambda}^0$'s transverse momentum but not to its polarization. Thus the $\bar{\Lambda}^0$ polarization at a fixed $p_\perp$ would be suppressed.

The polarization of the various hyperons could be calculated—relative to the Λ^0 polarization—using the SU(6) quark wave functions, assuming that all $q\bar{q}$ pairs are created with the same polarization. One such prediction for the polarization of the Σ^0 hyperon ($P_{\Sigma^0} = -1/3P_{\Lambda^0}$) agrees in sign but is off in magnitude. However, none of the already mentioned models predicts the magnitude of the Σ^0 polarization correctly.

3. EXPERIMENTAL TECHNIQUES

3.1 Detector systems

The study of Λ^0 production and polarization was performed in two basic types of experiments: i) with a fixed target, in the momentum range between 1.5 and 400 GeV/c, and ii) in a pp ($p\bar{p}$) collider, at $\sqrt{s} = 31$ –62 GeV. In the collider experiments, electronic tracking detectors were used,

whilst in the fixed-target experiments both electronic tracking detectors and bubble or streamer chambers were employed. The aims were to identify a Λ^0 vertex pointing at the interaction region, to track the trajectories of the decay products and to measure their momenta. We shall discuss in some detail the basic features of the two types of detectors and the corresponding methodology for event reconstruction and analysis.

3.1.1 Electronic tracking detectors

A typical electronic tracking system employed at the KEK 12 GeV proton synchrotron is shown in Fig. 4 [Ab84a]. The system consisted of two spectrometer magnets (D1 and D2), two sets of multiwire proportional chambers (PC1 and PC2), four sets of multiwire drift chambers (DC1–DC4) in pairs following the spectrometers, two sets of scintillation hodoscope counters (H1 and H2), a gas Cherenkov counter, and various other scintillation counters. A neutral beam was defined at an angle to the incident proton beam by a collimator in a sweeping magnet. The production angle θ' could be varied in the range 3.5° to 9.5° by deflecting the incident protons horizontally and restoring them to the target by means of two bending magnets upstream.

The Λ^0 hyperons were identified by detecting the proton and π^- from the $\Lambda^0 \rightarrow p\pi^-$ decay. The two spectrometers D1 and D2 and subsequently the corresponding drift chambers, each having four signal planes, analysed and measured the momenta of the π^- and the p, respectively. The Cherenkov counter identified the decay protons and vetoed the π^+ from the decay of K_S^0 .

Similar detector systems were used by other groups for the identification and measurement of the polarization of Λ^0 in fixed-target experiments [Lo79], and in a simpler approach [Bu76]. Of interest is also the Omega spectrometer at CERN, equipped with 16 multiwire proportional chambers (MWPCs) in the forward direction and 8 MWPCs at each side of the 60 cm long hydrogen target. In addition, two drift chambers downstream from the spectrometer tracked the forward-going particles. Two threshold Cherenkov counters triggered the spectrometer on the decay protons.

A somewhat different system was employed at the CERN Intersecting Storage Rings (ISR), the R608 forward spectrometer [Ch82e]. The detector was installed on an out-going beam pipe in an intersection region of the ISR. It consisted essentially of two independent magnetic spectrometers, one positioned above and the other below the beam pipe. Figure 5 shows a front view of the magnetic aperture, looking downstream. The magnetic field $\mathbf{B}$ is in the same direction in both the Up and the Down section, making the Λ^0 in the Up spectrometer have its normal to the reaction plane $\mathbf{n}$ to the right, whilst for the Λ^0 in the Down section, $\mathbf{n}$ is to the left. Since the magnetic field is the same in both spectrometers, the acceptance corrections with respect to $\mathbf{n}$ are different for the two sets of data, providing a good verification of the results.

The schematic layout of the double septum spectrometer is also shown in Fig. 5. Each septum consists basically of five MWPCs, each having four planes of wires for accurate track reconstruction and momentum measurement, an analysing magnet, two Cherenkov gas counters for π , K, and p particle identification, two hodoscopes, and a number of other veto counters. The global spatial resolution was measured to be $180 \mu\text{m}$, resulting in a momentum resolution of $\sigma p/p = 5.8\%$ at $26.7 \text{ GeV}/c$.

3.1.2 Hybrid detectors

The hybrid detectors consist basically of a large bubble or streamer chamber, positioned in a strong magnetic field, followed by electronic detectors. The purpose of the chamber is to record the vertex of the decayed Λ^0 on film, and to track the decay products. The particle's momentum can be obtained from a measurement of the track curvature. Appropriate triggering is accomplished by using several electronic detectors upstream and downstream of the chamber.

An important difference—and advantage—of hybrid detectors compared with electronic ones, is their almost 4π coverage of the event. This enables the study of Λ^0 production and polarization in

the entire phase space. In practice, a certain rapidity region close to the projectile rapidity and regions close to the interaction volume are excluded from the measurements owing to the large track density. In external targets, a region close to the target rapidity is also unavailable for measurement.

Typical hybrid detectors are the 2 m hydrogen bubble chamber BEBC at CERN (now out of commission), the KEK 1 m hydrogen bubble chamber, and the 2 m hydrogen bubble chamber 'Ludmila' at Serpukhov. These chambers were used for Λ^0 polarization measurements in hadron-nucleon interactions. Streamer chambers, such as the SKM-200 at Dubna, the one at the LBL Bevalac, and the one at CERN used by the NA35 Collaboration, offered greater spatial resolution and the possibility of using external solid targets of different elements. They have been used primarily for Λ^0 polarization studies in nucleus-nucleus interactions.

A number of difficulties, to some extent similar to those of the electronic detectors, arise in the identification of a Λ^0 in the hybrid detectors: selective losses of events in the regions of high track density or close to the interaction point, owing to poor visual resolution; too steep Λ^0 decay planes or secondary trajectories for reliable detection during scanning; decays outside the fiducial volume. These losses are compensated for with standard weighting procedures.

3.2 Analysis methods

The general data-reduction procedure and polarization analysis, common to both electronic tracking and hybrid detectors, employ the following steps:

i) Two-track events are examined by a track-finding program and filtered through various cuts to extract the $\Lambda^0 \rightarrow p\pi^-$ events. Neutral Λ , in which tracks of opposite charges form a vertex in the decay region, are selected. The vector sum of the two momenta in these events is traced back to the target, where geometrical cuts are applied. The purpose of the cuts, together with the electronic vetos in the trigger logic, is to exclude non-target events, $\gamma \rightarrow e^+e^-$ conversions, and K_S^0 decays into two charged pions. This procedure produces the invariant mass of the Λ^0 and reduces the background under the $(p\pi^-)$ mass peak (Fig. 6). Typical such background is of the order of 1%.

ii) The detector acceptance is calculated by a Monte Carlo program, taking into account the chamber efficiency as a function of position and particle momentum. The simulation program includes effects such as the finite size of the beam spot on the target, multiple scattering and energy loss of the daughter particles, pion decay in flight, and inefficiencies and spatial resolutions of the tracking chambers. The Monte Carlo events are processed by the track-finding program and filtered through the 'cut routines' in a similar way to that for real data. A typical detection efficiency, obtained for the KEK spectrometer in particular, is shown in Fig. 7. The strong dependence of the geometrical acceptance and efficiency on the Λ^0 's momentum is evident.

Figure 8 shows the kinematics of the $p + p \rightarrow \Lambda^0 + X$ reaction in the $p_\perp$ versus $p_\parallel$ plane in the centre-of-mass system. Also shown is the laboratory momentum $p_{\Lambda 0}$ and the scattering angle $\theta_{\Lambda 0}$, and the Feynman-x scaling variable x_F , for the reaction at 12 GeV/c [Ab83]; x_F is the fraction of the beam momentum taken by the emitted particle:

$$x_F = (p_\parallel/p_b)^{\text{cm}} \simeq 2p_\parallel^{\text{cm}}/\sqrt{s},$$

where $p_\parallel$ and p_b are the longitudinal momentum of the emitted hyperon and the beam momentum, respectively, in the centre of mass. It should be noted that, at a fixed production angle, the $p_\perp$ and x_F are dependent on each other. For example, at $\theta_{\Lambda 0} = 10^\circ$, the range $0.3 < x_F < 0.6$ corresponds approximately to the transverse momentum range $1 < p_\perp < 1.5$ GeV/c.

iii) The Λ^0 polarization is determined from the asymmetries in the angular distributions of the p and π^- decay products. According to parity conservation in strong interactions, the Λ^0 polarization vector $\mathbf{n}$ should be normal to the production plane (Fig. 9). We take the z-axis along the direction of flight of the Λ^0 , $\mathbf{n}_z = \mathbf{p}_{\Lambda 0}/|\mathbf{p}_{\Lambda 0}|$, and the y-axis normal to the production plane, defined by

$$\mathbf{n}_y = \mathbf{n} = \frac{\mathbf{p}_b \times \mathbf{p}_{\Lambda^0}}{|\mathbf{p}_b \times \mathbf{p}_{\Lambda^0}|}, \quad (3.1)$$

where $\mathbf{p}_b$ is the momentum vector of the incident beam particle and $\mathbf{p}_{\Lambda^0}$ is that of the reconstructed Λ^0 . We then have $\mathbf{n} \parallel \mathbf{P}$, where $\mathbf{P}(P_x, P_y, P_z)$ is the polarization vector of the Λ^0 . The polarization component P_x corresponds to the left-right asymmetry, the P_y to an up-down (transverse) asymmetry, and the P_z to a forward-backward (longitudinal) asymmetry.

Another requirement, imposed by the angular momentum conservation in the Λ^0 decay, is that the corrected distribution of the decay angle θ be linear in $\cos \theta$ and that no azimuthal angle ϕ dependent terms be necessary to fit the data. The uncorrected distributions $dN/d(\cos \theta)$ are usually highly non-linear in $\cos \theta$. In the rest frame of the Λ^0 , the angular distribution of the proton from the Λ^0 decay is given by

$$dN/d(\cos \theta_i) = 1/2 A(\cos \theta_i)(1 + \alpha P_i \cos \theta_i), \quad i = x, y, z, \quad (3.2)$$

where α is the analysing power (decay asymmetry parameter) for the $\Lambda^0 \rightarrow p\pi^-$ decay ($|\alpha| = 0.642 \pm 0.013$), $\cos \theta_i = \mathbf{n}_i \cdot \mathbf{k}_p$ is the directional cosine of the proton ($\mathbf{k}_p$ denoting its direction vector), and $A(\cos \theta_i)$ is the acceptance of the detector. A study by Erhan [Er84] has shown that there is no evidence for a dependence on the proton azimuthal angle ϕ , or for higher-order moments. Figure 10 shows the acceptance-corrected Λ^0 decay distribution in the p-p interaction at $\sqrt{s} = 62$ GeV, with the best fit corresponding to the polarization indicated [Sc85].

Theoretically, if the normal to the production plane (along the y-axis), and hence the polarization vector, is parallel to the magnetic field of the sweeping magnet, the precession of the Λ^0 magnetic moment is zero and $P_x = P_z = 0$. Measurements of P_x and P_z could be used to estimate systematic biases in the experiment. If, on the other hand, the magnetic field (say in the x-direction) is perpendicular to the polarization vector (in the y-direction), a precession of the Λ^0 magnetic moment in the y-z plane will be observed (Fig. 11). The precession angle $\pm \psi$ depends on the field integral over the path of the Λ^0 in the magnet and on the magnitude of the Λ^0 magnetic moment,

$$\psi \simeq (c/v)(\mu_B/\mu_N) \int B \, d\ell,$$

where v and μ_B are the velocity and magnetic moment of the Λ^0 , and $\mu_N = e\hbar/2m_p c$ is the nuclear magneton. The precession of the Λ^0 's polarization vector at an angle ψ from the y-direction on the y-z plane will affect the measured polarization P_y and produce a net polarization in the z-direction, while P_x remains equal to zero if the polarization conserves parity. The Λ^0 polarization will then be the weighted average of $P_z \sin \psi$ and $P_y \cos \psi$.

Data analysed for polarization have an inherent bias in the decay angular distributions due to the fact that only unambiguously identified Λ^0 are used. The effect of this ambiguity bias is to multiply the angular distribution of the decay proton by a function, which is symmetric in $\cos \theta$. The bias can be taken into account using the relation [Ba69, Fa79].

$$\alpha P \pm \Delta(\alpha P) = \frac{\langle \cos \theta \rangle}{\langle \cos^2 \theta \rangle} \pm \frac{1}{\sqrt{n}} \frac{[\langle \cos^2 \theta (1 - \alpha P \cos \theta)^2 \rangle]^{1/2}}{\langle \cos^2 \theta \rangle}, \quad (3.3)$$

where n is the total number of events and θ is the angle of the decay proton with respect to the normal $\mathbf{n}$. This method of moments, used to calculate the Λ^0 polarization [Fa79], is independent of the ambiguity bias in the proton angular distribution. The error determination takes into account the correlation between $\langle \cos \theta \rangle$ and $\langle \cos^2 \theta \rangle$.

Another source of bias in determining the Λ^0 polarization is its associated production through the decay of higher-mass polarized baryons, e.g. $\Sigma^0 \rightarrow \Lambda^0 \gamma$, which cannot be distinguished experimentally. To evaluate the extent of this contribution to the Λ^0 polarization, one must know the

cross-section, the decay parameters, and the polarization of the decaying parent. Here we shall not consider the relatively much weaker contribution of the Ξ and Σ resonances, of which only the $\Sigma^+(1385)$ contributes significantly to the Λ^0 polarization [Er79a].

The Λ^0 produced from the decay of a polarized Σ^0 is longitudinally polarized in the Σ^0 rest frame. The Λ^0 polarization has the same magnitude, but opposite sign, as the component of the Σ^0 polarization, in the direction of the Λ^0 line of flight [Ga58]. Thus the transverse polarization of Λ^0 , emitted in all directions from the polarized Σ^0 , is

$$P_{\Lambda^0_{\text{indir}}} = -1/3 P_{\Sigma^0}. \quad (3.4)$$

The net result is that the polarization of the Σ^0 -produced Λ^0 is about 66% of that of the promptly produced Λ^0 , assuming that the Σ^0 polarization is approximately equal to that of Λ^0 [Ba79].

