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Spin effects in inclusive strange particle production

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Rice University, 1989
SPIN EFFECTS IN INCLUSIVE STRANGE PARTICLE PRODUCTION

by

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SPIN EFFECTS IN INCLUSIVEStrange PARTICLE PRODUCTION

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Abstract

The origin of spin effects in inclusive particle production at high energies is still a puzzle. Various experiments since 1976, when large values of polarization were observed in inclusive Λ production [BUN76], have yielded measurements for the polarization $P$, of the baryon octet members, analyzing power $A$, for $\Lambda$, $\Sigma^0$, the pions and $K$, and depolarization parameter $D$ for $\Lambda$ production. In an ongoing effort to understand the dynamics of the phenomenon we have carried out an experiment to measure $P$, $A$ and $D$ parameters for inclusively produced $\Sigma^0$'s. We were also able to measure $A$ for $K_\pi$ production which is in good agreement with an earlier measurement [BON88]. We find that the polarization for $\Sigma^0$'s is $23.0 \pm 13.0\%$ also in good agreement with an earlier measurement of $28.0 \pm 13.0\%$ [DUK87]. The analyzing power and depolarization are $A = 1.8 \pm 5.5\%$ and $D = 26.0 \pm 16.0\%$ averaged over all the data with $x_F > 0.2$.

Comparing the results with a phenomenological model we find that the $A$ and $D$ values differ considerably from the predictions. This model is based on ideas from parton fragmentation-recombination models and uses SU(6) symmetry for the wavefunctions. The transition amplitudes are parametrized by parameters $\epsilon$, $\epsilon'$, $\delta$, and $\delta'$ in such a
way that fast quarks preferentially recombine with spin up and slow quarks with spin down. We have extended this model by allowing partial transfer of common valence quarks between the beam particle and the final state. Thus, whereas in the original version $p \rightarrow \Sigma^0$ could proceed only by (ud) diquark transfer now it is enhanced by u and d single quark transfer.

Another extension to the model is the inclusion of finite probability of transversity spin flip (XSF) during recombination. By fitting the ratio of the production cross sections for $\Lambda$'s and $\Sigma^0$'s we obtain a single XSF probability of $\Phi = 0.34\%$. With these modifications the predictions for $\Lambda$ and $D$ in $\Sigma^0$ production are 5.6% and 33% respectively in excellent agreement with the experimental values. With the inclusion of XSF, the analyzing power for $p \rightarrow \pi^+$ and $p \rightarrow \pi^-$ also come into agreement.
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Chapter 1

INTRODUCTION

1.1 Review

Spin effects in inclusive hadron production at high energies have unexpectedly large magnitudes and are not well understood at the present time. An inclusive reaction is defined as one in which we measure only some of the final state particles as opposed to exclusive reactions in which all final states are measured. In general an inclusive reaction would be

\[ a + b = c + d + \cdots + X \]  \hspace{1cm} (1.1)

where \( a \) denotes the beam projectile, \( b \) the target particle, \( c, d, \ldots \) refer to the observed particles which are produced in the reaction and \( X \) to all others which are not. In this thesis we will study the following inclusive reactions

\[ p + \text{Be} \rightarrow \Sigma^0 + X \]

\[ \rightarrow K_S + X \]

\[ \rightarrow \Lambda + X \]
in which a $\Sigma^0, K_s, \Lambda$ or $\bar{\Lambda}$ are produced in the collision of a high energy proton with a beryllium (Be) target.

The discovery of large values of polarization in inclusive $\Lambda$ production [BUN76] at Fermilab led to a concerted effort to understand the role of spin in high energy reactions. This observation was contrary to the prevailing opinion which predicted that polarization values should decrease with increasing energy [KAN78]. Since then many experiments have been carried out to measure the polarization values in inclusive production of the lowest baryon octet. Apart from $\Lambda$, which has been studied extensively, polarization measurements have been carried out for $\Xi^-$ [RAM86], $\Xi^0$ [HEL83], $\Sigma^-$ [DEC83], $\Sigma^+$ [WIL81], $\Sigma^0$ [DUK87] and $\Omega^-$ [LON88] production, the amount of precision decreasing as we go down the list. These investigations include energy dependence, kinematic behaviour and degree of polarization.

A variety of targets have been used for the above measurements among which Be is the most common. Other targets include $\text{H}_2, \text{D}_2, \text{C}, \text{Ir}$, Pb and W. The data covers a wide kinematic region. It extends up to $\sqrt{s}$ (center of mass energy) of 60 GeV/$c^2$, $x_F$ up to 0.8 and $p_T$ up to 4 GeV/$c$.

The transverse momentum, $p_T$ is a measure of the hardness of the collision. $x_F$, called the Feynman $x$, is the fraction of the projectile's longitudinal momentum carried by the leading fragment. If $p_{||}, p_{||,\text{max}}$ are the longitudinal momenta and the maximum momenta possible respectively of the projectile fragment, then

$$x_F = \frac{p_{||}}{p_{||,\text{max}}} \sim \frac{p^*}{\sqrt{s}/2}$$
where we have assumed that the momentum is much greater than the mass of the particles involved in the collision.

The results of all the experiments show that the polarizations are similar in magnitude. For proton induced reactions

\[ P_{\Sigma^+} \simeq P_{\Sigma^-} \simeq P_{\Sigma^0} \simeq -P_{\Lambda} \simeq -P_{\Xi^0} \simeq -P_{\Xi^-} \simeq 0.15 - 0.25 \]

\[ P_{\Lambda} = 0 \]

and for K\(^-\) induced reactions \(P_{\Lambda}\) is positive and has a greater magnitude. This can be seen in fig 1.1 which shows the measured values of polarization for all the members of the baryon octet.

From the available data a few general remarks can be made regarding the polarization of inclusively produced \(\Lambda\)'s.

- The polarization is independent of energy.

- All hyperons produced by proton fragmentation are polarized in a plane perpendicular to the production plane.

- The magnitude of the polarization is independent of \(p_T\) above \(p_T\) of ~ 1 GeV/c.

- The polarization depends approximately linearly on \(p_T\) below \(p_T\) of 0.8 GeV/c.

- The polarization depends approximately linearly on \(x_F\).

- The polarization depends weakly on target type.

To explain the regularities observed in the data we can appeal to perturbative QCD (PQCD) since the large production cross sections implies that the production is a strong
Fig 1.1 Polarization of inclusively produced baryons using a proton beam.
interaction process. The direction of the polarization also confirms this because polarization along any other direction would not conserve parity and hence need not be a strong interaction. Such a calculation based on quark scattering by gluon exchange shows that the polarization falls off like [KAN78]

\[ P \sim \alpha_s \frac{m_q}{\sqrt{s}} \]  

which vanishes at high energies. In this calculation the polarization arises due to the interference of a single gluon exchange amplitude, which is real, and a double gluon exchange amplitude, which can flip the helicity of the quarks during scattering. Since the latter violates helicity conservation, it falls off like \( m_q/\sqrt{s} \), where \( m_q \) is the mass of the quark, and \( \sqrt{s} \) is the center of mass energy. The extra factor of \( \alpha_s \) is from the second order diagram which has two gluons being exchanged. Here \( \alpha_s \) is the strong interaction coupling constant. The PQCD prediction of vanishing polarization values at high energies can be rationalized in the following way. The process which leads to substantial values of polarization is the coherent interference between helicity flip and non-flip amplitudes. At high energies the number of channels is so large that it is difficult to envisage such a coherent interference between a few “select” channels thereby leading to large values of polarization. It is important to remember that PQCD is applicable for hard scattering processes i.e. processes for which \( p_T \) is at least 4 GeV/c [ref], while most of the data is centered around 1-2 GeV/c. If the PQCD calculation is complete, then even a modest increase in \( p_T \) should lead to a large change in the polarization and should approach zero rapidly. This does not seem to be true at least for the \( \Lambda \) measurement for which some data exists at \( p_T \sim 4.0 \) GeV/c which shows that polarization still persists.
1.2 Theoretical Models

In the absence of a valid theoretical explanation, a few models have been put forward to explain the large values of polarization observed. These are semi-classical models based on spin orbit coupling which explain the sign of the polarization but do not have adequate calculational ability. We describe the features of a few of the important models which attempt to explain the origin of the polarization of the inclusively produced particles below.

1.2.1 Lund String Model

The Lund group considers polarization to occur due to the breaking of a color string [AND79] during recombination. Consider the case of Λ formation where it is easiest to see this process. A color dipole field is stretched between the fragment from the projectile and the interaction region as shown in fig. 1.2a. At a certain point the potential energy of the string becomes large enough that it breaks up into a quark anti-quark (s̅s for Λ) pair. Assuming that the transverse momentum is conserved locally in the string, the s̅s quarks are produced with equal and opposite transverse momentum k_τ, -k_τ. If the quarks produced from the string have mass then they are produced at a certain distance from each other such that \( \kappa l = 2(m_\tau^2 + k_\tau^2) \) where \( l \) is the distance between the quarks and \( \kappa \) is the energy/unit length of the string and \( m_\tau \) is the mass of the strange quark. This gives the produced pair of quarks an angular momentum. If the original string
Fig 1.2a Polarization mechanism for $\Lambda$ in the Lund model. The solid line is the ud diquark (D) and ss represents the strange sea quark pair produced with an angular momentum $m$, out of the plane of the paper.

Fig 1.2b Transition of the strange quark from the proton to the $\Lambda$ causes a boost along $\beta$ in the Thomas Precession model. The spin of the strange quark is thus favored to be into the plane of the paper.
has no transverse motion this angular momentum must be balanced by the spin angular momentum. Thus a relationship is established between the outgoing quark's spin and the outgoing fragment's momentum. The polarization occurs because we look for Λ's with a certain $p_T$ which preferentially chooses the s quark with its spin down (trigger bias effect). Using SU(6) quark wavefunctions for the baryons (appendix A), the spin of the Λ is determined by the spin of the s quark because the (ud) diquark from the proton is in a singlet state. The Λ then has negative polarization which is consistent with the observed sign.

The ss pair is produced in an identical manner for the case of $\Sigma^0$ production but the (ud) diquark is now in a spin triplet state. When combined with the negative spin of the s quark it leads to a positive polarization of the $\Sigma^0$ as observed experimentally.