In a sample of Λ^0 produced directly and indirectly (through the polarized Σ^0 decay), the net observed Λ^0 polarization is given by the relation

$$P_{\Lambda^0_{\text{obs}}} = P_{\Lambda^0_{\text{dir}}} \frac{\sigma(\Lambda^0_{\text{dir}})}{\sigma(\Lambda^0_{\text{tot}})} - \frac{1}{3} P_{\Sigma^0} \frac{\sigma(\Sigma^0)}{\sigma(\Lambda^0_{\text{tot}})}. \quad (3.5)$$

In most cases the second term is of the order of a few per cent and can be neglected. Thus the measured Λ^0 polarization is smaller than the polarization of the directly produced Λ^0 by the factor $[\sigma(\Lambda^0_{\text{dir}})/\sigma(\Lambda^0_{\text{tot}})]$, which depends mainly on the particular interaction and weakly on the energy [Ba79].

A final check, which ensures that no spurious asymmetry is introduced into the analysis, is an estimation of the polarization of $(p-\pi^-)$ combinations that did not originate from a Λ^0 decay. Any angular distribution of such combinations should not have moments corresponding to odd values of the angular momentum, since these can only be obtained from interference between two angular momentum states, which is possible only through weak decays.

4. EXPERIMENTAL RESULTS

In this section we shall examine in detail the experimental data on Λ^0 polarization, which were obtained in a wide energy range with a variety of projectiles ($\pi^\pm$, $K^\pm$, p , $\bar{p}$, and various nuclei) and with targets ranging from the nucleon to heavy nuclei.

4.1 Hadron-nucleon interaction

The study of Λ^0 polarization in hadron-nucleon interactions has provided a wealth of data for several projectiles: $K^\pm$, $\pi^\pm$, p , and $\bar{p}$. The meson-nucleon interaction differs from the nucleon-nucleon one in that, in the simple quark picture, the latter is a direct s-quark pick-up in both fragmentation regions, whilst the former may require, in addition, quark rearrangement for the Λ^0 production. Among the mesons there is also a difference, since the kaons themselves carry the s-quark, which must become polarized. It is therefore expected that the Λ^0 polarization (sign, magnitude) will vary in interactions induced by these hadrons. We shall discuss each case in some detail and point out the differences.

4.1.1 K^-p interaction

The Λ^0 polarization in K^-p interactions has been studied in the beam momentum range from 3.93 to 176 GeV/c and for hyperon transverse momenta between 0.2 and 1.5 GeV/c. We shall discuss the polarization observed in the following channels:

Associated production (strangeness non-annihilation)

$$K^- + p \rightarrow \Lambda^0 K \bar{K} + n\text{-pions} \quad (n = 0, 1, 2, \dots), \quad (4.1)$$

$$K^- + p \rightarrow \Lambda^0 + n\text{-pions} \quad (n = 1, 2, \dots) . \quad (4.2)$$

In reaction (4.1), $K\bar{K}$ stands for K^+K^- , $K^0\bar{K}^0$, $K^+\bar{K}^0$ or $K^-\bar{K}^0$.

Figures 12a,b show the invariant x_F distribution for the two processes and for three incident energies [Ge80]. For both reactions, and in particular for the hypercharge non-annihilation channel, the bulk of the cross-section resides in the target hemisphere. It is also interesting to note in Figs. 13 and 14 that the cross-section for the strangeness annihilation channel decreases with increasing beam energy, whilst that for the associated production channel exhibits the opposite trend. At the highest momentum shown, 110 GeV/c (Fig. 14), the cross-section for channel (4.1) exceeds that for channel (4.2) and constitutes almost the entire backward sample.

As has been pointed out in [In74], the production mechanism of Λ^0 in K^- -p interactions, and in particular in the proton fragmentation region, is different for the two channels: associated production (4.1) and off-mass-shell hypercharge annihilation (4.2). It is therefore expected that the Λ^0 polarization should also behave differently in these two channels. In reaction (4.2) the Λ^0 is produced—in a qualitative quark picture—through the combination of the valence ud-diquark of the proton and the valence s-quark of the K^- . The remaining u, $\bar{u}$ -quarks produce the pions (Fig. 15). In this case, Λ^0 polarization in either of the hemispheres should be seen only if the valence s-quark of the K^- becomes polarized during the scattering, since the ud-diquark is in a spin singlet state. The available polarization data^{*)} use different polarization conventions (Fig. 16), and in order that they can be compared and discussed, we have transformed them into a common convention. Table 2 summarizes the sign of the polarization measurements and indicates the assumed conventions. The polarization convention adopted in this article is

$$\mathbf{n} = \mathbf{p}_b \times \mathbf{p}_{\Lambda^0} , \quad \text{where } \mathbf{p}_b = \mathbf{p}_{K^-} \text{ for this reaction.}$$

The conclusion drawn from the data in Table 2 is that, on the basis of our convention, the Λ^0 polarization is positive in the projectile, K^- , fragmentation region $x_F > 0$, for all beam momenta studied (4–176 GeV/c). There is only one discrepancy in this general feature: in the data of [Ha85] at 110 GeV/c, the reported polarization—after being adjusted to our convention—is positive at small $p_\perp$ and becomes negative for $p_\perp > 0.4$ GeV/c, but with very large errors. This is in contradiction to the systematics of all other data.

According to our convention, in the target (proton) hemisphere $x_F < 0$, and for beam momenta less than about 10 GeV/c, the Λ^0 polarization is negative, whilst for higher incident momenta it is zero. The negative polarization at small beam momenta and $x_F \approx -1$ is mainly due to the resonance contribution of the two-body reaction, which is important at low energies but becomes negligible at higher energies. The reason for the zero polarization at higher energies is the relative cross-sections for the two channels (4.1) and (4.2) in the target hemisphere, as already discussed. Their contribution is comparable in the energy range between 15 and 35 GeV, whilst the Λ^0 polarization produced by these two processes is opposite in sign, as we shall discuss below. The net measured Λ^0 polarization in the inclusive reaction is the sum of the contributions (of opposite sign) from the two processes, and it is nearly consistent with zero.

Figures 17a,b show the dependence of the polarization on $p_\perp$ in both hemispheres. The sign of the polarization was recalculated, assuming our convention. In the target fragmentation region $x_F < 0$, the data at 4.2 GeV/c [Ga78] exhibit an increase of the polarization to negative values with increasing $p_\perp$, whilst at 10 and 16 GeV/c [Ba72] the polarization is consistent with zero, up to the largest momentum of 1.2 GeV/c, Fig. 17a.

*) See comment at start of References.

The Λ^0 polarization in the target hemisphere is qualitatively predicted by the s-quark scattering model [Sz81], where the valence s-quark of the K^- is forced to turn back and decelerate in order to combine with the diquark from the proton to form the Λ^0 at $x_F < 0$. In this case, the kaon effectively ‘moves’ in the opposite direction, producing a negative polarization in our convention. A correct prediction comes also from the DeGrand-Miettinen model, in accordance with the simple rule that slow sea partons combine with their spins down in the scattering plane, producing a negative polarization.

Figure 17b shows the Λ^0 polarization in the projectile fragmentation region $x_F > 0$ as a function of $p_\perp$ for several beam momenta [Ba79, Ar85, Go86, Ha85]. The polarization sign was adjusted according to our convention. We observe that the polarization grows larger (positive) with increasing transverse momenta, independently of the energy. A similar trend is seen in the data at 13 GeV/c [Ba73], not shown in the figure. The data at 110 GeV/c [Ha85] exhibit a departure from the systematics of all other measurements at lower incident energies, as already discussed. This was suggested to be an energy effect. However, a recent Λ^0 polarization measurement at 176 GeV/c [Go86] exhibits a strong positive polarization (adapted to our convention) with increasing $p_\perp$ (above 0.2 GeV/c), consistent with the systematics of all other data at lower energies.

Figure 18 shows the dependence of the Λ^0 polarization on x_F in the kaon hemisphere for the inclusive $K^- - p \rightarrow \Lambda^0 + X$ interaction, at several momenta in the range 4 to 32 GeV/c. The sign of the polarization in the different measurements is adapted to our convention (see Table 2). An overall increase of a positive polarization with increasing x_F is observed at all energies.

The quantitative predictions of the model by Gago et al. [Ga87] for the Λ^0 polarization in the beam (kaon) hemisphere are shown in Figs. 19a and 19b for several incident beam momenta p_b at a fixed $x_F = 0.8$, and for $x_F = 0.3-0.9$ at fixed $p_b = 14$ GeV/c, respectively. We observe a weak dependence on p_b and x_F , whilst the $p_\perp$ dependence determines the size of the polarization. The data are well reproduced for a reasonable choice of the parameters of the calculation, except for the colour field intensity, $C \approx 4.4$, which is roughly twice the estimated value. It is noted in this reference that, had the authors not made the transformation to the (s-q) centre-of-mass system, the prediction would have been up to an order of magnitude smaller and with opposite curvature.

Similar qualitative predictions are obtained from the DeGrand-Miettinen model. In the simple SU(6) limit, the Λ^0 polarization is due to the polarization of the s-quark, whose initial stage is a valence parton in the K^- wave function. For x_F large (positive), all the asymmetry resides in the leading s-quark and a positive polarization is expected, in accordance with the simple rule that fast (leading) partons combine preferentially with their spins up in the scattering plane, producing a positive polarization.

In the strangeness non-annihilation channel (4.1), according to the simple qualitative quark picture, the Λ^0 is produced through the combination of a slow sea s-quark and the proton valence diquark. The remaining quarks produce the $K\bar{K}$ pair and pions (Fig. 15). Therefore, we expect the Λ^0 to be polarized in the proton fragmentation region (via the pick-up of a polarized s-quark) and unpolarized in the kaon fragmentation region, since no ‘leading’ parton is involved.

The experimental data for this reaction channel are too scarce to allow a broad-base systematics to be formed. Table 3 summarizes the available data*) and denotes the polarization conventions used. The data at 110 GeV/c [Ha85] in the target fragmentation region show a negative polarization for $p_\perp > 0.5$ GeV/c and a positive one for $p_\perp < 0.3$ GeV/c. Adapting the various polarization conventions of the data to our convention, we may conclude that in the target hemisphere the Λ^0 polarization is positive. Note that the convention of [Ge80], although unspecified, appears to be

*) See comment at start of References.

opposite to ours (see Table 2 and conclusions thereof), whilst for the channel of strangeness non-annihilation, they report a positive polarization for $x_F \approx -1$, in accordance with our convention. In the projectile hemisphere, the polarization is probably zero. A weak positive polarization with large errors is indicated at 4.6 GeV/c (Fig. 20 [Ga78]) (adjusted to our convention) and a negative one with large uncertainties at 32 GeV/c [Ge80].

The qualitative features of these data in the target hemisphere are explained by the DeGrand-Miettinen and Szwed models, where the diquark from the proton picks up a slow sea s-quark. Considering, for a moment, the beam to be the proton, we would expect a negative polarization in the proton fragmentation region. This convention, shown in Fig. 16 case (2), is opposite to the one assumed here, i.e. case (1), and thus a positive polarization is expected—in the proton hemisphere—increasing with transverse momentum. The approximately zero polarization in the projectile hemisphere is predicted by the DeGrand-Miettinen model, since in this case the Λ^0 is formed from slow sea (s,u,d)-quarks, whose wave functions do not exhibit strong momentum ordering.

The dependence of the polarization on x_F is shown in Fig. 20 for both channels. The striking difference in the Λ^0 polarization for the two processes in the region $x_F < -0.5$ is evident. It is positive for reaction (4.1) and negative for reaction (4.2). The small statistical errors for channel (4.2) determine definitively the change of sign of the Λ^0 polarization at $x_F \approx -0.5$ in the hypercharge annihilation process. Therefore, the basic difference in the two reactions is manifested most prominently in the proton (target) hemisphere.

It is interesting to make a further comparison of the Λ^0 polarization obtained through channels (4.1) and (4.2). Figure 21 shows the dependence of the polarization on the Λ^0 's transverse momentum, adapted to our convention, in the proton fragmentation region, $-1 < x_F < -0.2$ [Ga78]. We notice a similarity in the magnitude but an opposite-sign trend of the polarization in the two channels—features that are understood qualitatively in terms of the s-quark scattering and DeGrand-Miettinen models.

The dependence of the Λ^0 polarization on the centre-of-mass energy $\sqrt{s}$ in the inclusive reaction $K^-p \rightarrow \Lambda^0 + X$ is shown in Fig. 22 for both hemispheres [Ha85], adapted to our convention. In the projectile fragmentation region the polarization is independent of the energy, with a weak indication of a decrease at high energy, from the data at 110 GeV/c [Ha85], although the errors are large. In the target fragmentation region, the polarization is negative at lower energies and becomes roughly consistent with zero at approximately $\sqrt{s} > 6$ GeV.

4.1.2 K^+p interaction

The Λ^0 polarization has also been studied in the K^+p interaction

$$K^+p \rightarrow \bar{\Lambda}^0 + X^{++}, \quad (4.3)$$

$$K^+p \rightarrow \Lambda^0 + X^{++}, \quad (4.4)$$

in the momentum range 8.2 to 70 GeV/c. Figures 23a,b show the invariant x_F -distributions, integrated over $p_\perp^2$, for reactions (4.3) and (4.4) in the momentum range 8.2 to 32 GeV/c. We note an increase in the cross-section with increasing energy for both reactions, contrary to the K^-p systematics. For the Λ^0 production the peak of the distribution is located in the target hemisphere $x_F < 0$, whilst for the $\bar{\Lambda}^0$ the peak appears more in the region of the projectile hemisphere $x_F > 0$, both as expected from the simple quark-picture kinematics.

In process (4.3) the $\bar{\Lambda}^0$ is created via the combination of the kaon valence $\bar{s}$ -quark and a sea antiquark. Therefore, we may expect the $\bar{\Lambda}^0$ to be polarized in the kaon fragmentation region if the $\bar{s}$ -quark becomes polarized in the scattering. In the proton hemisphere, the $\bar{\Lambda}^0$ could be formed either

from sea (u,d,s)-antiquarks, or from a sea (u,d)-antidiquark and the moving backwards (slow) $\bar{s}$ -quark of the K^+ . In the former case, the $\bar{\Lambda}^0$ polarization is expected to be zero. For the latter case, being rather similar to the $K^-p \rightarrow \Lambda^0 + X$ reaction at $x_F < 0$, the $\bar{\Lambda}^0$ polarization may depend on the beam energy. However, there are no polarization measurements at low (below 13 GeV/c) incident momenta for comparison. Table 4 summarizes the polarization measurements for reaction (4.3)* and denotes the assumed conventions. Adapting the various polarization conventions to ours, we conclude that the $\bar{\Lambda}^0$ polarization is consistent with zero in the target hemisphere $x_F < 0$, and positive in the projectile K^+ hemisphere for incident momenta in the range 13 to 70 GeV/c.

Figure 24a shows the measured polarization in both hemispheres, after adapting the data to our convention. Except for the 13 GeV/c data, which, owing to large errors, may be consistent with zero polarization in both hemispheres, at higher energies the data give qualitative support to the simple quark picture. Within large statistical errors, there is a strong positive polarization in the kaon hemisphere and zero polarization in the proton hemisphere. This behaviour of the $\bar{\Lambda}^0$ polarization in the kaon hemisphere is similar to that observed in the K^- -induced hypercharge annihilation process (4.2) (Figs. 18 and 19) at incident momenta larger than 10 GeV/c.

The polarization features for reaction (4.3) are qualitatively predicted by the DeGrand-Miettinen model. In the projectile hemisphere, the fast valence $\bar{s}$ -quark combines with a sea antidiquark to form the $\bar{\Lambda}^0$, keeping its spin preferentially up in the scattering plane, thus producing a positive polarization. In the target hemisphere, when only sea antiquarks are combined, the polarization is predicted to be zero. The model of Gago [Ga87] should also predict the polarization in the projectile hemisphere, since it does so for the similar reaction $K^-p \rightarrow \Lambda^0 + \pi$'s, as we discussed earlier (see Fig. 19).

In reaction (4.4) the Λ^0 is produced through the combination of a sea s-quark and the valence diquark of the proton. Therefore, we expect the Λ^0 to be polarized in the proton hemisphere via the pick-up of a polarized sea s-quark, producing (in our convention) a positive polarization, and unpolarized in the kaon hemisphere in the absence of a 'leading' parton. In Table 5 we summarize the polarization measurements for reaction (4.4)*. The data are rather scarce, and there are no measurements at low energies to allow definitive conclusions to be drawn.

The data at 32 and 70 GeV/c [Fa79, Ba81] do not support the prediction in the target hemisphere and are consistent, within large statistical errors, with zero polarization (Fig. 24b). Note that this feature is the same as that found in reaction (4.2) at incident momenta above 10 GeV/c. The data at 13 GeV/c [Ba73] may show, within large errors, positive (in our convention) polarization for $x_F \approx -1$, as expected. In the kaon hemisphere the polarization is consistent with zero for all energies, again within large errors. We should note here that the DeGrand-Miettinen model predicts a weak negative polarization for the transition $K^+ \rightarrow \Lambda^0$ in the kaon hemisphere, contrary to the expectations for the simple combinatorial model and experimental observations (see Table 1).

Because of the large statistical errors, it is not clear whether there is an outstanding energy dependence of the Λ^0 polarization in kaon-nucleon interactions. We may observe an apparent energy dependence of the polarization in inclusive data, because the different processes involved, which produce different polarization in magnitude and sign (see, for example, Fig. 20), are energy- and rapidity-dependent (Figs. 12 and 23a, b). This is evident in the $K^\pm p \rightarrow \Lambda^0 + X$ interactions (Figs. 17 and 24a, b).

We will now discuss pion-nucleon interactions. These interactions offer the possibility to study the hypercharge exchange process, since this differs dynamically from other hadron-nucleon

*) See comment at start of References.

reactions. It thus provides the opportunity to examine different effects of the interaction. We shall discuss the following reactions:

$$\pi^- - p \rightarrow \Lambda^0 + X, \quad (4.5)$$

$$\pi^+ - p \rightarrow \Lambda^0 + X^{++}, \quad (4.6)$$

for which there exist Λ^0 polarization data.

4.1.3 $\pi^- - p$ interactions

The differential invariant cross-section for the inclusive reaction (4.5) at two incident energies is shown in Fig. 25 as a function of x_F [Ad84]. We note that the peak of the Λ^0 cross-section is in the target hemisphere and most of the magnitude lies within $-0.9 < x_F < -0.2$, especially at high energies. Figure 26 shows the incident momentum dependence of the cross-section for process (4.5) [Ad84]. A rather smooth but weak increase of the cross-section with increasing momenta is observed in the range 4 to 205 GeV/c.

In Fig. 27 we compare the differential rapidity distributions of Λ^0 and $\bar{\Lambda}^0$ produced in the $\pi^\pm - p$ interactions at 18.5 GeV/c [St74], integrated over the transverse momentum. We note the predominant production of Λ^0 in the target rapidity region and the sharp peaking of the $\bar{\Lambda}^0$ production at mid-rapidity. The $\bar{\Lambda}^0$, being formed entirely out of sea antiquarks, appear predominantly in the central region.

On the basis of the qualitative quark model, the mechanism for leading Λ^0 production in $\pi^- - p$ interactions is the combination of a polarized sea s-quark and the proton valence diquark. We may therefore expect the Λ^0 polarization to be strong and positive in the target fragmentation region and zero in the projectile hemisphere, according to our convention.

Table 6 summarizes the limited available^{*)} data for reaction (4.5) and denotes the polarization conventions used. On the basis of our convention, the Λ^0 polarization is positive in the target (proton) hemisphere and consistent with zero in the beam (pion) hemisphere.

The polarization data shown in Fig. 28 [Ad84], adapted to our convention, support this notion. A strong positive polarization is observed with increasing $p_\perp$ in the proton hemisphere, $-1 < x_F < -0.2$, whilst in the pion hemisphere, $0.4 < x_F < 1$, the polarization is consistent with zero in the measured $p_\perp$ range up to about 1 GeV/c. Figure 29 shows the Λ^0 polarization as a function of x_F for two incident momenta of 3.95 and 18.5 GeV/c [Ad84, St74]. We note that the polarization in both hemispheres is rather similar for the two momenta, although the 18.5 GeV/c data suffer from large errors.

In Fig. 30 a comparison is made of the polarization as a function of $p_\perp$ for the reactions $K^- - p \rightarrow \Lambda^0 K \bar{K} + \pi$'s and $\pi^- - p \rightarrow \Lambda^0 + \pi$'s in the target fragmentation region, $-1 < x_F < -0.2$, at similar incident momenta of 4.2 GeV/c [Ga78] and 3.95 GeV/c [Ad84], respectively. The definite similarity of the polarization in both sign and magnitude, in the target hemisphere, demonstrates the common underlying mechanism of Λ^0 production and polarization for these two distinctly different reactions, at least at low energies. In the projectile fragmentation region, the two reactions also agree in the polarization, which is rather consistent with zero, as expected from the simple quark combinatorial model.

4.1.4 $\pi^+ - p$ interaction

To our knowledge, there is only one Λ^0 polarization measurement with the inclusive reaction (4.6) at 18.5 GeV/c [St74]. The Λ^0 should be produced in the same way as in the $\pi^- - p$ reaction,

*) See comment at start of References.

through the combination of a slow, polarized sea s-quark and the proton valence diquark. We therefore expect a similar behaviour of the polarization: positive in the target fragmentation region and zero in the projectile one, on the basis of our polarization convention.

The data shown in Fig. 31a,b contradict this expectation [St74]. The x_F -dependence of the polarization is consistent with zero in the target (proton) hemisphere (Fig. 31a), in contrast to the π^- -p data. The polarization as a function of $|t - t_{\min}|$, where t is the square of the four-momentum transfer from the target proton to the Λ^0 and $t_{\min}$ is the minimum value of t calculated for each event, is also consistent with zero in the measured range (Fig. 31b).

This unexpected behaviour of the Λ^0 polarization at $x_F < 0$ is similar to that observed in inclusive $K^+p \rightarrow \Lambda^0 + X^{++}$ and $K^-p \rightarrow \Lambda^0 + X$ reactions at higher energies (Figs. 24 and 17a, respectively), although in the latter it is known to be the result of the contribution of two processes with polarization of opposite sign, which cancel each other out, as discussed earlier. We should also note here that the DeGrand-Miettinen model predicts a weak negative polarization for the reaction $\pi \rightarrow \Lambda^0$ in the pion's hemisphere, contrary to the expectations from the simple combinatorial model and experimental observations, see Table 1.

4.1.5 Nucleon-nucleon interaction

The Λ^0 polarization induced in nucleon-nucleon interactions has been measured in fixed-target and colliding-beam experiments, in the momentum range between 1.5 and 300 GeV/c and $\sqrt{s} = 31$ to 62 GeV, respectively. The polarization was studied in the following reactions:

$$p-p \rightarrow \Lambda^0 (\bar{\Lambda}^0) + X, \quad (4.7)$$

$$\bar{p}-p \rightarrow \Lambda^0 (\bar{\Lambda}^0) + X, \quad (4.8)$$

$$p-p \rightarrow \Lambda^0 + K^+ + X. \quad (4.9)$$

The colliding-beam experiments, carried out at the CERN ISR (Intersecting Storage Rings), measured the polarization in the first two inclusive interactions and in the diffractive dissociation process (4.9). In these experiments, the beam and target fragmentation regions are indistinguishable or 'orthogonal' in p-p or $\bar{p}$ -p interactions, respectively.

In the p-p interaction, the Λ^0 is produced through the combination of a polarized sea s-quark and the proton valence diquark. Therefore, in both the projectile and target hemispheres the polarization is the same in magnitude and sign and, on the basis of our convention, negative. In Fig. 32 the Λ^0 polarization is shown as a function of $p_{\perp}$ at $\sqrt{s} = 53$ and 62 GeV/c [Er79]. A strong negative polarization with increasing $p_{\perp}$ is seen, with no statistically significant energy dependence. The (π^-p) pairs from a non- Λ^0 origin, with $p_{\perp} > 0.8$ GeV/c, exhibit zero polarization. The mean polarization for $p_{\perp} > 0.6$ GeV/c is: $P_{\Lambda^0} = -(0.34 \pm 0.07)$ and $-(0.40 \pm 0.1)$ at $\sqrt{s} = 53$ and 62 GeV/c, respectively.

The dependence of the Λ^0 polarization on the transverse momentum for fixed x_F -bins at $\sqrt{s} = 62$ GeV is shown in Fig. 33 [Sm87]. One observes that the polarization, being approximately zero for $|x_F| < 0.25$, obtains larger (negative) values with increasing $p_{\perp}$ and x_F , reaching an x_F -dependent maximum value at $p_{\perp} \approx 1$ GeV/c. This is consistent with the Λ^0 production mechanism. It is also interesting to note that the polarization increases with increasing x_F at any $p_{\perp}$, in agreement with the data at $\sqrt{s} = 27$ GeV [He85].

Similar dependence of the Λ^0 polarization on $p_{\perp}$ and x_F was obtained in a fixed-target measurement at 19 GeV/c [Aa78]. Figure 34 shows that the polarization tends to zero at non-zero values of both $p_{\perp}$ and x_F , in agreement with the ISR data.

Figure 35 shows the Λ^0 polarization, for $p_{\perp} > 0.96$ GeV/c, as a function of x_F [Sh88]. The average $p_{\perp}$ is approximately 1.14 GeV/c, and in this region the polarization ceases to be strongly

dependent on $p_{\perp}$ and only the x_F -dependence remains. A linear fit to the data of the form $P = a + bx_F$ at $\sqrt{s} = 3.6, 27, 62$ GeV ([Ra80, Po85, Sm87], respectively), gave the values $a = 7.3 \pm 3.5\%$ and $b = -56.6 \pm 7\%$, with a χ^2 of 1.8 for five degrees of freedom (DOF).

The independence of the polarization on the beam energy, for fixed $p_{\perp}$ and x_F bins, is shown in Fig. 36 [Sm87]. A simultaneous fit to the three sets of data points of the function $P_{\Lambda^0} = P_{\Lambda^0}(62 \text{ GeV}) + R(\sqrt{s} - 62.4)$, where $R = d(P_{\Lambda^0})/d(\sqrt{s})$, yields the value $R = (0.027 \pm 0.055)\% \text{ GeV}$, corresponding to a change of the polarization of $(0.8 \pm 0.17)\%$, in the energy range $\sqrt{s} = 31$ to 62 GeV. If one includes the fixed-target measurements at lower energies of 12 and 400 GeV, a remarkable agreement in both the magnitude and the kinematic systematics is observed, clearly indicating the independence of the Λ^0 polarization on the beam energy, at least up to $\sqrt{s} = 62$ GeV. Figures 37a,b compare the polarization of inclusive Λ^0 in p-N interactions. In both figures the 400 GeV data have been properly interpolated so as to match the x_F -values at each $p_{\perp}$ of the data at the other energies [He85].