### 1.2.2 Thomas Precession Model

De Grand and Miettinen (DGM) have an alternate model in which polarization arises due to the Thomas precession of the quarks during the process of recombination [DGM81]. This can be seen if we write the energy shift due to Thomas precession $\Delta V_{Th}$,

$$\Delta V_{Th} = \vec{E} \cdot \vec{\omega}_{Th}$$

(1.3)

where

$$\vec{\omega}_{Th} = \frac{\gamma}{\gamma + 1} \frac{F}{m} \times \vec{v}$$

(1.4)

is the Thomas frequency, $\vec{v}$ is the velocity and $F$ is the acceleration of the quark. The cross section for the reaction is inversely proportional to $(1 + \Delta V_{Th})$ which implies that
negative $\Delta V_{Th}$ is favoured. For example, during the formation of a lambda from a proton fragment a slow s quark from the target sea gets accelerated. This gives an $\omega_{Th}$ out of the scattering plane (fig 1.2b) which forces $\vec{s}$ to point into the scattering plane. Note that we have again chosen the direction of the outgoing $\Lambda$ which generates the trigger bias effect. Thus the $\Lambda$ has negative polarization in agreement with the Lund model and experiment. A simple rule emerges from this picture

Slow partons preferentially recombine with their spins down in the scattering plane while fast partons recombine with their spins up.

1.2.3 Multiple Scattering

This method, developed by Szwed [SZW81], has been applied only to $\Lambda$ production. The $\Lambda$'s in this model get their polarization from the s quark because the (ud) fragment from the proton is in a singlet state (assumption of SU(6) wavefunction). The model assumes that the transverse momentum of the $\Lambda$'s is due to the $p_T$ of the s quarks. In this model the strange quarks acquire their transverse momentum due to multiple scattering off the quark gluon matter. Since the s quarks are massive they become polarized.

The calculations for $\Lambda$ show adequate agreement with the data. Work is underway to include the $x_F$ and $p_T$ dependence for the polarization. There is also an effort to do the same calculation for inclusive $\Sigma^0$ production.

Recently calculations have been done to calculate the interference effects between various orders of PQCD scattering diagrams based on this idea. It has been found that the mechanism of gluon fusion could be the seed of a small value of the polarization
Although the numbers are still very small.

1.2.4 Problems With The Models

All the models discussed above use static SU(6) wave functions for the particles. Since we are dealing with soft processes one would expect to see effects of the strong binding due to the gluons. The models discussed above do not explicitly take this into effect. The general feature of all the models is that polarization arises due to some kinematic effect. Spin has proved to harbour deep and subtle principles which when understood has led to revolutionary advances e.g. spin as an internal quantum number, Fermi - Dirac statistics and Dirac’s relativistic equation.

The model implies that the effect should get bigger as we go up in $x_F$ and should vanish at $x_F = 0$. since it assumes that all the quantum numbers of the produced particles are carried by the valence quarks. This is borne out by experiments where the effects seem to saturate at high $x_F$ and diminishes at lower values of $x_F$. Apart from this general remark the models do not predict any values for these effects let alone give any kinematic dependence curves.

1.3 Motivation

Of all the spin parameters available for study viz; polarization, analyzing power, polarization transfer, depolarization etc, polarization has been studied exclusively for the baryons. Some measurements also exist for the analyzing power of inclusively produced mesons. To study the other parameters requires either a polarized beam, polarized target
or both. Polarized targets are more prevalent than high energy polarized beams which have been realized only in the last few years at Brookhaven and Fermilab. The other facility for high energy polarized beams was the Zero Gradient Synchrotron (ZGS) which accelerated polarized protons to 12 Gev/c. The experiments conducted here produced anomalous results which gave the impetus for building the new polarized beams at AGS and Fermilab at higher energies.

To understand the phenomenon better it is crucial to accumulate more data on the effects of spin on inclusive particle production. These include analyzing power and depolarization parameter measurements for the baryons listed above. We were thus motivated to extend the data to include measurements of spin parameters for inclusively produced $\Sigma^0$'s. Even though the polarization had been measured previously, the errors were large and the measurement was considered to be preliminary. Another incentive to choose $\Sigma^0$ was that the first polarized proton beam experiment to measure spin parameters was performed by us to study inclusive $\Lambda$ production. Since the setup for detecting $\Sigma^0$'s would include detecting a $\Lambda$, we would profit by our knowledge of the systematics of the detector.

In the $\Lambda$ production experiment we used the newly commissioned polarized proton beam which ran at energies of 13.3 and 18.5 GeV/c with an average polarization of 40%. The experiment measured the polarization, analyzing power and depolarization which agreed very well with the predictions of a model based on the Thomas Precession model described above. The model imitates the quark fragmentation-recombination models which have been successful in describing soft processes in hadro-production and uses
flavour SU(6) quark model wavefunctions to carry out the calculations [DGM81]. At the
time it was proposed, only polarization data was available and the model had considerable
success in predicting both the sign and relative magnitude of the polarization. The $\Lambda$
data we collected contained $\Lambda$'s produced directly in the interaction of the beam particle
in the target and $\Lambda$'s which came from the decay of higher mass resonances and most
significantly $\Sigma^0$. Taking this source of secondary $\Lambda$'s into account, the results were not
in as good agreement with the predictions. This indicated there might be something
interesting in the $\Sigma^0$ results.

1.4 Spin Parameters

In this experiment we measure the spin parameters of the leading beam fragment using
a polarized proton beam. We can then study the single particle parameters like analyzing
power, $A$, polarizing power (polarization), $P$, for the leading fragment and the two
particle parameter depolarization, $D$, for the beam channel. Other parameters require
information about the target and/or recoil particle spin which we do not attempt to
measure.

The polarization parameter, $P$, is an ensemble variable that arises due to the interference
of spin flip and non-flip amplitudes. It is given by the difference between the cross
sections for producing spin up and spin down scattered or recoil particles for the case
of an unpolarized initial state. This is translated to counting the number of particles
produced in each spin state \textit{viz.}:

$$P = \frac{\sigma(f = \uparrow) - \sigma(f = \downarrow)}{\sigma(f = \uparrow) + \sigma(f = \downarrow)}$$  \hspace{1cm} (1.5)
For the case of a polarized beam in the initial state, other parameters are defined. The two particle parameter, depolarization $D$ or polarization transfer $K$, is one such parameter for the beam or target channel respectively. We measure the depolarization by finding the difference between the production cross section for $i=f$ and $i\neq f$ spin states. $i$ denotes the beam (target) and $f$ denotes the spin state of the scattered (recoil) particle.

$$D = \frac{1}{P_B} \frac{\sigma(i = f) - \sigma(i \neq f)}{\sigma(i = f) + \sigma(i \neq f)}$$ (1.6)

where $P_B$ denotes the beam polarization. Physically, this parameter represents the probability of a spin flip in the $\Sigma^0$ production, that is the polarization of the $\Sigma^0$ is opposite that of the incident proton. This can be written as

$$\sigma(i \neq f) = \frac{1 - D}{2}$$ (1.7)

where the left hand side denotes the probability for a spin flip during the particle production.

Another parameter of interest is the analyzing power which denotes the difference between reaction cross sections for initial beam (target) spin up and down. For an unpolarized beam the scattering is isotropic. An asymmetry is induced due to a spin dependent preferential scattering. It is defined as the difference of left (up) and right (down) scattered particles for beam spin along $\hat{N}$ ($\hat{S}$, $\hat{L}$) direction. The asymmetry is normalized w.r.t. the beam polarization to make comparisons between experiments with different beam polarizations. This parameter is called the analyzing power, $A$. If $P_B$ is the beam polarization, then

$$\text{Asymmetry} = P_B \times \text{Analyzing Power}$$ (1.8)
\[ A = \frac{1}{P_B} \frac{\sigma(i = |) - \sigma(i = |)}{\sigma(i = |) + \sigma(i = |)} \]  

(1.9)

The asymmetry is the experimentally observed difference in the left-right scattering, \( P_B \) is the beam polarization and the analyzing power, \( A \), is determined by the interaction.

### 1.5 Description Of The Baryon \( \Sigma^0 \)

The discovery of abnormally long lived massive particles led to the hypotheses of a new additive quantum number called Strangeness, \( S \). (These particles were called "strange" because they would not decay to lighter hadrons by strong interaction even though charge and baryon number were conserved.) Coupled with the principle of associated production (they always occurred in pairs) a strangeness value was assigned to each hadron. Nucleons have \( S = 0 \), \( \Lambda \), \( \Sigma^0, \pm \) have \( S = -1 \), \( K \), has \( S = +1 \), \( \Xi^0, - \) have \( S = -2 \) and so on. In the modern language of quarks this is equivalent to the assignment of \( S = -1 \) for strange quarks, and have \( S = +1 \) for anti-strange quarks.

With the introduction of the quantum number \( S \), the symmetry group describing the "elementary" particles had to be expanded. This led to the proposal of a flavor \( SU(3) \) group incorporating the three flavors \( u, d \) and \( s \). In this system the ground state baryon multiplet is an octet and consists of \( p, n, \Lambda, \Sigma^+, \Sigma^0, \Sigma^-, \Xi^0 \) and \( \Xi^- \). The octet members differ in mass by \( \sim 400 \text{ MeV} \) which indicates that \( SU(3) \) grouping is not as good a symmetry as \( SU(2) \) which contained only the \( u \) and \( d \) quarks. The exact symmetry of strong interactions is believed to be color \( SU(3) \) and has nothing to do with flavor \( SU(3) \). We use the flavor \( SU(3) \) to enumerate the hadronic states and it serves our purposes well.
The $\Sigma^0$ is a neutral spin $1/2$ baryon and consists of one each of $u$, $d$ and $s$ quarks just like the $\Lambda$. It has been assigned an isospin $(I, I_3)$ value $(1, 0)$ and has $\Sigma^+(uus)$ with $(1, 1)$ and $\Sigma^-(dss)$ with $(1, -1)$ as its isospin partners. Unlike the other members of the octet, $\Sigma^0$ is the only particle that can decay electromagnetically and is therefore the shortest lived, with a lifetime of $(7.4 \pm 0.7) \times 10^{-20}$ s. It decays exclusively to $\Lambda \gamma$ (BR of 1). The strong decay channels for all members is inaccessible due to their low mass. The electromagnetic decay is forbidden for the other members due to conservation of other additive quantum numbers like strangeness and baryon number.

In designing an experiment to detect the $\Sigma^0$ its electromagnetic decay has two practical consequences.

- The decay vertex is in the production target instead of being downstream of the interaction point.

The spin parameters for the $\Sigma^0$ are calculated through its daughter particle, $\Lambda$. The $\Lambda$ decays weakly to either $\pi^- \Lambda$ (BR 0.64) or $n \Sigma^0$ (BR 0.36) which is a self analyzing reaction. We reconstruct the lambdas using the charged decay channel since it has a larger branching ratio (BR) and it is easier to identify the charged particles and measure their momenta as opposed to neutral particles.

- To reconstruct the parent $\Sigma^0$ the photon's energy and angle w.r.t. the $\Lambda$ have to be measured.