The Λ^0 polarization measured in inclusive reactions is diluted by the fraction of Λ^0 's produced from the decay of other particles, such as Σ^0 , Σ^{*+} , etc., and having smaller polarization [see relation (3.4)]. However, Λ^0 production in the diffractive dissociation channel in p-p interactions does not suffer from this effect, because of the elementary nature of the strangeness-producing process in reaction (4.9). Erhan et al. have reported the first such study, $p\text{-}p \rightarrow \Lambda^0 + K^+$ at $\sqrt{s} = 62$ GeV [Er84]. The candidate events for the diffractive dissociation process were selected by accepting only a narrow region (30 to 33 GeV/c) of the pronounced peak at $x_F \approx 1$, characteristic of high-energy diffractive processes. The average Λ^0 polarization measured for $0.5 < x_F < 0.8$ and $0.5 < p_{\perp} < 1.5$ GeV/c is $-(0.36 \pm 0.045)$. This value should be compared with the corresponding value obtained in the inclusive $p\text{-}p \rightarrow \Lambda^0 + X$ interaction at the same energy and x_F interval and for $\langle p_{\perp} \rangle = 1.1$ GeV/c [Sm87]. The average polarization in the inclusive process is $-(0.295 \pm 0.053)$, approximately 22% smaller than the corresponding value in the diffractive dissociation process.

The theoretical predictions concerning the Λ^0 polarization in p-p interactions are compared with measurements in Figs. 38a,b and 39a,b [Sh88, De81]. In Fig. 38a, the Lund model prediction for $x_F < 0.8$ [An79] is compared with the data of Fig. 33 at $\sqrt{s} = 62$ GeV for several x_F -bins. The solid line is the prediction, whilst the two dotted lines show the range of the uncertainty. The model predicts the correct sign but a much larger polarization; however, one should keep in mind that the prediction is for *directly* produced Λ^0 , whilst the data include Λ^0 from associated production with substantially lower polarization. As already discussed in Section 3 and just above, the measured polarization is smaller than the polarization of the directly produced Λ^0 by the factor $[\sigma(\Lambda_{\text{dir}}^0)/\sigma(\Lambda_{\text{tot}}^0)]$. This factor is estimated to be approximately 0.75 for the data of Fig. 33. Therefore, the polarization of the directly produced Λ^0 , at the $p_{\perp}$ saturation value of about 1 GeV/c and for $x_F = 0.77$, is now increased to about -0.5 , in good agreement with the model prediction.

In Fig. 38b, the DeGrand-Miettinen predictions for several x_F -bins are compared with the same data. Here the model agrees with the measurements for only $x_F < 0.3$ and $p_{\perp} < 0.8$ GeV/c, and underestimates the polarization for higher values of both variables. Figure 39 shows the model calculations by DeGrand and Miettinen [De81] as applied to the measurements of Λ^0 polarization in p-p inclusive interactions at 400 GeV [He81]. Adjusting the parameters of the model, a fair qualitative agreement with the data is obtained, better than that at higher energies Fig. 38b. The model by Szwed [Sz81] predicts the rise of the polarization with $p_{\perp}$, but does not explain the saturation observed at $p_{\perp}$ above 1 GeV/c. One general feature of the data, which is not predicted by any model, is that the polarization falls to zero at non-zero values of $p_{\perp}$ ($p_{\perp} \approx 0.4$ GeV/c). Both models, [An79] and [De81], predict zero polarization at zero $p_{\perp}$ for all values of x_F .

The p- $\bar{p}$ interactions offer the possibility to measure the polarization of both Λ^0 and $\bar{\Lambda}^0$ in the fragmentation hemispheres of p and $\bar{p}$, respectively. Figure 40 shows the invariant x_F distribution,

integrated over $p_{\perp}^2$ for the inclusive Λ^0 production in $\bar{p}$ -p interactions at 4.5 GeV/c [No84]. The Λ^0 is produced in the proton (target) hemisphere, and the sharp peak near $x_F = -1$ corresponds to two-body final states, such as $\Lambda^0 \bar{\Lambda}^0$ and $\Lambda^0 \bar{\Sigma}^0$. A similar distribution, but peaking in the projectile hemisphere, is obtained for the $\bar{\Lambda}^0$ production curve.

In Fig. 41 the dependence of the Λ^0 polarization on $p_{\perp}$ is shown at three energies in the target fragmentation region, $x_F < 0$. Adapting the polarization to our convention ($\mathbf{p}_{\bar{p}} \times \mathbf{p}_{\Lambda^0} = \mathbf{n}$), the polarization becomes more positive with increasing $p_{\perp}$ above approximately 0.4 GeV/c. The similarity of this reaction to the hypercharge non-annihilation reaction $K^-p \rightarrow \Lambda^0 K \bar{K} + \pi$'s (4.1) is shown clearly in Figs. 42a, b. The Λ^0 polarization is shown as a function of $p_{\perp}$ for $-1 < x_F < -0.2$ (a), and as a function of x_F (b). In particular, in Fig. 42b the similarity in the range of $x_F < 0$ is consistent with the simple quark combination model.

The comparative study of Λ^0 and $\bar{\Lambda}^0$ polarization in p-p and $\bar{p}$ -p interactions is instructive owing to the symmetry of the systems. Figure 43 shows the kinematics of Λ^0 and $\bar{\Lambda}^0$ production and polarization in terms of the recombination parton model. In the case of the $\bar{p}$ -p reaction, both Λ^0 and $\bar{\Lambda}^0$ should be equally polarized in the p and $\bar{p}$ fragmentation regions, respectively, whilst their polarization should be zero in the opposite hemispheres. This feature of the Λ^0 -polarization in p-p ($\bar{p}$ -p) reactions can be used to investigate the dominance of CP invariance in the weak Λ^0 decay.

In the strong $\bar{p}$ -p interaction, C invariance demands that particles produced at an angle θ have identical properties with those produced at the angle $(\pi - \theta)$ in the same reaction. This means that in the $\bar{p}$ -p interaction, the polarizations of Λ^0 and $\bar{\Lambda}^0$ are identical in the p and $\bar{p}$ fragmentation regions, respectively. The CP invariance in the weak Λ^0 decay requires the asymmetry parameter α to have equal magnitude and opposite sign for the particle and the antiparticle: $\alpha_{\Lambda^0} = -\alpha_{\bar{\Lambda}^0}$. Therefore, if both C and CP invariance hold true, then we expect that in the $\bar{p}$ -p interaction the quantity αP_{Λ^0} will be equal in magnitude and opposite in sign for Λ^0 and $\bar{\Lambda}^0$, in the two fragmentation regions of p and $\bar{p}$, respectively.

Figure 44 shows the polarization ($\alpha P/|\alpha|$) of Λ^0 and $\bar{\Lambda}^0$ as a function of $p_{\perp}$. The striking similarity in the magnitude of the polarization in the two reactions indicates that $\alpha_{\Lambda^0} = -\alpha_{\bar{\Lambda}^0}$, as expected. Over the entire measured range of $p_{\perp}$, the weighted average of these quantities is (-1.04 ± 0.29) [Ch85], assuming that $P_{\Lambda^0} = P_{\bar{\Lambda}^0}$. It is consistent with the expected value of -1 for dominant CP invariance in Λ^0 decay. A similar, statistically more precise, confirmation was made in a study of the $\bar{p}$ -p $\rightarrow \bar{\Lambda}^0 \Lambda^0$ reaction near threshold, 1.546 and 1.695 GeV/c [He88]. The measurement with 16,000 events gave the ratio $A = (\alpha_{\Lambda^0} + \alpha_{\bar{\Lambda}^0})/(\alpha_{\Lambda^0} - \alpha_{\bar{\Lambda}^0}) = -0.023 \pm 0.057$, which is consistent with zero, as required by CP conservation. We note also that in a study of the polarization of Λ^0 and $\bar{\Lambda}^0$, produced in the decay of J/ψ , the ratio A was measured to be 0.01 ± 0.1 [Ti88].

The accuracy of all these experiments remains insufficient for observing CP violation at the level predicted by the Standard Model: $A = -2 \times 10^{-5}$ in the Kobayashi-Maskawa model, or $A = -10^{-4}$ in the Weinberg model. As pointed out by Wolfenstein and Chang [Wo83], measurements of ϵ' provide a much more sensitive test of CP-violating amplitudes in weak decays than does any accurate experiment comparing the polarization of Λ^0 and $\bar{\Lambda}^0$.

The employment of the $\bar{p}$ -p interaction to measure Λ^0 polarization offers the possibility to study the effects of the missing mass on the Λ^0 polarization. Figure 45 shows the distribution of missing mass at 4 GeV/c [No84]. The peaks correspond to two-body reactions, such as $\bar{p}$ -p $\rightarrow \Lambda^0 + (\bar{\Lambda}^0, \bar{\Sigma}^0, \bar{\Lambda}^{0*}, \bar{\Sigma}^{0*})$, whilst the higher mass continuum corresponds to resonance decays. Therefore, the measurement of the Λ^0 polarization (in the target fragmentation region) with a cut in the missing mass below approximately 1.6 GeV/c² ensures that only two-body (or quasi-two-body) reactions are involved.

This effect is shown in Figs. 46a, b [No84], where the polarization is plotted as a function of $p_{\perp}$ for two missing-mass regions: a) $m_X < 1.58$ GeV/c² and b) $m_X > 1.58$ GeV/c² (note that the

polarization convention is the opposite of ours). The strong negative polarization in Fig. 46a and the zero value in Fig. 46b is a direct verification of the contribution of decay resonances in the latter case. In Fig. 46c the polarization for $p_{\perp} > 0.4$ GeV/c is shown as a function of the missing mass. A constant negative value is observed for $m_X < 1.6$ GeV/c² and a zero value for larger m_X . A similar feature has been observed in the polarization as a function of m_X^2/s in K^-p interactions for $x_F > 0$ (Fig. 47 [Ab76]). We note a constant positive polarization (adapted to our convention) of about 0.4 at all energies, for values of $m_X^2/s < 0.4$, and a subsequent decrease to zero polarization for larger values of m_X^2/s , corresponding to the decay of resonances.

4.2 Hadron–nucleus interaction

From the present examination and discussion of Λ^0 polarization it has become clear that the polarization is an effect on the hadron–hadron—or more precisely, the parton–parton—level. Therefore one may intuitively expect no such effect to appear in hadron–nucleus reactions, where secondary interactions and rescattering in the bulk of the nuclear matter may be present. It was thus with great surprise that a strong Λ^0 polarization was measured in p –Be interactions at the energy of 300 GeV [Bu76]. Since then, a number of other measurements at lower and higher energies and with very heavy targets have confirmed the existence of a strong polarization. We shall discuss the Λ^0 polarization measured in both pion- and nucleon-induced reactions.

4.2.1 π^- –nucleus interaction

It is of interest to examine the Λ^0 polarization arising from the $\pi^-A \rightarrow \Lambda^0 + X$ interaction, since it has important implications in both p – A and A – A polarization measurements. The Λ^0 is formed by the combination of a diquark from the target and a sea s -quark. Figure 48 shows the invariant cross-section (integrated over the transverse momenta) as a function of x_F for π^- -induced reactions on $(C + F + Cl)$, with $\langle A \rangle = 22.5$, at 3.9 GeV/c, and on carbon at 5 GeV/c [Go78]. We observe that the cross-section peaks at $x_F \approx -0.6$ and that it lies mostly in the target hemisphere, as in the case of the π^-p reaction (Fig. 27). A similar distribution, shown in Fig. 49, is observed at 40 GeV/c [Ba88]. The histograms, normalized to the data, represent the predictions of the dual topological unitarization (DPU) model, which has been successful in describing inclusive high-energy hadron–nucleus interactions [Ra85].

As in the case of the π^-p interaction, on the basis of our polarization convention we expect the Λ^0 polarization to be positive in the target and zero in the projectile hemisphere. In [Dz81], a Λ^0 polarization measurement is reported in the π^- –propane reaction at 40 GeV/c. The assumed polarization convention is the same as ours; however, the x -axis is normal to the production plane and the y -axis is along the momentum of the Λ^0 in the laboratory (compare this coordinate system with the one in Fig. 9). On the basis of this system, the transverse polarization is given by the P_x component of the polarization vector, whilst the P_y component corresponds to the longitudinal polarization. Their measurement gave the values of $\langle P_x \rangle = 0.08 \pm 0.07$ for the transverse polarization and $\langle P_y \rangle = -(0.1 \pm 0.11)$ for the longitudinal one, with $p_{\perp}$ in the range $0.1 < p_{\perp} < 1.5$ GeV/c and x_F in the entire range of the experiment in the 2 m propane bubble chamber. The zero average value of the transverse polarization in this $(p_{\perp}, x_F)$ range is quite consistent with expectations and with the measurements in π^-p interactions (see Figs. 28 and 29).

The $\pi^+A \rightarrow \Lambda^0 + X$ reaction should exhibit systematics similar to those of the π^-p interaction:

- i) The Λ^0 production cross-section should lie mostly in the target hemisphere and be of the same magnitude as in the π^-A reaction, since the $\pi^{\pm}p \rightarrow \Lambda^0 + X$ cross-sections are approximately equal (see Fig. 25). A study of the A -dependence of the inclusive Λ^0 production in $\pi^{\pm}A$

interactions at $x_F > 0$ has shown that the target mass dependence is roughly the same for both reactions [Ab84b].

- ii) The Λ^0 polarization may be approximately zero in the entire x_F range (see Fig. 31), although a positive polarization is actually expected at $x_F < 0$.

To our knowledge, there are no Λ^0 polarization measurements in π^+ -A interactions and, therefore, we have to rely on the information provided by the only π^+ -p measurement [St74].

4.2.2 Nucleon-nucleus interaction

The production of Λ^0 in interactions induced by nucleon beams on nuclei involves the recombination of the valence diquark of a nucleon and a sea s-quark. Figure 50a shows the dependence of the invariant cross-section for Λ^0 production at 12 GeV/c, as a function of the variable $(x_0 - x_F)$, for various values of the transverse momenta [Ab87]; x_0 is the maximum value of x_F which is allowed kinematically at a given $p_\perp$. The straight lines are the fits for several $p_\perp$ values of the relation

$$E(d^3\sigma/dp^3) = A(p_\perp)(x_0 - x_F)^{m(p_\perp)} . \quad (4.10)$$

Investigation has shown that for the Λ^0 , there is a weak (if any) dependence of the power $m(p_\perp)$ on $p_\perp$ (Fig. 50b [Ab87]). The dependence of $m(p_\perp)$ on the mass of the target for several incident energies (12–2070 GeV) shows also a weak dependence. This dependence is more pronounced at low $p_\perp$ values. It suggests that the Λ^0 production from a heavy nucleus in the forward direction is attenuated, compared with a light target nucleus. This is consistent with the reported nuclear attenuation effect [Ab84c, He77].

In the $\bar{p}$ -nucleus interaction, the bulk of the Λ^0 's is produced in the target rapidity, since in this case they are formed out of a diquark from a target nucleon and a sea s-quark. Figure 51 shows the Λ^0 rapidity distribution in the reaction $\bar{p}$ -Ta at 4 GeV/c [Mi84]. The distribution has an asymmetric tail on the higher rapidity side, just in the rapidity region of the Λ^0 from p- $\bar{p}$ interactions. The peak of the distribution goes to $y_{cm} = 0$ if one assumes a 'p + 13N' centre-of-mass system, moving with $b = 0.24$. The large number of target nucleons appearing to participate in the interaction (there should be only about six, as we will show in Section 4.3), may only be the effect of possible Λ^0 rescattering in the nuclear matter of the target, or of secondary Λ^0 production, as we shall discuss below.

The effects of the mass of the target nucleus on the production and polarization of the Λ^0 are referred to as 'A-dependence'. A common functional form used to express the dependence of the cross-section on A is a simple power law:

$$\sigma(A) = A^a \sigma(A=1) . \quad (4.11)$$

If the nucleons completely screen each other inside the nucleus, then the cross-section increases as $A^{2/3}$. If, however, the target partons appear as geometrical points with very short-range interactions, the cross-section should be proportional to A. Experimentally, it is found that for high-energy protons the power takes the value $a \approx 0.7$, which indicates near-total screening.

A detailed study of the Λ^0 polarization as a function of the target mass A was carried out by Abe at 12 GeV/c [Ab86] and by Aleev at 40 GeV/c [Al87]. In the former study, targets of Be, Cu, and W were used, and Fig. 52 shows the polarization as a function of $p_\perp$ at fixed production angles. The straight lines are simultaneous fits to the W data, which were divided into $p_\perp$ bins at intervals of $\Delta p_\perp = 0.1$ GeV/c, with a χ^2 value of 17 for 12 DOF. Similar fits were performed for the other two targets. The conclusion reached by this study [Ab86] is that the $p_\perp$ -dependence of Cu and W is the

same, whilst that of Be is a little steeper, giving a slightly larger polarization of about 10%, with marginal statistical significance, however. A similar trend was observed at higher energies of 28 GeV [Ra80] and 400 GeV [He83, Lu84]. Figures 53a-c show the target mass dependence of the polarization, as measured in these three experiments at $x_F > 0$. In Fig. 53c the effect is small, of the order of 5%. For heavier targets (and at higher energies) the A-dependence appears to be more pronounced, of the order of 30%, as can be seen in Fig. 54, which contains the p-A data at 400 GeV/c from [He83] and [Lu84]. Here the ratio of the average Λ^0 polarization from Cu and Pb to that from Be is plotted versus $p_\perp$ [Po85]. No statistically significant A-dependence has been observed for any other hyperon polarization.

In the latter study on the mass dependence of the polarization [Al87], targets of carbon, aluminium, and copper were bombarded with 40 GeV/c neutron beams. An earlier experiment [Al83], employing the n-C interaction at 40 GeV/c, measured the Λ^0 polarization to be -0.3 ± 0.04 for x_F in the range $0.2 < x_F < 0.9$ and $\langle p_\perp \rangle = 0.88$ GeV/c. The polarization results from the three targets, obtained with the same Λ^0 detector efficiency, were fitted with an A-dependent function:

$$P = a A^b . \quad (4.12)$$

The minimum χ^2 value of 46 for 58 DOF corresponds to the values of the parameters: $a = -1.1 \pm_{-0.3}^{+0.4}$ and $b = -0.15 \pm_{-0.6}^{+0.07}$. The result indicates that b is negative within 3 standard deviations, which may be interpreted as evidence for a decrease of the polarization with increasing mass of the target.

An effect that could cause a decrease of the polarization with target mass could be a difference in the elastic rescattering of the Λ^0 in targets of different scattering lengths. In the study by Aleev [Al87], this effect corresponds to a value of $b \leq 0.02$ and thus does not alter the observed result. Another possible cause for the decrease of the polarization may be an increase of the Σ^0 production cross-section with target mass. This will result in a larger number of indirectly produced Λ^0 with smaller polarization, causing an overall reduction of the measured value. However, it is shown in [Ba83] that, in hadron-nucleus interactions the A-dependence of the inclusive production of hadrons is nearly the same (see also [Ch75]).

A third effect, which is most probably responsible for the decrease of the polarization with increasing target mass, is the secondary production of Λ^0 through π^- -nucleon interaction in the nuclear matter. Pions that are produced via N-N scattering in the initial stage, interact with nucleons in the target and produce polarized Λ^0 through the reaction $\pi^- - N \rightarrow \Lambda^0 + X$. The (secondary) produced Λ^0 will be positively polarized at $x_F < 0$ (target hemisphere) and unpolarized at $x_F > 0$ (projectile hemisphere), as discussed earlier.

A qualitative argument for the influence of this effect is as follows. Pion production in inclusive p-A $\rightarrow \pi^- + X$ reactions exhibits a symmetric distribution about $x_F = 0$. The A-dependence of the cross-section is parametrized as $\sigma(\pi^-) \approx A^{0.66}$ in the energy range $E_p = 24-400$ GeV, and for $0.2 \leq |x_F| < 0.5$ and $p_\perp \approx 0.3$ GeV/c [Ba83]. Since the bulk of the pions move in the forward direction in the laboratory, the sense of rapidity retained by the π^- -A interaction is roughly the same as that of the primary reaction. The Λ^0 production via the secondary interaction $\pi^- - A \rightarrow \Lambda^0 + X$ exhibits a distribution centred at $x_F \approx -0.6$ to -0.3 for pion momenta of 4-40 GeV/c [Go79, Ba88], and the cross-section, measured at $E_{\pi^-} = 40$ GeV, is parametrized as $\sigma(\Lambda^0) \approx A^{0.95}$ [Ba88]. The A-dependence of the cross-section for the direct production of Λ^0 via the elementary interaction $N - N \rightarrow \Lambda^0 + X$ in the p-A reaction is given by $\sigma(\Lambda^0) \approx A^{0.66}$, in the energy range $E_p = 12-300$ GeV, and for $0.2 \leq |x_F| < 0.5$ and $p_\perp$ in the range 0-0.6 GeV/c [Ab84]. The distribution is symmetric about $x_F = 0$.

We now note that on the basis of our polarization convention, the Λ^0 polarization arising from the π^- -induced reaction is *positive* at $x_F < 0$ and *zero* at $x_F > 0$. On the other hand, the polarization of the Λ^0 produced directly in p-N reaction is *negative* for all x_F . Therefore, a polarization

measurement of inclusive Λ^0 at $x_F < 0$ should give an approximately *zero* value (or even a positive one, depending on the relative cross-sections), and at $x_F > 0$ a *negative* value, with smaller magnitude than the corresponding value in p-p interactions, since many Λ^0 's (from π -N interactions) are unpolarized in this region. This reduction in magnitude is evident when comparing the polarization in p-p and p-A, shown in Figs. 22 and 55, respectively. The former prediction is probably verified in the $\bar{p}$ -Ta reaction, by a measurement of the polarization in the target hemisphere (see discussion immediately below). The latter prediction is observed in p-A interactions in the projectile hemisphere, the so-called A-dependence of the polarization.

Experimental evidence for indirect Λ^0 -production is conjectured from the study of the $\bar{p}$ -Ta interaction at 4 GeV/c [Mi84]. Miyano et al. observed a Λ^0 cross-section that is about 10 times larger than what is expected from the extrapolation of the value in the $\bar{p}$ -p $\rightarrow \Lambda^0$ reaction to the Ta target (an increase by a factor $A^{0.66} = 31$). The excess Λ^0 cross-section is estimated to come from secondary processes [Na88]. It exhibits different kinematics compared with the $\bar{p}$ -p interaction, as seen in Figs. 40 and 51, and has a small overlap with the latter, estimated to be about 8%. A measurement of the polarization of the secondarily produced Λ^0 gave the value $\langle P \rangle = 0.02 \pm 0.09$, consistent with zero.

It should be mentioned here that secondary Λ^0 production through π -N (and $\bar{K}$ -N) interactions in the nucleus has been assumed in explaining quantitatively the strangeness enhancement in high-energy proton-nucleus [Ni88] and nucleus-nucleus collisions [Ga89]. The former study gives a good quantitative description of the Λ^0 production characteristics observed in p-Xe and p-Ag reactions [De82, De84]. The involvement of particles produced originally in intranuclear cascade, in particular close to the target rapidity, has also been discussed by Brick et al. [Br89]. These authors suggest that the observed secondary collisions, in 200 GeV/c hadrons on nuclei, arise mainly from rescattering of recoiling nucleons rather than from produced particles at this very high energy. It is therefore obvious that there is still no general consensus on the origin of the secondary Λ^0 production.

The dependence of the Λ^0 polarization on x_F was studied by Abe [Ab86], in the interval $0.26 \leq x_F \leq 0.77$, at fixed $p_\perp$. Figure 56 shows this dependence for the combined data of p-induced reactions on the targets Be, Cu, and W at 12 GeV/c. The data indicate that the polarization increases with x_F in the measured range, especially for the high $p_\perp$ -bins. For $p_\perp < 0.5$ GeV/c it depends only on $p_\perp$, but for larger transverse momenta, it also depends on x_F . This dependence is similar to the one reported at higher energies [He81, He83, Lu82].

The polarization predictions of the DeGrand-Miettinen model are also shown in Fig. 56 for the same average $p_\perp$ values [Ab86]. We observe that the model underpredicts the polarization for almost all $p_\perp$ -bins, if we take into account the fact that the predictions are for directly produced Λ^0 , whilst the data are inclusive and there is a substantial contribution from indirectly produced Λ^0 with smaller polarization, rendering the measured values lower.

A qualitative description of the x_F -dependence of the Λ^0 polarization is given by Pondrom [Po85], based on the 'projectile straggling model' [He77, Hw84]. According to this model, the momenta of the valence and sea quarks of the incoming proton are degraded as the partons go through the nuclear matter. At high momenta, the degraded quarks combine outside the nucleus to form a Λ^0 . Since the straggling of the quarks in a heavy nucleus shifts high x_F to lower values, and since the Λ^0 polarization increases with increasing x_F , the polarization at a fixed x_F should increase in a heavy nucleus. This expectation is not in agreement with the observed trend, which shows a constant—if not decreasing—polarization with target mass. This may suggest the presence of a depolarization mechanism during the straggling, assuming that the s-quark is polarized when it is created inside the nucleus. If, however, the s-quark becomes polarized during the quark-combination process, which takes place outside the nucleus, then the Λ^0 polarization at a given x_F would not

depend on the mass of the target. Therefore, a possible A-dependence of the polarization may also be related to the question, When and where does the s-quark become polarized in the space-time development of the Λ^0 production from nuclei? There is no statistically significant answer to this problem as yet.

As in the case of the reaction $p-p \rightarrow \Lambda^0 + X$, the p-nucleus interaction exhibits a similar kinematic behaviour of the Λ^0 polarization. It is a simple simultaneous dependence on both x_F and $p_\perp$: for a certain x_F -value, the polarization increases with $p_\perp$ until approximately 1 GeV/c. For $p_\perp > 1$ GeV/c, the polarization is independent of $p_\perp$ and depends linearly on x_F (Fig. 55a). A schematic representation of this behaviour of the polarization as a function of both x_F and $p_\perp$ is shown in Fig. 55b [He85].

The energy independence of the Λ^0 polarization is shown in a comparison of the data at 12 GeV/c [Ab86] with the measurement at 400 GeV/c [He78]. Figure 57 compares the measurements in the common $p_\perp$ and x_F ranges. The excellent agreement between the two sets of data demonstrates the energy independence of the polarization in p-nucleus interactions. This feature is shown also in Fig. 58, where the polarization for a Be target is plotted versus laboratory momentum. The data points are from measurements in the range $1.15 \leq p_\perp \leq 1.58$ and $0.43 \leq x_F \leq 0.58$. A χ^2 fit gives $P = (0.7 \pm 0.1) \ln p_\perp - 26.3 \pm 2$. Within the error bars, there is no apparent dependence on the energy.

We shall close this section by briefly discussing two interesting observations. The polarization of $\bar{\Lambda}^0$ was measured in the p-Be interaction at 300 GeV/c [He78] and compared with that of Λ^0 , as a function of $p_\perp$ (Fig. 59). One observes a $\bar{\Lambda}^0$ polarization that is consistent with zero up to $p_\perp \approx 1.4$ GeV/c, as expected from the combination of the three sea antiquarks.

The polarization of heavier hyperons has also been measured in the p-Be interaction at 400 GeV/c [He81, He83]. Figure 60a shows the polarization of Λ^0 , Ξ^- , and Σ^+ as a function of the momentum at 5 mrad production angle. The Σ^+ has a polarization that is opposite in sign, but with magnitude in agreement with that of the other hyperons. Figure 60b shows the polarization of Λ^0 and Ξ^0 measured in the same reaction at 7.5 mrad production angle. The polarization of both inclusive hyperons is equal; however, the Λ^0 sample includes contributions from the Σ^0 decay. Therefore, the polarization of the Λ^0 is greater than that of the Ξ^0 . The striking agreement between Λ^0 , Ξ^0 , and Ξ^- polarizations, as well as the reversed sign of the Σ^+ polarization, is consistent with the gluon bremsstrahlung mechanism, in which the produced s-quarks are polarized [He78].