We used an electromagnetic calorimeter for this purpose. The use of such a device sets inherent limits on the resolution of the $\Sigma^0$ mass.
1.6 Overview

In the next chapter we discuss the detectors used for the experiment and the setup for the production of the polarized beam. We also give a brief description of the calibration of the lead glass detector which was used to measure the photon energy and position coming from $\Sigma^0$ decay. In chapter 3 we describe the procedures for analyzing the data and identifying the particles of interest. The results of the analysis for $P$, $A$ and $D$ are presented in chapter 4. A description of the theoretical model follows in chapter 5 in which we have included the comparison of predictions to this and other experimental data. Two appendices follow the thesis which describe the formalism for recasting the SU(6) quark wavefunctions for baryons into a quark doublet-singlet form and the relationship between $\Sigma^0$ and its daughter $\Lambda$'s polarization.
Chapter 2

Experimental Setup

2.1 Detector Layout

The experiment was performed at the Multi Particle Spectrometer (MPS) at Brookhaven National Laboratory. The facility includes a set of drift chambers (DCs) and proportional wire chambers (PWC's) placed in a magnet. We used the spectrometer for tracking the charged particles. This facility has been described elsewhere at length [MPS83] so we will restrict ourselves to a short review of the salient features of the different components.

2.1.1 Magnet

The main component of the spectrometer consists of a large aperture 700 ton C shaped magnet. The magnetic field volume is 48 inches high by 72 inches wide and 180 inches long. The magnet floats on a 0.005 inch film of oil so it can be rotated about its pivot which is 46 inches from one end of the magnet. The spectrometer can be rotated to be used in the high energy primary proton beamline (23 GeV/c) or in the lower energy secondary beamline (8 GeV/c π−, K−, p). The magnet was used at half its maximum
field at 5kG.

2.1.2 Drift Chambers

The drift chambers form the heart of the tracking system. We used a set of 7 drift chamber modules arranged in the magnet as shown in fig 2.1. Each module consists of 7 planes with wire orientations X' X X Y U V Y'. The orientation X measures the coordinate of the track in the horizontal coordinate (wires are vertical) and Y in the vertical plane. U, V planes are rotated by ±30° w.r.t. Y. The two planes X', Y' represent configurations in which the wires have been displaced by 0.32 in. (equal to half the anode wire - field wire separation) in order to resolve the left - right ambiguity which exists in any DC. The different planes are separated by a cathode plane which is 0.25 in from an anode plane. There are 1677 wires/chamber. All the individual wire electronics and interface circuits are mounted on the chamber. The active area of the chamber is 173 cm by 100 cm. The chambers used a gas mixture of Argon (79%), isobutane (15%) and dimethoxy methane (6%). The chambers were operated with 2.4 kV on the cathode planes and 1.8 kV on the field wire planes.

2.1.3 Proportional Wire Chambers

Each PWC consists of a single X plane with a wire separation of 0.1 in. The active area of each chamber is 172 cm by 96 cm. Two PWC's were located at the front and rear ends of the magnet while the third was placed near the center. The PWC's were used for triggering and also as additional planes for tracking.
Fig. 2.1 Arrangement of the spectrometer, triggering elements and the lead glass array used in the experiment.
2.1.4 Auxiliary Setup

The upstream part of the detector consists of the target, the polarimeter to monitor the beam polarization and detectors to identify the decay of the lambda particles.

The scintillators S2 and S3 defined the interacting beam particle. S3 is a scintillation counter with a 1.4 cm diameter hole to match the circular scintillator S2. We require our beam particles to pass through S2, giving a signal, and the hole counter S3, giving no signal. This insures that the beam particle is travelling in a straight line and will hit the target. The scintillators S4 and S5 defined a volume for a neutral particle (Λ) decaying to two charged minimum ionizing particles (π⁻ p). The position and size of S4 was determined by optimizing the number of Λ's with \( p_T \approx 1 \text{ GeV/c} \). S4 is a single scintillation counter with dimensions 7.6 cm \( \times \) 15.2 cm. It subtends a central angle of 5.5° w.r.t the beam direction. S5 is built such that it covers the solid angle subtended by S4. It is made from two pieces of scintillators and viewed by four photomultiplier tubes.

A PWC with three planes X, U, and V, was placed directly behind S5 to track the charged particles for defining the vertex more accurately. The planes U and V were rotated by \( \pm 15 \) deg w.r.t X. Each plane had an effective area of 33 cm \( \times \) 66 cm.

The sizes and positions of the different detector elements are shown in Tables 2.1 and 2.2. In our co-ordinate system the origin is midway between the pole tips of the magnet and directly above the pivot. The beam has coordinates \( x=-53 \text{ in} \), \( y=0 \text{ in} \).
Table 2.1
Dimensions Of Detector Elements

<table>
<thead>
<tr>
<th>Device</th>
<th>x(cm)</th>
<th>y(cm)</th>
<th>z(cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>7.64</td>
<td>12.7</td>
<td>0.32</td>
</tr>
<tr>
<td>S2</td>
<td>1.43 dia</td>
<td></td>
<td>0.32</td>
</tr>
<tr>
<td>S3</td>
<td>25.4</td>
<td>25.4</td>
<td>0.32 w/1.27 cm dia hole</td>
</tr>
<tr>
<td>S6</td>
<td>38.1</td>
<td>25.4</td>
<td>1.27</td>
</tr>
<tr>
<td>Target</td>
<td>4 cm dia</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>S4</td>
<td>15.24</td>
<td>8.89</td>
<td>0.64</td>
</tr>
<tr>
<td>S5</td>
<td>35.56</td>
<td>17.78</td>
<td>0.64</td>
</tr>
<tr>
<td>R1</td>
<td>66.04</td>
<td>33.0</td>
<td>7.62</td>
</tr>
<tr>
<td>P1</td>
<td>154.4</td>
<td>96.0</td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td>172.0</td>
<td>96.0</td>
<td>17.8</td>
</tr>
<tr>
<td>D2</td>
<td>172.0</td>
<td>96.0</td>
<td>17.8</td>
</tr>
<tr>
<td>D3</td>
<td>172.0</td>
<td>96.0</td>
<td>17.8</td>
</tr>
<tr>
<td>P2</td>
<td>172.0</td>
<td>96.0</td>
<td></td>
</tr>
<tr>
<td>D4</td>
<td>172.0</td>
<td>96.0</td>
<td>17.8</td>
</tr>
<tr>
<td>D5</td>
<td>172.0</td>
<td>96.0</td>
<td>17.8</td>
</tr>
<tr>
<td>D6</td>
<td>172.0</td>
<td>96.0</td>
<td>17.8</td>
</tr>
<tr>
<td>D7</td>
<td>172.0</td>
<td>96.0</td>
<td>17.8</td>
</tr>
<tr>
<td>P3</td>
<td>171.0</td>
<td>100.0</td>
<td></td>
</tr>
<tr>
<td>HLG</td>
<td>181.3</td>
<td>126.05</td>
<td>0.64</td>
</tr>
<tr>
<td>LG</td>
<td>123.1</td>
<td>97.0</td>
<td>33.0</td>
</tr>
<tr>
<td>Device</td>
<td>Position</td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>----------</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$x$(cm)</td>
<td>$y$(cm)</td>
<td>$z$(cm)</td>
</tr>
<tr>
<td>S1</td>
<td>-138.64 to -130.8</td>
<td>-6.35 to +6.35</td>
<td>-458.3</td>
</tr>
<tr>
<td>S2</td>
<td>-135.34 to -133.91</td>
<td>-0.72 to +0.72</td>
<td>-441.8</td>
</tr>
<tr>
<td>S3</td>
<td>-135.26 to -133.99</td>
<td>-0.64 to +0.64</td>
<td>-427.2</td>
</tr>
<tr>
<td>S6</td>
<td>-133.99 to -95.89</td>
<td>-12.7 to +12.7</td>
<td>-427.68</td>
</tr>
<tr>
<td>Target</td>
<td>-136.62 to -132.62</td>
<td>-4.0 to +4.0</td>
<td>-405.13</td>
</tr>
<tr>
<td>S4</td>
<td>-132.72 to -117.48</td>
<td>-4.45 to +4.45</td>
<td>-373.2</td>
</tr>
<tr>
<td>S5</td>
<td>-122.56 to -87.0</td>
<td>-8.89 to +8.89</td>
<td>273.2</td>
</tr>
<tr>
<td>R1</td>
<td>-122.56 to -56.52</td>
<td>-16.5 to +16.5</td>
<td>-208.92</td>
</tr>
<tr>
<td>P1</td>
<td>-114.3 to +40.1</td>
<td>-48.0 to +48.0</td>
<td>-144.6</td>
</tr>
<tr>
<td>D1</td>
<td>-86.0 to +86.0</td>
<td>-48.0 to +48.0</td>
<td>91.4</td>
</tr>
<tr>
<td>D2</td>
<td>-86.0 to +86.0</td>
<td>-48.0 to +48.0</td>
<td>121.9</td>
</tr>
<tr>
<td>D3</td>
<td>-86.0 to +86.0</td>
<td>-48.0 to +48.0</td>
<td>152.4</td>
</tr>
<tr>
<td>P2</td>
<td>-86.0 to +86.0</td>
<td>-48.0 to +48.0</td>
<td>201.6</td>
</tr>
<tr>
<td>D4</td>
<td>-86.0 to +86.0</td>
<td>-48.0 to +48.0</td>
<td>233.6</td>
</tr>
<tr>
<td>D5</td>
<td>-86.0 to +86.0</td>
<td>-48.0 to +48.0</td>
<td>264.1</td>
</tr>
<tr>
<td>D6</td>
<td>-86.0 to +86.0</td>
<td>-48.0 to +48.0</td>
<td>294.6</td>
</tr>
<tr>
<td>D7</td>
<td>-86.0 to +86.0</td>
<td>-48.0 to +48.0</td>
<td>355.7</td>
</tr>
<tr>
<td>P3</td>
<td>-86.0 to +85.0</td>
<td>-50.0 to +50.0</td>
<td>473.7</td>
</tr>
<tr>
<td>HLG</td>
<td>-91.58 to +89.71</td>
<td>-61.9 to +64.15</td>
<td>575.0</td>
</tr>
<tr>
<td>LG</td>
<td>-47.61 to +75.51</td>
<td>-61.9 to +35.1</td>
<td>578.42</td>
</tr>
</tbody>
</table>
2.2 Lead Glass

To detect the photon from the $\Sigma^0$ decay, we made use of an electromagnetic lead glass calorimeter. This calorimeter was originally built to reconstruct $\pi^0$s from the reaction $\pi^+p\rightarrow\Delta^++\pi^0\pi^0$ at 8 GeV/c $\pi^+$ momentum [BAU82]. At a later stage a different set of lead glass blocks (SF5) were added to use it for detecting the two photons coming from $\Sigma^0\rightarrow\Sigma^0\gamma$ [ZOG89]. Although the considerations in building the detector were to optimize the results for the above two experiments, it was adequate for our purposes.

The LG array consists of 129 blocks arranged in 10 staggered rows as shown in fig 2.2. As the block sizes are quite big this arrangement was chosen to maximize the number of blocks which participate in the shower development to improve position resolution.

Each block is wrapped in a mylar sheet with aluminized inner faces to reflect the light and painted black on the outside to absorb refracted light. The salient features of the two kinds of LG used are given in Tables 2.3 and 2.4 below.

### Table 2.3

<table>
<thead>
<tr>
<th>Composition</th>
<th>Mol. Wt.</th>
<th>% Wt.</th>
<th>% Wt.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PbO</td>
<td>223.21</td>
<td>0.51</td>
<td>0.55</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>60.06</td>
<td>0.42</td>
<td>0.385</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>94.19</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>61.99</td>
<td>0.03</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Fig 2.2 A front view of the lead glass detector with the blocks numbered.
Table 2.4

Properties of SF2 and SF5 Lead Glass

<table>
<thead>
<tr>
<th></th>
<th>SF2</th>
<th>SF5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (gm/cc)</td>
<td>3.86</td>
<td>4.08</td>
</tr>
<tr>
<td>Refractive Index, n</td>
<td>1.648</td>
<td>1.673</td>
</tr>
<tr>
<td>Radiation Length, X₀ (cm)</td>
<td>2.62</td>
<td>2.36</td>
</tr>
<tr>
<td>Critical Energy, E_c (MeV)</td>
<td>17.5</td>
<td>15.8</td>
</tr>
<tr>
<td>Nuclear Collision Length, (cm)</td>
<td>21.8</td>
<td>21.4</td>
</tr>
<tr>
<td>Atomic Number, Z</td>
<td>31.79</td>
<td>34.81</td>
</tr>
<tr>
<td>Front Face Size (cm)</td>
<td>8.9</td>
<td>10.14</td>
</tr>
<tr>
<td>Length (cm)</td>
<td>33.0</td>
<td>35.0</td>
</tr>
<tr>
<td>Length (X₀)</td>
<td>12.6</td>
<td>14.7</td>
</tr>
<tr>
<td>Moliere Radius (cm)</td>
<td>3.14</td>
<td>3.14</td>
</tr>
</tbody>
</table>

The length of the LG blocks was designed to contain more than 90% of the incident energy of the showering particles at low energies. We have calculated the fraction of the incident energy contained in the lead glass using a shower curve parametrization [FAB85]. It is inferred from shower data at energies greater than a few GeV and has the following form

\[
\frac{dE}{dl} = \frac{E_0 \alpha^{\alpha+1}}{\alpha!} \ell^\alpha e^{-bt} \tag{2.1}
\]

where

\[
E = \text{energy contained}
\]
Below we show the results for our blocks for incident electrons and photons of 1 and 2 GeV incident energy.

Table 2.5

<table>
<thead>
<tr>
<th></th>
<th>1 GeV</th>
<th>2 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\gamma$</td>
<td>$e^+, e^-$</td>
</tr>
<tr>
<td>SF2</td>
<td>94.7%</td>
<td>94.8%</td>
</tr>
<tr>
<td>SF5</td>
<td>97.2%</td>
<td>97.3%</td>
</tr>
</tbody>
</table>

The LG array was originally operated in the fringe field of a streamer chamber which made good magnetic shielding a necessity. There are two kinds of shields used on this array. The outer shield, which is made of soft iron, bends the field lines along the tube's axis. It also supports the photomultiplier tubes and the electronic bases. The inner shield consists of a mu-metal cylinder placed around the pm tube. It extends 1.6in past the photo cathode which makes it necessary to use light guides to transmit the Čerenkov radiation from the lead glass block. This arrangement apparently lowered
the energy resolution from $10\%/\sqrt{E}$ with an air gap between the lead glass block and
the photomultiplier tube to $20\%/\sqrt{E}$ with a lead glass cylinder acting as a light guide
[BAU82].

Each block is further equipped with a plastic waveguide one end of which sees an
LED (light emitting diode) and the other end rests against the back of the lead glass
block. Each waveguide consists of 7 plastic strands (300μdiameter) arranged such that
the bundle has a diameter of 1000 μ. The LED system is used to monitor the drift of the
pm tubes with time, temperature or due to fluctuations in the HV supply. We used an
HLMP 3950 green LED which has a uniform output over a long time and behaves well
under continuous on-off operation.

\[2.3\] Veto Hodoscope

The veto hodoscope consists of a set of ten scintillators each of which covers a LG layer.
Its dimensions are given in Table 2.6. There are two sizes, one to cover the rows of the
LG made of SF2 glass and the other to cover the SF5 rows. This hodoscope was used as
a veto for hadronic events which triggered the LG. The hodoscope layers also doubled
as a proton detector if the layers were a certain distance from the origin of the shower.
To further improve the acceptance of the protons after they had crossed the magnet,
additional counters were added to this hodoscope around the LG as shown in fig 2.3. We
constructed six new counters which are numbered 11 through 16. The other two (17, 18)
were spare scintillators for the SF2 rows of the LG and were also added on to this array.

The scintillators are glued to a plastic light guide and the light is collected by a
Fig 2.3 The scintillators which form the Lead Glass hodoscope. The dashed lines show the boundary of the Lead Glass behind the hodoscope.
photomultiplier tube. The light is converted to electrical signals using an electronic base designed locally [BUC89].

Table 2.6

Dimensions Of The Lead Glass Veto Hodoscope Elements

<table>
<thead>
<tr>
<th>Counter #</th>
<th>Dimensions (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
</tr>
<tr>
<td>1,2,8,9,10</td>
<td>137.32</td>
</tr>
<tr>
<td>3,4,5,6,7,17,18</td>
<td>137.32</td>
</tr>
<tr>
<td>11,12,13,14,15,16</td>
<td>102.24</td>
</tr>
</tbody>
</table>

2.4 Trigger

There were essentially three sets of signals used to define the Λ and Σ⁰ trigger. These consisted of pulse heights from the scintillator counters, multiplicity hits from the PWC's and signals from the lead glass. The Λ trigger was defined as

Λ: beam.Ś4 . (Ś5 ≥ 2) . (2 ≤ P2 ≤ 5) . (1 ≤ P3 ≤ 5) . HP

beam : $S2 . Ś3$
Ś4 : neutral going through S4
Ś5 ≥ 2 : at least 2 minimum ionizing particles through Ś5
HP : scintillator hodoscope in front of the lead glass to detect a minimum ionizing particle.
The $\Lambda$ trigger isolates neutral particles produced in the target which decay to two charged particles between S4 and S5, one of which travels all the way to the hodoscope covering the lead glass array.

The $\Sigma^0$ trigger was defined as

$$\Sigma^0 : \Lambda \left( \sum_{i=1}^{129} E_i > 100\text{MeV} \right).\bar{V}_{\text{LG}}$$

It consisted of the $\Lambda$ trigger with a minimum energy deposition of 100 MeV in the lead glass. $\bar{V}_{\text{LG}}$ denotes the requirement for no hits in the scintillator counter covering the particular lead glass block layer in which the energy was deposited. This requirement was essential for rejecting hadron induced showers in the lead glass. Each of the scintillators covering the LG were timed into a time-to-digital converter (TDC) along with the time of the interaction in the target to reduce accidentals in the LG.

In addition to the $\Lambda$, $\Sigma^0$ triggers discussed above there were some secondary triggers from the LG. These were the LED, PED and Am triggers. The LED trigger monitored the response of the PM tubes on the lead glass blocks as a function of time. The PED trigger monitored the variation of the zero of the ADC modules (pedestal) used to calculate the energy deposited in each LG block. The Am trigger was set up to monitor the stability of the LED output. These triggers have been described in more detail elsewhere [KRI88].

The requirement $S4.S5 \geq 2$ proved to be a powerful trigger requirement and coupled with the PWC multiplicity requirements gave a good $\Lambda$ sample. The $\Sigma^0$ trigger was enhanced by the extension of the veto hodoscope in front of the LG and worked quite well. A total of $17 \times 10^4$ reconstructed events contained a $\Lambda$ (8% efficiency) of which $10^4$ were $\Sigma^0$'s.
2.5 Polarized Proton Beam

The polarized beam used in this experiment was the newly commissioned high energy polarized proton beam at Brookhaven National Laboratory. Here polarized protons were accelerated in the Alternating Gradient Synchrotron (AGS) up to 18.5 GeV/c with an average polarization of 45%. The beam polarization was reversed every spill to reduce systematic errors. The description of the polarized beam given below follows that in [KHI89].

Molecular hydrogen from a gas bottle is transformed into a polarized H⁻ ion beam and injected into an RFQ. This beam is then accelerated in the linac and injected into the AGS main ring where a C foil strips the electrons to give a beam of polarized protons.

In the initial stage the molecular hydrogen is dissociated to form a beam of atomic hydrogen. The beam is cooled to thermal velocities and passed through a strong inhomogeneous magnetic field of a sextupole magnet. The magnetic field couples more strongly to the electrons than the protons (μₑ = 660μₚ) and serves to focus only the hydrogen atoms in which the electrons have their spins parallel to the magnetic field (Stern-Gehrlach effect). Thus we get a beam of atomic hydrogen in which all the electrons are polarized and the protons are unpolarized. The spin of the electrons is then transferred to the protons using appropriate magnetic fields and rf power. This can be seen in the energy level diagram of the 1S₁/₂ hyperfine splitting of H in an external magnetic field, fig 2.4. The electrons initially populate the mₑ = 1/2 level. Two rf cavities are tuned to excite the transitions from either level 1 to 3 (spin down protons) or level 2 to 4 (spin up protons). The magnetic field in the two cavities is set at 10 G and 150
Fig 2.4 Hyperfine splitting of \((1S_{1/2})\) levels of atomic hydrogen in a weak external magnetic field.
G respectively. This fixes the rf power at 19 MHz and 1480 MHz respectively for the two transitions. The cavities are operated alternately to get a reversal in spin after each spill.

The beam is then injected into a 500 G solenoid with the proton spin along the magnetic field. Here the beam interacts with a neutral beam of C's atoms and picks up an electron to become an H⁻ ion beam in which the protons are polarized and the electrons unpolarized. This beam is then focused and extracted through a solenoid which precesses the spin by 90° to give the protons vertical polarization. At this stage the polarization of the protons is 75%. The beam is then injected into a Radio Frequency Quadrupole (RFQ) which focuses and accelerates the beam. The RFQ consists of four metallic vanes distributed symmetrically around the central axis. The vanes are energized with rf power with adjacent vanes having opposite voltage to generate an electric quadrupole field which oscillates at a point. The field is thus focusing during one half of the cycle and defocusing during the other half. A modulation of the distance between the vane tips and the central axis provides a longitudinal electric field which accelerates the beam.