4.2.3 Summary of nucleon-nucleus results

The important conclusions, which are drawn from the study of the hyperon polarization in a wide range of energy, x_F , $p_\perp$, and target mass, could be summarized as follows:

- 1) All hyperons exhibit a transverse polarization; antihyperons are unpolarized.
- 2) The direction of polarization of the s-quarks is the same for all hyperons. The opposite sign of the polarization of the Σ hyperon is a consequence of the static quark wave functions.
- 3) The polarization is independent of the beam energy in the range between 12 and 400 GeV.
- 4) The $(x_F, p_\perp)$ dependence of the polarization is similar to the one observed in p-p interactions. For $p_\perp < 1$ GeV/c, the magnitude of the polarization depends on both x_F and $p_\perp$. For $p_\perp > 1$ GeV/c, it depends only linearly on x_F .
- 5) The $(x_F, p_\perp)$ -dependence of the polarization scales with energy in the 12 to 400 GeV range.
- 6) The polarization shows a weak target-mass dependence, its value becoming smaller with heavier nuclei. This is most probably the result of the secondary production of Λ^0 through the π -N interaction.
- 7) The DeGrand-Miettinen model underpredicts the $(x_F, p_\perp)$ -dependence of the polarization for all values of the variables.

4.3 Nucleus–nucleus interaction

The production and study of Λ^0 hyperons in nucleus–nucleus interactions has only recently been successful, with the availability of heavy ion beams at energies above the Λ^0 production threshold of 1.58 GeV for the $N-N \rightarrow \Lambda^0 KN$ channel. There are very few measurements of the Λ^0 polarization in nucleus–nucleus reactions, and these are in the momentum range 1.8 to 4.5 GeV/c per nucleon and for beams ranging from helium to argon. These few measurements suffer from large statistical errors, which makes it rather difficult to achieve a precise quantitative comparison and evaluation between them and with hadron-induced polarization data. A more qualitative discussion of the results will therefore have to suffice.

As in the case of nucleon–nucleus interaction—but much more so here—the Λ^0 may be produced by the elementary $N-N$ interaction, as well as by the secondary $\pi-N$ interaction in the bulk of the nuclear matter. The Λ^0 polarization is therefore expected to have features similar to those discussed in $p-A$ interactions, as a function of x_F . That is, at $x_F < 0$ the polarization of the inclusive Λ^0 should be approximately zero (depending on the relative cross-sections of the direct and secondary Λ^0 's), whilst at $x_F > 0$ it should be negative but reduced in magnitude, compared with the $p-p$ interaction.

Harris et al. reported the first Λ^0 polarization measurement in the $Ar + KCl$ inclusive reaction (central collisions) at a beam energy of 1.8 GeV per nucleon, just above the $N-N \rightarrow \Lambda^0 KN$ threshold [Ha81]. A streamer chamber at the LBL Bevalac was used for the measurement, covering the rapidity range $0 < y < 1.34$. They observed that most of the Λ^0 's are located outside the $N-N \rightarrow \Lambda^0 KN$ kinematic phase space. They attributed this to the Fermi motion and to collective multiparticle interactions, which are important at their low beam energy and small phase space. The quoted average value of the Λ^0 polarization in their rapidity range and for $\langle p_\perp \rangle = 0.49$ GeV/c, extracted from this measurement using $\alpha = -0.642$, is $P = -0.10 \pm 0.05$. The negative value for the analysing power α and the negative sign of the polarization suggest that Harris et al. have used a polarization convention opposite to ours.

Anikina et al. have reported Λ^0 polarization measurements at 4.5 GeV/c per nucleon, in C- and O-induced reactions on several nuclei ranging from carbon to lead [An84]. The measurements were done with the SKM-200, a 2 m neon streamer chamber. The solid targets were mounted inside the chamber, allowing full 4π coverage of the event. Figure 61 shows the transverse momentum versus rapidity for the produced Λ^0 for several targets. The kinematic limits for the reaction channels $N-N \rightarrow \Lambda^0 KN$ and $N-N \rightarrow \Lambda^0 KN\pi$ are denoted by the solid and dashed curves, respectively. Anikina et al. found the majority (about 80%) of the Λ^0 's within the $N-N$ phase-space limit, in contrast to the findings of [Ha81]. Another study of the $C + Ta$ reaction at 4.2 GeV/c per nucleon has found 40% of the Λ^0 's to be beyond the free $N-N$ phase-space limit [Ak82]. Therefore, it is not conclusive what per cent of the Λ^0 's are products of secondary interactions or have their kinematics influenced by other effects.

It should be noted that in nucleus–nucleus collisions it is not correct to work in the $N-N$ frame, but rather in a new effective system ($N + nN$), where n is the number of target participant nucleons per incident nucleon. The value of n depends on the masses of both the target and the projectile and could be realistically calculated by the ‘clean-cut geometry’ model. This model leads to a simple relation predicting the number of participating target nucleons per incident projectile nucleon for central collisions:

$$n = c(A_{\text{targ}}/A_{\text{proj}})^{1/3}, \quad (4.13)$$

where $c \simeq 1.5$; for a single incident nucleon, $c \simeq 1.1$. This effect is seen clearly in the shift of the rapidity distribution to lower values of rapidity with increasing target mass, following the corresponding decrease of ‘ $y_{\text{mid-rapidity}}$ ’ (Fig. 62 [An84]).

In [An84] the calculation of the polarization was performed for the total sample of the data within the N–N kinematic limit, separated into two transverse momentum bins: $p_{\perp} < 0.5$ GeV/c and $p_{\perp} \geq 0.5$ GeV/c. The values are given in Table 7, together with those of other measurements; Fig. 63 shows the data of this table. The average Λ^0 polarization is plotted as a function of the average value of $p_{\perp}$ (in the $p_{\perp}$ -bins in which the data are grouped) for the different reactions. Despite the large errors, a negative polarization is seen at $\langle p_{\perp} \rangle > 0.6$ GeV/c. The polarization for lower transverse momenta is inconclusive owing to the large statistical errors, with a tendency, however, for a positive value.

Another study of the Λ^0 polarization in C+C and C+Ta reactions at 4.2 GeV/c per nucleon reports polarization values similar to those of [An84] in the two transverse-momentum bins $p_{\perp} \leq 0.4$ GeV/c and $p_{\perp} > 0.4$ GeV/c [Io87]. The results are given in Table 7 and included in Fig. 63. Finally, a recent measurement of the Λ^0 polarization in the reaction $^{32}\text{S} + ^{32}\text{S}$ at 200 GeV per nucleon has given a preliminary polarization value of about zero in the target fragmentation region [Ba89].

Summarizing the very few Λ^0 polarization measurements in nucleus–nucleus interactions and the predictions based on known systematics, we may conclude that

- i) the polarization measured is the combined (net) value of the polarization of the direct Λ^0 (produced by the elementary N–N interaction) and the secondary Λ^0 (produced mainly by the pion–nucleus interaction);
- ii) the average polarization of Λ^0 within the N–N kinematic limit is negative for $p_{\perp} > 0.5$ GeV/c. For lower transverse momenta, there is a tendency towards zero or even positive values.

4.4 Global systematics and summary

From the discussion of hadron–nucleon and hadron–nucleus reactions it has become apparent that the Λ^0 polarization is due to an interaction on the parton level. As such, we can describe and predict the observed polarization according to the following general rules, independent of the particulars of the interacting system.

1) The Λ^0 is always polarized when formed by the recombination of a *valence* diquark (leading constituent) and a *sea* s-quark. The polarization is negative in the fragmentation hemisphere of the diquark, with respect to the axis perpendicular to the scattering plane, defined by the momenta of the diquark and the Λ^0 :

$$\mathbf{n} = \frac{(\mathbf{p}_{\text{diquark}} \times \mathbf{p}_{\Lambda^0})}{|(\mathbf{p}_{\text{diquark}} \times \mathbf{p}_{\Lambda^0})|}. \quad (4.14)$$

This rule covers all hadron–nucleon, hadron–nucleus, and nucleus–nucleus interactions. There may be a possible exception to this rule, namely the $\pi^+p \rightarrow \Lambda^0$ interaction, in which the only measurement of the inclusive Λ^0 polarization at 18.5 GeV/c gives a zero value at $x_F < 0$, while a positive value is expected (Fig. 31) [St74]). It is more probable, however, that other competing processes cause this result, as in the case of $K^+p \rightarrow \Lambda^0$. [Note that the polarization convention of relation (4.14) is opposite to the one assumed in the previous discussions.] New measurements at several lower energies and with better statistics will be very interesting, since there is no obvious reason for zero polarization in this case.

2) The Λ^0 is polarized when it is formed by the recombination of a *valence* s-quark (leading constituent) and a diquark. The polarization is positive in the fragmentation hemisphere of the s-quark, with respect to the axis perpendicular to the scattering plane, defined by the momenta of the s-quark and the Λ^0 :

$$\mathbf{n} = \frac{(\mathbf{p}_{\text{s-quark}} \times \mathbf{p}_{\Lambda^0})}{|(\mathbf{p}_{\text{s-quark}} \times \mathbf{p}_{\Lambda^0})|}. \quad (4.15)$$

This rule is applicable in the inclusive production of Λ^0 ($\bar{\Lambda}^0$) by the K^- (K^+)-nucleon interaction.

3) The Λ^0 is *unpolarized* when formed by the recombination of three sea quarks, since in this case there is no preferred direction and hence no unique scattering plane.

Regarding the magnitude of the polarization, this is given approximately by the relation

$$|P| = c[1 - \exp(-p_\perp/1.8)] \approx \text{const } p_\perp. \quad (4.16)$$

This x_F -independent empirical relation holds true at all energies and for all reactions studied so far, at least up to $p_\perp = 1 \text{ GeV}/c$. At higher $p_\perp$ values, and for nucleon-induced reactions in particular, the magnitude of the polarization is only a function of x_F .

With respect to the theoretical model predictions of the Λ^0 polarization, there is still no adequate theory which could describe, from first principles, the observed phenomena and quantitatively predict the magnitude of the polarization. The semiclassical models discussed can only qualitatively be compared with some data, without the possibility of a global application. Despite these limitations, it is interesting to see how the different basic assumptions of the models can give similar predictions for some cases of the observed polarization. The possible existence of a common underlying element in these models may form the basis for a new treatment within the framework of the Standard Model.

On the experimental front, additional high-statistics data with good coverage in $p_\perp$ and x_F will be very helpful for clarifying certain obscure and inconclusive cases of Λ^0 polarization, such as

- the inclusive $\pi^+ - p \rightarrow \Lambda^0 + X^{++}$ and $K^+ - p \rightarrow \Lambda^0 + X^{++}$ interactions in the target hemisphere;
- the inclusive $K^\pm - p \rightarrow \Lambda^0 + X$ interactions as a function of the beam energy;
- hadron-nucleus reactions in both the target and projectile hemispheres, to clarify the extent of the contribution of secondary produced Λ^0 ;
- nucleus-nucleus reactions in both hemispheres at relativistic and ultrarelativistic energies, to study the contribution of secondary production and also the influence of the thermalized hadronic-matter 'fireball' on the Λ^0 polarization.

In addition, new measurements should be made in order to extend previous ranges:

- in energy, to make a further test of the energy dependence of the polarization; $p\bar{p}$ measurements at $\sqrt{s} = 546$ and 900 GeV (at the CERN $p\bar{p}$ Collider) and at 1.8 TeV (at the FNAL Tevatron) will provide valuable information;
- in transverse momentum, to further test the QCD predictions for zero polarization at high transverse momenta ($p_\perp \approx 3\text{--}5 \text{ GeV}/c$);
- of hyperon species, in particular the multistrange hyperons Ξ and Ω^- , in a wide ($p_\perp, x_F$) range. For the Ω^- hyperon, the predicted polarization in the $p \rightarrow \Omega^-$ transition is zero, owing to the lack of spin-flavour ordering of the three s-quarks in the wave function of the proton before combination into the Ω^- [De85]. In order to produce a polarized Ω^- , it is necessary to have a strange-particle beam (with leading s-quarks), so that the possibility of spin-flavour rapidity correlations can exist.
- Strange-particle beams will be very useful for the study of various s-quark recombination cases. In particular, polarized hyperon beams (Λ^0, Ξ^0) are of paramount importance for the production of polarized Ω^- [De85].

New measurements may provide answers to the following additional questions:

- Is the Λ^0 polarization greater when measured with respect to the $\Lambda^0 K^+$ plane rather than the Λ^0 production plane, in either diffractive or inclusive production?
- Can the longitudinal Λ^0 polarization be used effectively as a probe of heavy-flavour decay?
- Does the Λ^0 polarization depend on various reaction parameters, such as particle multiplicity etc.?

All these measurements will provide interrelated systematics and will fill in the experimental picture of the Λ^0 polarization, which still remains a puzzle for theory.

5. Λ^0 POLARIZATION AS A SIGNAL OF QUARK MATTER IN NUCLEUS-NUCLEUS INTERACTIONS

A great deal of interest and enthusiasm has recently been directed towards the possible creation of the quark-gluon plasma (QGP), the primordial state of matter, which existed only up to a few microseconds after the cosmogenic Big Bang. The essential conditions for the formation of the QGP are high energy density ($\epsilon \approx 2\text{--}3 \text{ GeV/fm}^3$) and temperature ($T \approx 150\text{--}200 \text{ MeV}$) in an extended volume, conditions that can be achieved in nucleus-nucleus central collisions at ultrarelativistic energies.

Among the possible signals suggested for the identification of the created QGP, a change in the state of the Λ^0 polarization has been proposed [Pa86, Ja87, Ja88]. The first reference considers the effect that the QGP may have on the state of the transverse polarization of the hadronized Λ^0 , whilst the others discuss the effect on the longitudinal polarization. We shall examine each case separately in some detail.

5.1 Transverse polarization

In the p-p and p-A interactions that we have discussed, the number of participating nucleons is just the very few interacting in the primary collisions. Furthermore, the size of the interaction region is considerably smaller than the nuclear size, too small to be able to speak of a QGP confined in an extended volume. In addition, even the most energetic of the interactions in which the polarization was measured, cannot provide the necessary conditions (energy density and temperature) for the formation of the QGP. (In p-p interactions for example at $\sqrt{s} = 62 \text{ GeV}$, the energy density is approximately 0.5 GeV/fm^3). The A-A interactions at 4.5 GeV/c are also at too low an energy for the creation of abundant quark matter, even though the full nuclear stopping could create conditions of large nuclear-matter density.