The H⁻ beam comes out of the RFQ with an energy of 760 keV and proton polarization at 75%. It is then injected into the AGS linac which further accelerates the negative beam to 200 MeV before the final acceleration cycle in the main AGS circular ring. Just after injection into the main ring the H⁻ beam passes through a thin Carbon foil which strips the two electrons from the ion, thereby sending a beam of polarized protons for acceleration. By timing the injection correctly the H⁻ beam is placed on top of the protons already in the main ring. Since they are different types of particles,
Liouville’s phase space restrictions do not apply. The mixed beam then passes through the C-foil electron stripper which results in having an extra bunch of protons on top of the existing bunch. We can thus use multiple injection of spills from the linac into the main ring to increase the luminosity without making the emittance of the beam any larger.

2.5.1 Resonances

The main obstacle in accelerating a high energy polarized beam is the large number of depolarizing resonances which exist in the accelerator. The AGS is a strong focusing synchrotron which means that it has strong vertical dipole fields for bending and strong alternate quadrupole fields for focusing the beam vertically. The vertical fields do not cause significant polarization losses because the spins of the protons are parallel to the vertical axis of the dipole field and precess around it such that an average over time cancels out giving no net change in the vertical polarization. The horizontal focusing fields can however flip the spins of some of the protons causing depolarization. This occurs whenever the frequency of the proton encountering the perturbing fields is equal to that of the precession frequency of the proton spin. This is in turn related to the energy of the beam. Thus as the energy of the beam increases, it passes through many resonant conditions which vary in strength. Another source of horizontal fields which also leads to rapid depolarization is imperfections in the magnet construction or alignment.

The spin precession of a proton beam with polarization vector, $P$, moving in an
external magnetic field is given by

\[
\frac{dP}{d\theta} \propto P \times \Omega
\]  

where \( \theta \) is the angle along the accelerator’s path in the local rest frame of the protons and

\[
\Omega = \frac{e \rho}{\gamma \gamma mc} [(1 + G\gamma)B_\perp + (1 + G)B||]
\]  

e, m, v — charge, mass and velocity of the proton

\( \gamma \) — Lorentz factor

\( \rho \) — local bending radius

G — anomalous magnetic moment of the proton

\( B_\perp, B|| \) — magnetic field \( \perp \) and || to the velocity of the proton

There are two types of resonances which can cause depolarization during the acceleration in the main ring. These are called the intrinsic and imperfection resonances and the names signify their origin. Intrinsic resonances occur when the following condition is satisfied

\[
G\gamma = nP \pm \nu_y
\]  

where \( n \) is an integer and \( P \) is the periodicity of the accelerator ring. The periodicity is the number of identical magnet lattices that the beam crosses in a single pass around the ring. The vertical betatron tune, \( \nu_y \), is the number of vertical betatron oscillations a particle executes in one cycle around the ring. If \( \nu_y \) is an integer, the beam will encounter the same field configuration during its acceleration cycle and any tendency to deviate
from the synchronous path will be enhanced. Under such an unstable condition the beam eventually hits the beam pipe and is lost before the acceleration cycle is completed. Thus $\nu_p$ is chosen to be non-integer to keep the beam from blowing up. For the AGS $\nu_p$ is 8.75 and $P$ is 12. We can thus understand the origin of intrinsic resonances given in equation 2.4 which occur when the polarization vector of the proton beam encounters the same magnetic field after an integral number of precessions. If the frequency of the precession matches the vertical tune, $\nu_p$, then the protons will see the same quadrupole field during consecutive cycles around the ring. There is a coherent build up of precession which flips some of the spins causing depolarization. Since the magnet lattice is repeated every 30° of arc in the AGS ring, the resonant condition is enhanced as given in equation 2.4.

Imperfection resonances occur due to magnet misalignments and imperfections in the magnet construction. When the spin frequency is equal to an integer a resonant condition occurs causing polarization loss. The resonant condition can be expressed as

$$G\gamma = k$$

(2.5)

where $k$ is an integer. When $k \sim \nu_p$, the resonant condition is very strong; as was seen at the AGS for $k = 9$.

In a physical environment the motion of the protons due to the imperfection fields is coupled to the strong horizontal focusing fields, because the vertical deflection due to imperfection fields sends the proton into the strong horizontal focusing field. Under such conditions the beam passes through beat resonances which are produced when

$$G\gamma = nP \pm k'$$

(2.6)

where $k'$ is an integer. We can consider the imperfection resonances described above as
beat resonances occurring when $n = 0$.

The loss in polarization is determined by the time spent by the beam in crossing a resonance. This is expressed by the parameter $\alpha$ which is the rate at which the resonance is adiabatically crossed. We can write it as

$$\alpha = G \frac{d\gamma}{dt} \pm \frac{d\nu_p}{dt} : \text{Intrinsic Resonances} \quad (2.7)$$

$$\alpha = G \frac{d\gamma}{dt} : \text{Imperfection Resonances} \quad (2.8)$$

After encountering a depolarizing resonance, the polarization $P$ is given by

$$\frac{P}{P_0} = 2\exp \left( -\frac{\pi \varepsilon^2}{2n} \right) - 1 \quad (2.9)$$

where $\varepsilon$ represents the strength of the resonance for the AGS ring. It is calculated from the field geometry of the magnets and the lattice structure of the acceleration cycle.

From this we see that if $\varepsilon$ is very small there is no depolarization and if $\varepsilon$ is very large there is a spin flip, but again no depolarization. It is only for the intermediate values of $\varepsilon$ that we need to make provisions for suppressing the depolarization.

Intrinsic resonances were overcome by making $\alpha$ large, by changing the vertical tune of the accelerator rapidly just as the beam reached a resonant condition. This was achieved by using fast pulsed quadrupole magnets which were pulsed with a very short risetime power supply. Twelve fast quads were built, one for each superperiod of the AGS, but due to the high cost of the power supplies only ten of these were powered up. The change in $\nu_p$ was limited to $+0.25$ because it is restricted to be non-integral. One intrinsic resonance ($36-\nu_p$) overlapped an imperfection resonance ($k = 27$) and could not be corrected with the fast quads. To overcome this resonance, slow pulsed quadrupoles...
were used to shift the tune to 8.87 which separated the two resonances. The fast pulsed quads then brought the tune down by 0.28 to pass the \((36-\nu_q)\) intrinsic resonance.

Imperfection resonances were overcome by reducing their strength i.e. by making \(\epsilon\) very small. This reduced the polarization loss but did not eliminate it completely. This was achieved by generating correction fields for each imperfection resonance. The amplitudes of the correction field were determined by experiment. To accomplish this ninety five correction dipoles (8 for each superperiod), which already existed in the ring, were used.

During the acceleration cycle in the AGS, 5 intrinsic resonances and 49 beat resonances had to be overcome.

The machine accelerated \(\sim 2 \times 10^{10}\) polarized protons to an energy of 18.5 GeV/c in each spill. The rep rate of the AGS was 2.2 sec with a single spill lasting 800 ms. The machine achieved peak polarizations of 52% with an average polarization of 44% over the whole run. We received a few million particles in each spill in the A1 primary beamline at the MPS site. Due to the uneven spill structure of the beam we were unable to increase the beam intensity. This was not rectified till the end of the experiment and as a consequence we could not take as much data as we had hoped to. The spill structure was critical because when we tried to increase the beam intensity, the wire chambers drew a large amount of current. This could eventually lead to broken wires in the chamber which would cause a delay of a few days, at least. The chambers were consequently protected by a trip meter which caused the high voltage to be turned off when the current was too high. Thus we ran with a low intensity. The beam spill...
structure affected us in a different way during data acquisition, which was not welcome either. A good spill would have the protons evenly distributed over the whole spill length, but due to the bad duty cycle, the beam was bunched up at certain points. Since our data buffers and the electronics could record only a limited amount of triggers, we could not take advantage of all the $\Sigma^0$'s which were produced during the experiment.

2.6 Measurement Of Beam Polarization

After the beam has been accelerated and extracted the polarization is degraded due to the depolarizing resonances and it is rotated due to the vertical bends in the beamline. This happens because the corrections described above do not completely cancel the effects of the resonances but reduce their influence.

We measured the polarization of the beam at the site of our experiment using a set of four telescopic scintillator arms which viewed a $(\text{CH}_2)_n$ target. This polarimeter was placed $\sim 6\text{m}$ upstream of the interaction target. Each arm of the polarimeter consists of two scintillators (sizes given in Table 2.7) whose thickness is adjusted so that a recoil proton from a pp backward elastic scattering gets stopped in the last scintillator. This was ensured by requiring a large pulse height ($>3$ times minimum ionizing particle) in the last scintillator. Each arm was centered at an angle of $74.5^\circ$ w.r.t the beam axis and operated independently. Two arms in the horizontal plane measured the left right asymmetry (to calculate vertical beam polarization) while those in the vertical plane measured the up down asymmetry (to calculate the sideways component of beam
polarization). The asymmetry was calculated using the relation

\[
\text{Asymmetry} = \frac{1 - r}{1 + r} \quad ; \quad r = \frac{L | R \mid}{L | R |}
\]  

(2.10)

which has the advantage that it is independent (to first order) of differences in detector efficiency, different solid angles, different beam up, down flux and alignment errors for the two arms [OHL73]. \( L, R \) are the number of left, right scatters while \( \uparrow, \downarrow \) are the directions of beam spin. The beam asymmetry is calculated at the end of each run and averaged over spin up and down. To obtain the beam polarization from this we use relation 1.9 which requires the knowledge of the analyzing power of our polarimeter.

The analyzing power of our polarimeter was obtained by calibrating it against the absolute polarimeter (external polarimeter) in the D beamline. The external polarimeter was calibrated using a polarized beam and polarized target to obtain the four cross sections \( \sigma_{\uparrow\uparrow}, \sigma_{\downarrow\downarrow}, \sigma_{\uparrow\downarrow}, \sigma_{\downarrow\uparrow} \). The beam polarization is given by equation 1.9 in which the analyzing power is obtained from graphs of pp elastic scattering from previous measurements. To calibrate our polarimeter, we calculated the polarization of the beam if it were transported from the D beamline to our polarimeter by accounting for known precessions in the beamline. This value was used to normalize the polarization obtained by our polarimeter. The polarization was noted and used in relation 1.9 with the asymmetry from our polarimeter to give the analyzing power of our polarimeter. The beam polarization was calculated using this value of the analyzing power and using equation 2.10 to calculate the asymmetry. It was not possible to measure the polarization of the beam by keeping track of it at the D beamline during all the period of data accumulation because
they may not always be taking data,

- they can only measure the left right asymmetry and consequently the vertical component of the beam polarization. We also needed to measure the sideways component.

The analyzing power for our polarimeter was found to be $0.0146 \pm 0.00028$ at 18.5 GeV/c. The same quantity in the earlier run was $0.0124 \pm 0.0006$. The discrepancy could be due to a different target size and a different location of the polarimeter. The average polarization was

vertical component $= 38.9 \%$

horizontal component $= -21.2 \%$

which implies the beam was rotated by 28.5deg w.r.t. the vertical towards the -x axis. This compares favorably with the calculated value of 29°. We are using the fact that the longitudinal component is negligible as is shown by beamline calculations.

Table 2.7

Dimensions Of The Polarimeter Scintillator Counters

<table>
<thead>
<tr>
<th>Counter #</th>
<th>Dimensions (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
</tr>
<tr>
<td>R1, L1</td>
<td>3.18</td>
</tr>
<tr>
<td>R2, L2</td>
<td>5.08</td>
</tr>
<tr>
<td>U1, D1</td>
<td>5.08</td>
</tr>
<tr>
<td>U2, D2</td>
<td>5.72</td>
</tr>
</tbody>
</table>
Chapter 3

Data Acquisition And Analysis

In this chapter we describe the procedures used to analyse the data to reconstruct the parent particles. A detailed description of the various cuts made on the data during the analysis to extract the spin parameters is also given.

The description of the pattern recognition programs and other software used for the preliminary analysis has been documented by its authors in detail [LOV81], so we will only describe it briefly. It is worth mentioning that the preliminary analysis is similar in some respects to the procedure used for an earlier experiment on the polarization of inclusively produced $\Lambda$'s. A similar and sometimes overlapping description can be found in [TON88].

3.1 Data Acquisition

The data consisted of a set of hardware signals which indicated an "interesting" event whenever the trigger requirements, described in section 2.4, were satisfied. The data from the electronic modules was passed on through a data highway via CAMAC modules to a
VAX 11/750 (MPSVAX) computer which is a dedicated computer for data acquisition. The data, which arrived after each event and at the end of the spill, was written on a magnetic tape for storage and later analysis.

The data buffer for each event contains the wire numbers and the drift times of the wires registering hits, ADC and TDC pulse heights from the LG and veto hodoscope and a trigger word. The trigger word consists of a 32 bit word which is read from a coincidence latch. It is wired such that certain bits when set represent certain triggers. The end of spill buffer contained the cumulative scaler numbers from the hits in the polarimeter arms, coincidences between various scintillators and hits in the triggering scintillators for efficiency calculations. We had two sets of scalers which were updated for beam spin up and spin down respectively. This separation was maintained to calculate the total beam flux for the two spin states which was necessary to obtain an accurate measure of the analyzing power and depolarization parameters. At the beginning of each spill we recorded the polarization tag word and one LED trigger. The polarization tag word is a bit which can be 0, 1 or 2. Each bit represents a different state of polarization for the beam spill e.g. spin up (0), spin down (1) and polarization unknown (2). The LED trigger was written to tape for calibration purposes.

After each run with physics triggers, which typically lasted for ~ 6 hours, we took data with only the LED. PED or Am triggers. These runs were taken for a few minutes each to monitor the calibration of the LG. They were analysed online and the mean of each run was stored in a file on the computer.
3.2 Analysis

Before any data could be analysed offline, the programs had to be modified for running on the IBM 3090 supercomputer acquired by BNL as a replacement for the CDC 7600. Each run took ~ 1 hour of CPU time for processing on the IBM, and the whole analysis took three months.

The analysis consisted of two parts. The initial analysis was the time consuming processing which calculated the particle momenta and vertex position. This analysis looked for a set of oppositely charged particles which originated from a vertex. This would isolate $K_S$, $\Lambda$ and $\bar{\Lambda}$. A good event was one which had a valid trigger and polarization word, a negatively charged particle and a vertex. Events with two positive tracks and a vertex were also included because an energetic pion would not have a large curvature and would be indistinguishable from a positive particle. All such events were written on two summary files, one long and the other short. The short file contained the run number, spill number, event number, polarization tag word, vertex position, momentum and charge of the decay particles, information from the LG and veto hodoscope, and some miscellaneous information regarding the trigger bits, etc. In addition to this, the long file contained all the tracking information such as reconstructed track and vertex information, all the wire numbers and a matrix showing wire hits corresponding to different tracks. The long file was created as a backup in case some information was needed at a later stage or an error had been made in the analysis. In case of such an event we could probably go back to the long file and not have to do all the laborious analysis on the IBM again.
3.2.1 Pattern Recognition

The first stage of the analysis consisted of calculating the momentum and charge of the particles which formed a vertex. The pattern recognition program which did this first fit straight tracks to hits within a chamber (local pattern recognition) and then joined all the segments (global pattern recognition). First a set of 2D tracks in the xz plane (X view) and yz plane (Y view) were obtained. Only the X and Y planes were used for this section. Hits in each DC were joined by a straight line ignoring the bending due to the magnetic field (the different planes are separated by only 1/2 inch). Since the track separation is larger at the downstream end the tracks were started from this end and extrapolated upstream. The tracks in the X view were made by joining the segments found in each chamber to a circular arc. Only segments inside the magnet were considered where the field is uniform. For the Y view a polynomial of the form $ay + by^3$ was used. After all the 2D tracks had been identified the program looked for correspondences between them by using the signals from the U and V planes to reconstruct 3D tracks. After identifying the 3D tracks the program picked up the missed hits in the DC's and the PWC's on or near the tracks and extrapolated them to the downstream end, where the magnetic field is not uniform, to pick up events in that region. The curvature of the track is adjusted to minimize the $\chi^2$ between the track and the corresponding hits to obtain the magnitude of the momentum of the charged particle.
3.2.2 Vertex Search

The next stage of the analysis looked for vertices to see if the parent particle originated in the decay volume. The tracks were extrapolated upstream towards the target. Due to the effects of the fringe fields the track was extrapolated in steps of 5 cm and the B field was adjusted if necessary. The field was neglected when the track was ~ 60 cm away from the front face of the magnet and the extrapolation was completed using a straight segment. A vertex was assigned to a set of tracks if they were separated by ≤ 4 cm. The vertex position was fixed as the midpoint of the line joining the two tracks at the point of closest approach.

3.3 Particle Identification

After writing data summary tapes (DST's) from the preliminary analysis on the IBM, we worked with the short files to extract the physics results presented in this thesis. The Σ^0 was identified by reconstructing the daughter lambda from the charged particle tracking and the photon from the shower in the LG. We also gathered a reasonable sample of K, mesons and a small sample of Λ's.

3.3.1 Source Of Background Events

The event sample we wish to analyse consists of Λ, Σ^0, K, and Λ particles. It is easy to separate them by reconstructing their effective masses from their decay product momenta. Although the Λ sample is free of background events, the effective mass plot of the Σ^0's shows a substantial background. This is due to the identification of Λ's with
uncorrelated neutral showers which give an effective mass in the correct region. We detect \( \Lambda \)'s which are produced directly in the interaction and those which are decay products of \( \Sigma^0 \), \( \Xi^0 \) and other heavy resonances. The events due to \( \Xi^0 \) decay are easily eliminated because of the weak decay to \( \Lambda \pi^0 \) which occurs outside the target. A projection of the sum of the \( \Lambda \gamma \) momentum from this event will not reach the target. Let us now consider the other sources of background errors.

The biggest source of background for the \( \Lambda \)'s was poor reconstruction due to missed chamber hits. This was more severe when the chamber was closer to the target. Monte Carlo analysis show that missed hits at the downstream end of the magnet have little or no effect on the invariant mass plot, while switching off key planes in the chambers closest to the target resulted in no reconstructed vertices.

The \( \Lambda \)'s which are produced downstream of the target such that \( S_4 \) can no longer eclipse \( S_5 \) are another source of background in the data sample. These two sources of background can be removed by applying cuts on the reconstructed vertices, projections of the \( \Lambda \) momenta back to the target and the invariant mass. By removing the \( K_\pi \) events, which have a well defined mass peak, we can eliminate more of the background in the \( \Lambda \) sample.

The width of the \( \Sigma^0 \) mass peak is governed by the errors in reconstructing the \( \Lambda \) momentum, \( \gamma \) energy and position. The relative errors in the \( \Sigma^0 \) mass for errors in reconstructing the two particles is given in the next section. The errors for the photon reconstruction come from the detector limitations and are described in section 3.6.3. The \( \Sigma^0 \) mass is also affected if we reconstruct its mass using a \( \gamma \) which does not come
from a Σ⁰ decay. Spurious neutral showers can be produced by π⁰ decay, due to debris coming from interactions in the beam pipe or in the chamber walls in the MPS magnet. Showers which are generated by hadrons must also be eliminated.

3.3.2 Λ and ¯Λ Reconstruction

To separate the real Λ's from the background we required the data to satisfy the following conditions.

1. The Λ vertex should be between S4 and S5 for efficient reconstruction.

2. The Λ should originate in the target.

   This can be checked by projecting the vector sum of the daughter particles to the target.

3. The invariant mass of the Λ should be within ± 5.6 MeV/c² of its actual mass of 1115.6 MeV/c².

   The Λ invariant mass is calculated by hypothesizing that the two charged particles we detect are π⁻ and p. This requirement eliminates Λ's which are on the shoulder of the mass peak and occur because they were poorly reconstructed due to missed chamber hits.

We employed the following vertex and target cuts to identify the Λ.

- \(-132 \leq x_{vertex} \leq -70\)
- \(-20 \leq y_{vertex} \leq 20\)
- \(-390 \leq z_{vertex} \leq -220\)
\begin{itemize}
\item $-130 \leq x_{\text{target}} \leq -139$
\item $-5.5 \leq y_{\text{target}} \leq 5$
\end{itemize}

We plot the distribution of the reconstructed vertex position and extrapolation to the target for the \(\Lambda\) sample in figs 3.1 and 3.2. The mass of the reconstructed \(\Lambda\)’s is shown in fig 3.3. We see that there is little background under the peak. The \(x_{\text{F}}\) and \(p_{\text{T}}\) distribution for the \(\Lambda\) events is shown in figure 3.4.

### 3.3.3 \(K_{s}\) Reconstruction

Neutral particles which have a lifetime and mass such that they decay between S4 and S5 will satisfy all the trigger requirements if they decay to two oppositely charged particles. \(K_{s}\) mesons have a mean lifetime of \(0.8923 \times 10^{-10}\) s compared to \(2.632 \times 10^{-10}\) s for the \(\Lambda\) and they have the similar decay lengths. We were able to reconstruct \(K_{s}\) particles under the decay hypothesis \(K_{s} \rightarrow \pi^{+}\pi^{-}\). The peak rests on a flat background coming from the \(\Lambda\) reconstruction (fig. 3.5). The vertex and target cuts for this case were the same as that employed for the \(\Lambda\) case. The \(x_{\text{F}}\) and \(p_{\text{T}}\) distribution are shown in fig 3.6.