It is therefore interesting to examine the state of the Λ^0 polarization in ultrarelativistic nucleus-nucleus collisions where it is conjectured that a phase transition to quark matter may occur [Qu82]. There is a speculation that a phase transition may be accompanied by symmetry breaking—reflected in a change of the Λ^0 polarization anisotropy—under the assumption that the Λ^0 is formed by the recombination of uncorrelated quarks or sea quarks. Since the polarization is predominantly a ‘kinematic’ effect, in a QGP any memory of direction or polarization of the quarks is erased.

Before examining the polarization, we should note that there are basically two ways of forming the QGP:

- i) by vacuum excitation in the central rapidity region, in nucleus-nucleus collisions at ultra-high energies ($\sqrt{s}$ per nucleon of the order of 200 GeV [Pa89]), and probably in p-p interactions at $\sqrt{s} \geq 1 \text{ TeV}$;
- ii) by ‘nucleon melting’ in the mid-rapidity region, in central collisions of heavy nuclei at $\sqrt{s}$ per nucleon greater than several GeV .

In the first case, the Λ^0 of interest is produced and emitted from the central rapidity zone, which is fairly well separated from the two fragmentation regions ($\Delta y = \pm 1\text{--}2$). These Λ ’s are formed through the combination of independent, slow sea (u,d,s)-quarks [Ca79], and will be emitted via an evaporation-like process. In most respects, the mechanism of creation and the properties of QGP Λ ’s are the same as those of the Λ^0 ’s produced in the e^+e^- annihilation process [Al85]. Furthermore, the colour field in the QGP could possess transverse momenta, which would provide $p_\perp$ to the $s\bar{s}$ pair, thereby destroying the (polarization-producing) correlation between the ‘inherent’ transverse momentum and the spin of the s-quark. This correlation arises from local conservation of momentum in the string force field [An79].

Therefore, the Λ^0 's created from the QGP at mid-rapidity are expected to exhibit zero polarization, in contrast to those in the fragmentation regions (formed through normal hadronic interactions), which should possess negative polarization. It will be very interesting to measure and compare the Λ^0 polarization in the inclusive $p\text{-}\bar{p} \rightarrow \Lambda^0$ interaction at $\sqrt{s} = 900$ GeV [An89], in the rapidity intervals: $|\Delta y| < 1$ and $|\Delta y| > 1$, since there is a suggestion that QGP through vacuum excitation may begin at energies above $\sqrt{s} = 500$ GeV [Pa89].

In the case of quark-matter formation through 'nucleon melting' in central collisions of heavy nuclei, the Λ^0 produced in the mid-rapidity region will also have the same characteristics as those of the former case. Here, however, the experimental situation is more difficult, since the separation of the central (quark-matter 'fireball') and fragmentation regions is not so well established. The presence also of secondary interactions, which may overlap in rapidity with the primary ones creating the QGP, may obscure the effect.

5.2 Longitudinal polarization

In the case of hot and dense nuclear matter transforming to QGP, where the change of the transverse Λ^0 polarization state may not give an unambiguous signal, the study of the longitudinal polarization of the $\bar{\Lambda}^0$ has been proposed [Ja87, Ja88]. It is argued that in this region an abundant creation of multistrange baryons is expected, yielding a ratio of the relative abundances of $\bar{\Xi}(\bar{s}\bar{s}\bar{q})/\bar{Y}(\bar{s}\bar{q}\bar{q}) \approx 1/2$. This ratio, when compared with the corresponding value of 0.06 ± 0.02 in the $p\text{-}p$ interactions at $\sqrt{s} = 62$ GeV, suggests that the QGP state would yield a ratio up to ten times greater.

An indirect way of measuring this ratio is through the change of the longitudinal polarization state of the $\bar{\Lambda}^0$. This change is caused by the weak decay of the $\bar{\Xi} \rightarrow \bar{\Lambda}^0 + \pi$. If the $\bar{\Xi}$ is unpolarized, parity violation in the $\bar{\Xi}$ decay will induce a non-vanishing longitudinal polarization in the $\bar{\Lambda}^0$, the mean value of its helicity being given by the $\bar{\Xi}$ decay asymmetry parameter $\alpha_{\bar{\Xi}}$. In the subsequent weak $\bar{\Lambda}^0$ decay this polarization is analysed, yielding observable effects (asymmetry). The antiproton asymmetry distribution in the $\bar{\Lambda}^0$ rest frame, correlated with the $\bar{\Lambda}^0$ momentum in the $\bar{\Xi}$ rest frame, is given by the relation

$$dN/d\Omega = 1/4\pi [1 + \alpha_{\bar{\Lambda}^0} \alpha_{\bar{\Xi}} (\mathbf{p}_{\bar{\Lambda}^0} \cdot \mathbf{p}_{\bar{\Xi}})] , \quad (5.1)$$

where $\mathbf{p}_{\bar{\Lambda}^0}$ and $\mathbf{p}_{\bar{\Xi}}$ are the momentum of the $\bar{\Lambda}^0$ and $\bar{\Xi}$, respectively. We note that the $\bar{\Xi}^0$ and $\bar{\Lambda}^0$ are totally unpolarized, since they are formed from sea antiquarks. The $\bar{\Lambda}^0$ produced indirectly through the $\bar{\Xi}$ weak decay acquires a longitudinal polarization but no transverse.

The longitudinal polarization asymmetry is measured with respect to a plane perpendicular to the momentum of the $\bar{\Lambda}^0$. This asymmetry is given by [Ja87]

$$(N_{\uparrow} - N_{\downarrow})/(N_{\uparrow} + N_{\downarrow}) = 1/2 [\langle \bar{\Xi} \rangle / \langle \bar{V} \rangle] \alpha_{\bar{\Lambda}^0} \alpha_{\bar{\Xi}} , \quad (5.2)$$

where the quantity in square brackets is the relative abundance of all polarized $\bar{\Lambda}^0$ to the total abundance of 'V' decay patterns, $\alpha_{\bar{\Lambda}^0} = -0.642$ and $\alpha_{\bar{\Xi}} = 0.456$ are the $\bar{\Lambda}^0$ and $\bar{\Xi}^-$ decay parameters, respectively. Assuming the ratio $\bar{\Xi}/\bar{Y}$ to be approximately 1/2, relation (5.2) gives a polarization asymmetry of about 7%. The same effect in the $p\text{-}p$ interaction at $\sqrt{s} = 62$ GeV gives a 1.6% asymmetry, which appears to be independent of the beam energy in the range 62 to 900 GeV [An89]. Therefore, the QGP may cause an apparent longitudinal polarization on the $\bar{\Lambda}^0$, which is about five times larger than the corresponding polarization expected in normal hadronic interactions that do not produce QGP. In absolute terms this is not, however, a very large effect, and it may easily be lost in the statistics.

It should also be noted that, as discussed in subsection 3.2, the longitudinal polarization could be influenced by the precession of the $\bar{\Lambda}^0$'s magnetic moment under the action of the magnetic field of a sweeping magnet. This effect will depend on the precession angle ψ and should be taken into account when evaluating the polarization. Therefore, in order to apply this QGP signal meaningfully, a very high precision, high-statistics experiment must be done, measuring the longitudinal polarization of the $\bar{\Lambda}$'s only. The Λ sample, the bulk of which comes from direct and secondary interactions, is prone to having 'residual' longitudinal polarization, irrespective of the Ξ decay. This will obscure the already small effect.

6. CONCLUSIONS

The study of hyperon production and polarization is very interesting and important. It offers an excellent and precise method of probing the mechanisms of particle production and polarization by using the strange quark(s) as a tracer. Spin characteristics may be observed in their weak decay, since the parity-violating weak interaction automatically reveals the hyperon's polarization. Much interesting physics remains to be done in the study of spin effects in high energy and relatively small transverse-momentum reactions. Polarization asymmetries have been observed to be strong, and more surprising effects may be seen in the future.

Despite intensive research during the past fifteen years, we are, however, still lacking a serious understanding of the subtle dynamical origin of these important phenomena. This is a clear case where experiment is far ahead of theory. Several attempts to estimate spin effects in hadron processes in the framework of perturbative QCD have predicted polarizations that are about one order of magnitude smaller than those experimentally observed, i.e. consistent with zero [Dr80, Ef82].

On the other hand, the simple semiclassical models for quark polarization, based on analogy with QED and explaining at least qualitatively the observed polarizations, can give only some hints for a new theory of soft processes, presumably non-perturbative QCD. It is hoped that new experimental measurements of particular exclusive cases will provide definitive tests of the current models and help in the formation of a non-perturbative QCD theory.

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Table 1

Λ^0 polarization predicted by the DeGrand-Miettinen model for several beam particles, with respect to the axis perpendicular to the scattering plane

Hadron $\rightarrow \Lambda^0$ transition	Λ^0 polarization
$p, n \rightarrow \Lambda^0$	Negative (strong)
$p, n \rightarrow \bar{\Lambda}^0$	Zero
$K^- \rightarrow \Lambda^0$	Positive (strong)
$K^+ \rightarrow \bar{\Lambda}^0$	Positive (strong)
$\pi, K^+ \rightarrow \Lambda^0$	Negative (weak)

Table 2

Summary of Λ^0 polarization measurements in the reaction $K^- - p \rightarrow \Lambda^0 + \pi$'s

Beam momentum (GeV/c)	Λ^0 polarization		Polarization convention ($\mathbf{n} = \mathbf{p}_{K^-} \times \mathbf{p}_{\Lambda^0}$)	Ref.
	$x_F < 0$	$x_F > 0$		
3.93	+	-	$\mathbf{p}_{\Lambda^0} \times \mathbf{p}_{K^-} = -\mathbf{n}$	[Bo74]
4.2	+	-	$\mathbf{p}_p \times \mathbf{p}_{\Lambda^0} = -\mathbf{n}$	[Ga78]
4.2	-	+	$\mathbf{p}_{K^-} \times \mathbf{p}_{\Lambda^0} = \mathbf{n}$	[Ma77]
7.3	+	-	$\mathbf{p}_p \times \mathbf{p}_{\Lambda^0} = -\mathbf{n}$	[Ch75]
8.25	+	-	Unspecified	[Ba79]
8.25	+	-	$\mathbf{p}_p \times \mathbf{p}_{\Lambda^0} = -\mathbf{n}$	[Al81]
10	0	-	$\mathbf{p}_{\Lambda^0} \times \mathbf{p}_{K^-} = -\mathbf{n}$	[Ba72]
10+16	0	-	$\mathbf{p}_p \times \mathbf{p}_{\Lambda^0} = -\mathbf{n}$	[Gr78]
13	0	-	$\mathbf{p}_{\Lambda^0} \times \mathbf{p}_{K^-} = -\mathbf{n}$	[Ba73]
14.3	0	-	$\mathbf{p}_{\Lambda^0} \times \mathbf{p}_{K^-} = -\mathbf{n}$	[Bo74]
12+16		+	$\mathbf{p}_{K^-} \times \mathbf{p}_{\Lambda^0} = \mathbf{n}$	[Ar85]
32	0	-	Unspecified	[Fa79]
				[Ge80]
110 ^{a)}		+	$\mathbf{p}_p \times \mathbf{p}_{\Lambda^0} = -\mathbf{n}$	[Ha85]
176		-	$\mathbf{p}_{\Lambda^0} \times \mathbf{p}_{K^-} = -\mathbf{n}$	[Go86]

a) The polarization measured in this reference has opposite sign to the systematics and the convention (see text for discussion).

Table 3

Summary of Λ^0 polarization measurements in the reaction $K^-p \rightarrow \Lambda^0 K \bar{K} + \pi's$

Beam momentum (GeV/c)	Λ^0 polarization		Polarization convention ($\mathbf{n} = \mathbf{p}_{K^-} \times \mathbf{p}_{\Lambda^0}$)	Ref.
	$x_F < 0$	$x_F > 0$		
4.2	—	$0 \approx -$	$\mathbf{p}_p \times \mathbf{p}_{\Lambda^0} = -\mathbf{n}$	[Ga78]
32	+	$0 \approx -$	Unspecified	[Ge80]
110 ^{a)}	$+ \rightarrow -$		$\mathbf{p}_p \times \mathbf{p}_{\Lambda^0} = -\mathbf{n}$	[Ha85]

a) The polarization measured in this reference has opposite sign to the systematics and the convention (see text for discussion).