### 3.3.4 Photon Identification

The photon was reconstructed by using a modular LG array. We measured the energy and position of the photon using data from a calibration performed earlier [KRI88]. We give a brief description of the LG analysis here.
Fig 3.1 Vertex positions of all Λ's
Fig 3.2 Extrapolation of parent particle momentum to the target for all $\Lambda$'s
<m_{\text{pr}}>=1116 \pm 2.9 \text{ MeV/c}^2

Fig 3.3 Effective mass assuming that positive tracks are protons and negative tracks belong to \( \pi^- \). The peak occurs at the \( \Lambda \) mass.
Fig 3.4 (a) $x_F$ and (b) $p_T$ distributions for the $\Lambda$ events
Fig. 3.5 Effective mass assuming that positive tracks are $\pi^+$ and negative tracks belong to $\pi^-$. The peak occurs at the $K_\pi$ mass.
Fig 3.6 (a) $x_F$ and (b) $p_T$ distributions for the $K_s$ events
Definition of a Cluster

All the active blocks whose centers lie within a radius of 17 cm from the central block (block with largest energy deposited) are said to belong to a cluster. When two clusters form close by such that there is an overlap of their showers the set of contiguous active blocks show a local maximum. In such a case it is assumed that the energy in the block common to both clusters is shared in direct proportion to the energy in their central blocks.

Energy Resolution

The LG array was calibrated in the summer of 1986 using a beam of electrons produced by the decay of $\pi^0$s in the MESB at the AGS. The range of energies chosen for the calibration were 1 and 2 GeV/c. This was the energy of the photons from $\Sigma^0$ decay in the experimental setup as calculated by a Monte Carlo study. The results of the calibration are reported in [KRI88].

The energy for block $i$ is obtained by using the relation

$$E_i = A_i X_i + B_i$$

where $A_i$ refers to the energy conversion factor obtained from the calibration (fig 3.7), $X_i$ is the pedestal subtracted ADC value and $B_i$ is found to be zero.

Position Resolution

Even though complicated algorithms were used to calculate the position of the incident particle it was found that the centroid of the energy distribution worked as well. As a
Fig. 3.6 Energy conversion factors $\times 10^{-3}$ for all the blocks. The ADC value times the conversion factor gives the energy deposited in the block.
first step we used this method to find the position of the photon

\[
X_\gamma = \frac{\sum_i E_i x_i}{\sum_i E_i}, \quad Y_\gamma = \frac{\sum_i E_i y_i}{\sum_i E_i}
\]  

(3.2)

where \( i \) runs over all the blocks in the cluster. \( (x_i, y_i) \) refer to the coordinates of the center of block \( i \).

Sources of Errors

The processes that lead to a shower development are statistical in nature. This leads to a natural fluctuation in the energy deposited by a monoenergetic beam of particles. Variations in photocathode gain and fluctuations in the multiplication stage of the PM tube can also cause fluctuations which have to be monitored. Another source of errors is the noise in the active medium and electronics.

The energy resolution is governed by energy leakage from the back due to insufficient material, improper interfacing between the PM tube and the lead glass block and pedestal fluctuation in the ADC modules. We noticed a pedestal fluctuation of 1-2 channels which corresponds to \( \Delta E \sim 5 \text{ MeV} \). A calculation of the energy containment, shown in Table 2.5, gives a leakage of \( \sim 30 \text{ MeV} \). The interfacing was judged to be the main factor in diminishing the energy resolution from the tests done on the bench during the assembly of the array [BAU82]. The errors in position determination have relatively little effect on the \( \Sigma^9 \) mass determination, as shown in the next section.

During calibration the electrons were incident normal to the LG face. In the experiment the photons are incident at angles of up to 3.5°. Monte Carlo simulations show that up to 2% of the energy could be lost if the photons were incident at an angle of 3° w.r.t
the axis of the block [FOR88]. As the incident angle increases the number of Čerenkov photons above the critical angle for internal reflection increases thereby causing a loss.

Another source of error is the anomalous readings obtained due to the presence of the lead glass guide. A photon incident at the center of the block would give a multiplication of the shower in the light guide whereas a photon incident near the edges would mostly miss the light guide.

We monitored the stability of the LG during the experiment by using the LED system. We show the results over the entire period in figure 3.8a and 3.8b. In figure 3.8a we have plotted the total LED value for all the blocks in the LG. This is an indicator of the stability of the LED light source. From the plot we can be reasonably certain that there is no large fluctuation in the output of the LED. In figure 3.8b we plot the mean of the LED values for individual blocks averaged over the whole run. The variance of the mean value is shown as the error bar. We see that it is reasonable except for those blocks which were known to be fluctuating from the calibration run too.

3.4 \( \Sigma^0 \) Reconstruction

\( \Sigma^0 \)'s were identified by reconstructing the invariant mass of \( \Lambda \)'s and \( \gamma \)'s which came from the same event. The \( \Sigma^0 \) mass is calculated from the relation

\[
m_{\Sigma^0}^2 = m_\Lambda^2 + 2p_\gamma \left( \sqrt{p_\Lambda^2 + m_\Lambda^2} - p_\Lambda \cos \theta \right)
\]

\( \theta \) : angle between \( \Lambda \) momentum and \( \gamma \) direction

\( p_\Lambda \) : \( \Lambda \) momentum

\( p_\gamma \) : \( \gamma \) momentum
Fig 3.8 Mean LED values for (a) all the blocks for a single run, and (b) individual blocks.
\[ m_A : \text{mass of } \Lambda \text{ taken to be } 1115.6 \text{ MeV}/c^2 \]

\[ m_{\Sigma^0} : \text{mass of } \Sigma^0 \]

The \( \Lambda \) was identified as described earlier in 3.6.1. The range of reconstructed mass for allowed \( \Lambda \)'s was 1110 and 1122 MeV/c\(^2\). Once we have identified a \( \Lambda \) with its mass within the tolerance range specified we take its mass to be the one given in the Particle Data Booklet for calculating the \( \Sigma^0 \) mass. We required the photon to have an energy greater than 0.45 GeV. The photon energy for the events which reconstruct to a mass within the specified limits for \( \Sigma^0 \) is shown in fig 3.9. We see that the energy peaks at \(~1\) GeV as expected from Monte Carlo results and the minimum cut of 0.45 GeV for the cluster energy is reasonable. Monte Carlo analysis suggests that for the placement of the LG as used in our experiment the photon energy from \( \Sigma^0 \) decay starts at 0.4 GeV and peaks at 1.0 GeV. To further isolate the shower as coming from a neutral non-hadronic interaction we used information from the scintillator veto hodoscope placed in front of the LG. If any of the scintillators fired which covered the LG blocks which were a part of the photon cluster or were adjacent to it. If the extrapolated track of any charged particle passed within 13.0 cm from the center of the cluster, the event was rejected. To be certain that the photon was generated in the same event as the \( \Lambda \), we required the photon to arrive within a certain time of the proton interacting in the target. This was accomplished by using time-to-digital counters (TDC) which were attached to each layer of the lead glass array.

After determining the photon energy and position we can obtain its momentum. We extrapolated the centroid position to the target in a straight line to get the momentum.
Fig 3.9 Photon energy of events in the $\Sigma^0$ mass peak.
components. If $c_1$, $c_2$, $c_3$ are the components of the centroid in the $x$, $y$ and $z$ directions respectively, then the photon's momentum is given by

$$p_\gamma^x = (c_1 \hat{x} + c_2 \hat{y} + c_3 \hat{z}) E_\gamma,$$

where $E_\gamma$ is the photon energy.

From the calibration of the calorimeter we obtained the following energy and position resolutions

$$\frac{\Delta E}{\sqrt{E}} = 18\% \quad \Delta x = \Delta y \sim 2 - 3\text{cm}$$

The error in calculating the $\Sigma^0$ mass comes from the error in determining the $\Lambda$ momentum $p_\Lambda$, photon energy and the photon position. The first error is a measure of the error in tracking charged particles in the magnet which is negligible. For a typical photon ($\sim 1 \text{ GeV}/c$), we obtain the following relative errors in the $\Sigma^0$ mass.

$$\Delta m_{\Sigma^0} \bigg|_{p_\Lambda} = 0.12 MeV/c^2$$
$$\Delta m_{\Sigma^0} \bigg|_{E_\gamma} = 17.5 MeV/c^2$$
$$\Delta m_{\Sigma^0} \bigg|_{\theta_\gamma} = 1.3 MeV/c^2$$

Thus we see that the error in determining the photon's energy is responsible for the width of the $\Sigma^0$ mass peak apart from its natural width, of course. The calorimeter also introduces an error by counting photons from sources other than $\Sigma^0$ decay. These photons can fool the trigger system and when coupled with the $\Lambda$ mass give a $\Sigma^0$ mass which is not unreasonable. The source of this background can be due to pion decay ($\pi^0 \rightarrow \gamma\gamma$), showers from particles hitting the drift chambers or material upstream of the calorimeter, decay of higher mass baryons etc. .
The vertex and target cuts for the $\Sigma^0$ events are identical to those for the $\Lambda$ events. We show the vertex position and target projection for all events in the $\Sigma^0$ mass peak, which includes all events within 1180 MeV/c$^2$ and 1230 MeV/c$^2$, in fig 3.10 and 3.11 respectively. The $x_p$, $p_T$ distributions of the events in the $\Sigma^0$ peak are shown in figures 3.12a and 3.12b respectively. The $\Sigma^0$ mass for all events in which $E_\gamma > 0.45$ GeV is shown in fig 3.13. The energies of $\Lambda$'s and $\Sigma^0$'s in the $\Sigma^0$ mass peak are shown in fig 3.14.
Fig 3.10 Vertex positions of Λ's in the Σ⁰ mass peak.
Fig 3.11 Extrapolation of $\Sigma^0$ momentum to the target.
Fig 3.12 (a) $x_F$ and (b) $p_T$ distributions for the $\Sigma^2$ events.
Fig 3.13 Effective mass of $\Delta \gamma$ for $E_\gamma > 0.45$ GeV.
Fig 3.14 Energy distribution of (a) $\Lambda$'s and (b) $\Sigma^0$'s within the $\Sigma^0$ mass peak.
Chapter 4

Results

The spin parameters polarization $P$, analyzing power $A$ and depolarization $D$ are defined as

$$P = \frac{(W_{\|} - W_{\|}) + (W_{\perp} - W_{\perp})}{W_{\|} + W_{\|} + W_{\perp} + W_{\perp}} \quad (4.1)$$

$$P_{BA} = \frac{(W_{\|} - W_{\|}) + (W_{\perp} - W_{\perp})}{W_{\|} + W_{\|} + W_{\perp} + W_{\perp}} \quad (4.2)$$

$$P_{BD} = \frac{(W_{\|} - W_{\|}) + (W_{\perp} - W_{\perp})}{W_{\|} + W_{\|} + W_{\perp} + W_{\perp}} \quad (4.3)$$

$W_{fi}$ denotes the probability of scattering from beam spin state $i$ to target projectile spin state $f$ and $p_B$ is the beam polarization. We define a new parameter, $p^\pm$, for the polarization of the particle due to beam spin up or down, as

$$p^+ = \frac{W_{\|} - W_{\|}}{W_{\|} + W_{\|}}$$

$$p^- = \frac{W_{\|} - W_{\|}}{W_{\perp} + W_{\perp}}$$
From the relations given above we can derive the following useful expression which combines all the three parameters

\[ p^\pm = \frac{P \pm P_B D}{1 \pm P_B A} \] (4.4)

where ± refers to the beam polarization.