Table 4

Summary of $\bar{\Lambda}^0$ polarization measurements in the reaction $K^+p \rightarrow \bar{\Lambda}^0 + X^{++}$

Beam momentum (GeV/c)	$\bar{\Lambda}^0$ polarization		Polarization convention ($\mathbf{n} = \mathbf{p}_{K^+} \times \mathbf{p}_{\bar{\Lambda}^0}$)	Ref.
	$x_F < 0$	$x_F > 0$		
13	0	0	$\mathbf{p}_{\bar{\Lambda}^0} \times \mathbf{p}_{K^+} = -\mathbf{n}$	[Ba73]
32	0	—	Unspecified	[Fa79]
32,70	0	+	$\mathbf{p}_{K^+} \times \mathbf{p}_{\bar{\Lambda}^0} = \mathbf{n}$	[Aj83]
70		—	$\mathbf{p}_{\bar{\Lambda}^0} \times \mathbf{p}_{K^+} = -\mathbf{n}$	[Ba81]

Table 5

Summary of Λ^0 polarization measurements in the reaction $K^+p \rightarrow \Lambda^0 + X^{++}$

Beam momentum (GeV/c)	Λ^0 polarization		Polarization convention ($\mathbf{n} = \mathbf{p}_{K^+} \times \mathbf{p}_{\Lambda^0}$)	Ref.
	$x_F < 0$	$x_F > 0$		
13	—	0	$\mathbf{p}_{\Lambda^0} \times \mathbf{p}_{K^+} = -\mathbf{n}$	[Ba73]
8.2,16		0	Unspecified	[Ch76]
32	0	0	Unspecified	[Fa79]
70	0	0	$\mathbf{p}_{\Lambda^0} \times \mathbf{p}_p = \mathbf{n}$	[Ba81]

Table 6

Summary of Λ^0 polarization measurements in the reaction $\pi^-p \rightarrow \Lambda^0 + X$

Beam momentum (GeV/c)	Λ^0 polarization		Polarization convention ($\mathbf{n} = \mathbf{p}_{\pi^-} \times \mathbf{p}_{\Lambda^0}$)	Ref.
	$x_F < 0$	$x_F > 0$		
3.95	—	0	$\mathbf{p}_{\Lambda^0} \times \mathbf{p}_{\pi^-} = -\mathbf{n}$	[Ad84]
15	—		$\mathbf{p}_{\Lambda^0} \times \mathbf{p}_{\pi^-} = -\mathbf{n}$	[Ba78]
16		0	Unspecified	[Be83]
18.5	+	0	$\mathbf{p}_{\pi^-} \times \mathbf{p}_{\Lambda^0} = \mathbf{n}$	[St74]
100,200,300	+		$\mathbf{p}_{\pi^-} \times \mathbf{p}_{\Lambda^0} = \mathbf{n}$	[Bi80]
3–6 ^{a)}	+		Unspecified	[Wa77]
4, 6.2 ^{a)}	+		Unspecified	[Be70]

a) The Λ^0 polarization is measured in the semi-inclusive reaction $\pi^-p \rightarrow \Lambda^0 K^0 + X$

Table 7

Summary of Λ^0 polarization measurements in nucleus–nucleus $\rightarrow \Lambda^0 + X$

System	Beam momentum (per particle)	$p_\perp$ bins	Rapidity range	Polarization	Ref.
C + C	4.2 GeV/c	≤ 0.4		0.23 ± 0.2	[Io87]
		> 0.4		-0.36 ± 0.17	"
C + Ta	4.2 GeV/c	≤ 0.4		0.28 ± 0.41	"
		> 0.4		-0.45 ± 0.39	"
C + C	4.5 GeV/c	≤ 0.5	$0.6 \leq y \leq 2.2$	-0.03 ± 0.22	[An84]
		> 0.5	"	-0.36 ± 0.2	"
O + Pb	4.5 GeV/c	≤ 0.5	$0.4 \leq y \leq 2.2$	0.42 ± 0.5	"
		> 0.5	"	-0.40 ± 0.29	"
Ar + KCl	1.8 GeV	$= 0.49$		-0.10 ± 0.05	[Ha81]

Figure captions

- Fig. 1 Kinematics and momenta of the $s\bar{s}$ pair created in the colour force field. The orbital angular momentum is in the direction $\mathbf{L} = [\mathbf{q} \times \mathbf{k}_\perp / |\mathbf{q} \times \mathbf{k}_\perp|]$, out of the page [An79].
- Fig. 2 Momentum vectors for the s-quark in the scattering plane: s/p, in the proton (sea); s/ Λ^0 , in the Λ^0 (valence). The recombination force is along the beam direction and the Thomas frequency $\omega_\perp$ is out of the scattering plane [De81].
- Fig. 3 The gluon bremsstrahlung mechanisms in N-N interactions [He78].
- Fig. 4 A typical fixed-target electronic detector [Ab84a].
- Fig. 5 The R606 spectrometer at the CERN ISR, and front view.
- Fig. 6 Invariant mass reconstruction for Λ^0 [Ab87].
- Fig. 7 Λ^0 detection efficiency of the KEK spectrometer [Ab87].
- Fig. 8 Kinematics in the centre-of-mass system for the reaction $p\text{-}p \rightarrow \Lambda^0 + X$ in the $p_\perp$ versus $p_\parallel$ plane. Also shown is the corresponding x_F variable; θ is the laboratory production angle of the Λ^0 .
- Fig. 9 Momentum vector diagram of Λ^0 decay. The y-axis is perpendicular to the scattering plane.
- Fig. 10 Acceptance-corrected Λ^0 decay distribution; θ_p is the proton emission angle and the line is a linear fit through the data [Sc85]. The ordinate has units 10^3 .
- Fig. 11 Precession of Λ^0 magnetic moment in the magnetic field of a sweeping magnet. The beam momentum is along the z-axis and the Λ^0 polarization vector is along the y-axis.
- Fig. 12 Invariant x_F distribution of the Λ^0 for three energies [Ge80].
- Fig. 13 Dependence of total Λ^0 cross-section on the beam momentum for two reaction channels [Ge80].
- Fig. 14 Energy dependence of the Λ^0 production in the semi-inclusive $K^-p \rightarrow \Lambda^0 K \bar{K} + \pi$'s and inclusive $K^-p \rightarrow \Lambda^0 + X$ reactions. The line is to guide the eye [Ha85].
- Fig. 15 Quark diagrams for the reactions $K^-p \rightarrow \Lambda^0 + \pi$'s and $K^-p \rightarrow \Lambda^0 K \bar{K} + \pi$'s.
- Fig. 16 Frequently used polarization conventions. The normal to the scattering plane is into or out of the page.
- Fig. 17 The $p_\perp$ -dependence of Λ^0 polarization in the $K^-p \rightarrow \Lambda^0 + X$ reaction in the proton hemisphere (a) and in the $K^-p \rightarrow \Lambda^0 + \pi$'s in the kaon hemisphere (b). The data are adapted to our polarization convention.
- Fig. 18 The x_F -dependence of Λ^0 polarization in the projectile hemisphere at several incident energies [Ha85]. The sign of the different measurements is adapted to our convention.
- Fig. 19 a) Comparison of the data with predictions at $x_F = 0.8$. b) Comparison of the data with predictions at $p_b = 14$ GeV/c. Strange-quark scattering model as developed by Gago [Ga87].
- Fig. 20 The x_F -dependence of Λ^0 polarization in the two processes at 4.2 GeV/c [Ga78].
- Fig. 21 The $p_\perp$ -dependence of Λ^0 polarization in the two processes at 4.2 GeV/c in the target hemisphere, $-1 < x_F < -0.2$ [Ga78].
- Fig. 22 The dependence of the Λ^0 polarization on the centre-of-mass energy $\sqrt{s}$ in the target (a) and projectile (b) hemispheres [Ha85].
- Fig. 23 Invariant x_F -distributions, integrated over $p_\perp^2$, for Λ^0 and $\bar{\Lambda}^0$ in K^+p interactions [Ch77].
- Fig. 24 The x_F -dependence of the polarization of $\bar{\Lambda}^0$ (a), and Λ^0 (b) in the K^+p interaction at several energies.
- Fig. 25 Differential invariant cross-section for the inclusive reaction $\pi^-p \rightarrow \Lambda^0 + X$ at two energies [Ad84].
- Fig. 26 Energy dependence of the inclusive $\pi^-p \rightarrow \Lambda^0 + X$ reaction cross-section [Ad84].

- Fig. 27 Differential rapidity distributions for the inclusive reactions $\pi^\pm \rightarrow \Lambda^0 (\bar{\Lambda}^0) + X$ at 18.5 GeV/c [St74].
- Fig. 28 The $p_\perp$ -dependence of the Λ^0 polarization in the π^- -p inclusive interaction, in the target and projectile hemispheres [Ad84].
- Fig. 29 The x_F -dependence of the Λ^0 polarization in the inclusive π^- -p interaction for two incident momenta.
- Fig. 30 The Λ^0 polarization in the target fragmentation region for the reactions $K^-p \rightarrow \Lambda^0 K \bar{K} + X$ and $\pi^-p \rightarrow \Lambda^0 + X$ [Ga78, Ad84].
- Fig. 31 a) x_F and b) $|t - t_{\min}|$ dependence of Λ^0 polarization in the inclusive $\pi^\pm$ -p reactions at 18.5 GeV/c [St74].
- Fig. 32 Λ^0 polarization in the p-p interaction as a function of $p_\perp$. The open triangle point comes from non- Λ^0 (π^- -p) pairs with $p_\perp > 0.6$ GeV/c [Er79].
- Fig. 33 Λ^0 polarization versus $p_\perp$ for fixed x_F -bins in the inclusive p-p interaction at $\sqrt{s} = 62$ GeV [Sm87].
- Fig. 34 a) $p_\perp$ and b) x_F -dependence of inclusive Λ^0 polarization in the p-p interaction [Aa78].
- Fig. 35 The x_F -dependence of the Λ^0 polarization at $p_\perp > 0.96$ GeV/c in the p-p interaction at three energies.
- Fig. 36 The dependence of Λ^0 polarization on incident energy in the p-p interaction for three ($p_\perp$, x_F)-bins. The lines are drawn through the average polarization values for each bin [Sm87].
- Fig. 37 The $p_\perp$ -dependence of the Λ^0 polarization in inclusive p-N interactions at several energies. The data points have their ($p_\perp$, x_F) values properly matched [He85].
- Fig. 38 a) Lund model and b) DeGrand-Miettinen model predictions for the inclusive Λ^0 polarization as a function of $p_\perp$, compared with the data in the p-p interaction at $\sqrt{s} = 62$ GeV [Sh88].
- Fig. 39 Comparison of the DeGrand-Miettinen model predictions for the Λ^0 polarization with data from the inclusive p-p interaction at 400 GeV: a) fixed x_F , b) fixed $p_\perp$.
- Fig. 40 Invariant Λ^0 cross-section as a function of x_F in the $\bar{p}$ -p interaction at 4.5 GeV/c [No84].
- Fig. 41 The $p_\perp$ -dependence of Λ^0 polarization in $\bar{p}$ -p interactions at three energies, in the target fragmentation region [No84].
- Fig. 42 a) $p_\perp$ and b) x_F -dependence of the Λ^0 polarization in the reactions $K^-p \rightarrow \Lambda^0 K \bar{K} + \pi^0$'s and $\bar{p}p \rightarrow \Lambda^0 + X$.
- Fig. 43 Kinematics of Λ^0 and $\bar{\Lambda}^0$ production and polarization in terms of the recombination parton model.
- Fig. 44 The ratio $(\alpha P/|\alpha|)$ of inclusive Λ^0 and $\bar{\Lambda}^0$ versus $p_\perp$ [Ch85].
- Fig. 45 Distribution of missing mass m_X versus Λ^0 in $\bar{p}$ -p at 4 GeV/c [No84].
- Fig. 46 Λ^0 polarization as a function of $p_\perp$ for $m_X < 1.58$ GeV/c² (a) and $m_X > 1.58$ GeV/c² (b), and as a function of m_X for $p_\perp > 0.4$ GeV/c (c), in the $\bar{p}$ -p interaction at 4 GeV/c [No84].
- Fig. 47 The Λ^0 polarization as a function of m_X^2/s for $|u| < 2$ GeV², in K^-p interactions [Ab76].
- Fig. 48 Invariant cross-section for the $\pi^-(C+F+Cl)$ (•) and π^-C (—) reactions versus x_F [Go78].
- Fig. 49 The x_F distributions of Λ^0 in π^-A interactions at 40 GeV/c. The histograms are the predictions of the DTU model [Ba88].
- Fig. 50 a) Λ^0 invariant cross-section versus $(x_0 - x_F)$ for several $p_\perp$ values. For a discussion, see the text. b) The variation of the power $m(p_\perp)$ with A in relation (4.10) versus $p_\perp$ [Ab87].
- Fig. 51 Rapidity distribution of Λ^0 production in $\bar{p}$ -Ta. The arrow indicates the mid-rapidity in the $\bar{p}$ -p system [Mi84]. The dashed line shows a symmetric curve for the distribution.

- Fig. 52 The Λ^0 polarization in p-A interactions at 12 GeV versus $p_\perp$ at fixed production angles. For clarity, the Be and Cu data are plotted at slightly displaced $p_\perp$ values. The solid line is a linear fit to the W data [Ab86].
- Fig. 53 Dependence of the Λ^0 polarization on target mass in the projectile hemisphere. Within each set of data, the points have the same $(p_\perp, x_F)$ values [He83].
- Fig. 54 The ratio of the average Λ^0 polarization from Cu and Pb targets to that from Be versus the average transverse momentum. The polarization and $p_\perp$ were averaged at each lab. angle [Po85].
- Fig. 55 a) Inclusive Λ^0 polarization versus $p_\perp$ for approximately constant x_F . The lines are only to guide the eye [He85]. b) Schematics of the behaviour of Λ^0 polarization as a function of $(p_\perp, x_F)$ [He85].
- Fig. 56 Combined target Λ^0 polarization versus x_F for fixed $p_\perp$ values. The errors are statistical only. The curves are predictions of the DeGrand-Miettinen model [Ab86].
- Fig. 57 Λ^0 polarization at 12 GeV (combined targets of Be, Cu, W) and at 400 GeV (Be) versus $p_\perp$ at fixed production angles. Data are from [Ab86] and [He78].
- Fig. 58 Λ^0 polarization as a function of lab. energy. The points have $(p_\perp, x_F)$ values in the range indicated. The point at 24 GeV/c is the average of three measurements at 20, 24, and 28.5 GeV/c [Ra80].
- Fig. 59 Inclusive Λ^0 and $\bar{\Lambda}^0$ polarization versus $p_\perp$, measured in the p-Be reaction at 300 GeV/c [He78].
- Fig. 60 Polarization of hyperons in the p-Be interaction at 400 GeV versus the laboratory momentum [He81].
- Fig. 61 $p_\perp$ versus lab. rapidity (y_{lab}) for central collisions at 4.5 GeV/c per nucleon. Solid and dashed curves denote the kinematic limits for $N-N \rightarrow \Lambda^0 KN$ and $\Lambda^0 KN\pi$ channels, respectively. Events within the hatched area ($p_\perp < 0.46$ GeV/c, vicinity of interaction point) were not included.
- Fig. 62 Rapidity distributions of Λ^0 in central nucleus-nucleus collisions. The arrows indicate the mid-rapidity for the N-N system.
- Fig. 63 Average Λ^0 polarization in central nucleus-nucleus collisions versus average transverse momentum. Data are from [Ha81], [An84], and [Io87].

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