### 4.1 Analyzing Power For Λ Production

The analyzing power \( A \) is obtained, by definition, from the relation

\[ \epsilon \equiv P_N A = \frac{N^+ - N^-}{N^+ + N^-} \] (4.5)

where \( N^\pm \) are the number of Λ’s produced for beam spin up and spin down respectively.

If the beam fluxes for both spin up and spin down spills are not equal over the whole run then we can normalize \( N^\pm \) to correct for it. We have taken this into account for calculating the spin parameters but do not show it here to keep the equations from looking cluttered. We estimate that neglecting this correction leads to a difference in the analyzing power of ~ 1%. Thus we arrive at the relation for the analyzing power

\[ A = \frac{1}{P_N} \frac{N^+ - N^-}{N^+ + N^-} \] (4.6)

\( P_N \) is the component of the polarization along the normal to the scattering plane, \( \hat{N} \), defined by

\[ \hat{N} = \frac{P_{\text{beam}} \times P_\Lambda}{|P_{\text{beam}} \times P_\Lambda|} \] (4.7)

which gives

\[ A = \frac{1}{p_B \cos \phi} \frac{N^+ - N^-}{N^+ + N^-} \] (4.8)
where

\[ \langle \cos \phi \rangle = \frac{\langle \hat{N} \cdot \mathbf{p}_B \rangle}{p_B} \]

\( \cos \phi \) is the angle which the polarization axis of the beam makes with the \( \hat{N} \) direction. The subscript \( N \) denotes the component of the beam polarization. We have shown in fig 4.1 the distribution of this angle for all the events in the \( \Sigma^0 \) mass peak.

### 4.1.1 Detector Asymmetry Correction

The lead glass array was intentionally not placed symmetrically with respect to the horizontal plane to maximize the polarization of the observed \( \Lambda \)'s. This led to a necessary correction due to the different detection efficiencies of the MPS along the different parts of the lead glass. If the beam has polarization only along the normal direction (as defined above), then the scattering will be left-right asymmetric. Since the MPS has no coverage for the right scattered particles (particles which go to the right when looking along the beam) there is no induced asymmetry. If the beam has a polarization in the horizontal plane then the scatterings are up-down asymmetric and the detector asymmetry can give a systematic error. Consider a beam with polarization \( p_x \), along the \( x \) axis. Let \( N_{u,d} \) be the number of up, down scatterings, \( N_\pm \) be the number of particles going up, down with beam polarization along \( \pm x \) respectively. If \( E_{u,d} \) are the detection efficiencies for up, down part of the detector, then

\[ N^u = E^u N_+ + E^d N_- \]  \hspace{1cm} (4.9)

\[ N^d = E^d N_+ + E^u N_- \]  \hspace{1cm} (4.10)
Fig 4.1 Angle between the normal to the $\Sigma^0$ production plane and the beam polarization for all events in the $\Sigma^0$ mass peak.
\[ \frac{N^u - N^d}{N^u + N^d} = \left( \frac{N_+ - N_-}{N_+ + N_-} \right) \left( \frac{E^u - E^d}{E^u + E^d} \right) \quad (4.11) \]

= raw u,d asymmetry

= \( A_P \) \( E \) \quad (4.12)

We find that if the beam polarization has a component along the x direction the induced asymmetry is given by eqn 4.14. For our coordinate system the beam is polarized such that the horizontal component is along the \(-x\) direction. Thus the analyzing power is given by

\[ \epsilon = p_B \langle \cos \phi \rangle A - |P_x| A E \]

\[ A_N = \frac{\epsilon}{p_B \langle \cos \phi \rangle - |P_x| E} \quad (4.13) \]

We can estimate \( E \) by counting all the particles with momentum along \( \pm y \), \( N_{P_\pm} \) averaged over both spins.

\[ E = \frac{N_{P_+} - N_{P_-}}{N_{P_+} + N_{P_-}} \quad (4.14) \]

We have shown the momentum distribution for \( \Lambda \)'s coming from \( \Sigma^0 \) decay for the whole kinematic region of our experiment in fig 4.2.

Finally, we have the relation for calculating the analyzing power of the \( \Lambda \)'s corrected for detector asymmetries

\[ A_\Lambda = \frac{\epsilon}{p_B \langle \cos \phi \rangle - P_x E} \quad (4.15) \]

Table 4.1 below gives the results of the calculations for \( \Lambda \) analyzing power, \( A_\Lambda \).

In fig 4.3 we show the \( x_F \) and \( p_T \) dependence of the analyzing power for \( \Lambda \) production. The variation with respect to \( x_F \) shows a clear indication of approaching zero at higher
Fig 4.3 Distribution of Λ Momentum for all events in the Σ^0 mass peak.

\[
\langle p_y \rangle = -0.06
\]
TABLE 4.1
Results For Analyzing Power Of Directly Produced \(\Lambda\)'s.

<table>
<thead>
<tr>
<th>(x_F)</th>
<th>(p_T)</th>
<th>(&lt;x_F&gt;_\Lambda)</th>
<th>(&lt;p_T&gt;_\Lambda)</th>
<th>(E)</th>
<th>(&lt;\cos\phi&gt;_\Lambda)</th>
<th>(\epsilon \times 10^{-3})</th>
<th>(A)</th>
<th>(A_{\Lambda})</th>
</tr>
</thead>
<tbody>
<tr>
<td>all</td>
<td>all</td>
<td>0.251</td>
<td>1.103</td>
<td>.249</td>
<td>0.840</td>
<td>-7.78</td>
<td>-0.021</td>
<td>-0.024</td>
</tr>
<tr>
<td></td>
<td></td>
<td>± 2.33</td>
<td>± 0.006</td>
<td>± 0.007</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>.0-.2</td>
<td>all</td>
<td>0.123</td>
<td>0.963</td>
<td>.288</td>
<td>0.857</td>
<td>-13.62</td>
<td>-0.036</td>
<td>-0.043</td>
</tr>
<tr>
<td></td>
<td></td>
<td>± 3.89</td>
<td>± 0.011</td>
<td>± 0.012</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>.2-.3</td>
<td>all</td>
<td>0.250</td>
<td>1.108</td>
<td>.259</td>
<td>0.840</td>
<td>-8.95</td>
<td>-0.024</td>
<td>-0.028</td>
</tr>
<tr>
<td></td>
<td></td>
<td>± 4.67</td>
<td>± 0.013</td>
<td>± 0.015</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>.3-.4</td>
<td>all</td>
<td>0.346</td>
<td>1.211</td>
<td>.229</td>
<td>0.839</td>
<td>-6.22</td>
<td>-0.107</td>
<td>-0.019</td>
</tr>
<tr>
<td></td>
<td></td>
<td>± 5.06</td>
<td>± 0.014</td>
<td>± 0.016</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>.4-.8</td>
<td>all</td>
<td>0.08</td>
<td>0.684</td>
<td>.113</td>
<td>0.857</td>
<td>-1.56</td>
<td>-0.004</td>
<td>-0.004</td>
</tr>
<tr>
<td></td>
<td></td>
<td>± 7.78</td>
<td>± 0.020</td>
<td>± 0.020</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>.0-.2</td>
<td>.8-.2.</td>
<td>0.130</td>
<td>1.037</td>
<td>.337</td>
<td>0.840</td>
<td>-16.34</td>
<td>-0.044</td>
<td>-0.054</td>
</tr>
<tr>
<td></td>
<td></td>
<td>± 4.67</td>
<td>± 0.013</td>
<td>± 0.016</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>.2-.35</td>
<td>.8-.2.</td>
<td>0.273</td>
<td>1.146</td>
<td>.261</td>
<td>0.839</td>
<td>-7.78</td>
<td>-0.021</td>
<td>-0.025</td>
</tr>
<tr>
<td></td>
<td></td>
<td>± 3.89</td>
<td>± 0.011</td>
<td>± 0.012</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>.35-1.</td>
<td>.8-.2.</td>
<td>0.439</td>
<td>1.308</td>
<td>.192</td>
<td>0.839</td>
<td>-3.11</td>
<td>-0.008</td>
<td>-0.009</td>
</tr>
<tr>
<td></td>
<td></td>
<td>± 4.67</td>
<td>± 0.013</td>
<td>± 0.014</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>.2-.1.</td>
<td>all</td>
<td>0.337</td>
<td>1.200</td>
<td>.230</td>
<td>0.839</td>
<td>-5.45</td>
<td>-0.015</td>
<td>-0.017</td>
</tr>
<tr>
<td></td>
<td></td>
<td>± 3.11</td>
<td>± 0.008</td>
<td>± 0.009</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[
\epsilon = \frac{N^+ - N^-}{N^+ + N^-}
\]

\[
A = \frac{1}{p_B <\cos\phi>} \frac{N^+ - N^-}{N^+ + N^-}
\]

\[
A_{\Lambda} = \frac{1}{p_B <\cos\phi>} - P_{\pi E} \frac{N^+ - N^-}{N^+ + N^-}
\]
Fig 4.3 Variation of the Analyzing Power for all Λ's w.r.t. (a) $p_T$ and (b) $x_F$. ○ : all data.
x_F values. This is in agreement with the previous measurement [BON87]. The data has been plotted by averaging over all p_T and taking bins in x_F only. The p_T variation is however skewed because each point on the graph has a different x_F value. The relation between x_F and p_T is linear. The higher p_T data also has higher x_F. The first data point is binned over the lowest p_T values and averaged over all x_F. It includes data that has undergone a very mild collision in the target and so does not show any effect. From the two figures we can see that the analyzing power for Λ's is very small and approaches zero for modest p_T and x_F.

4.2 Analyzing Power For Σ^0 Production

The procedure for determining the analyzing power of the Σ^0's is more complicated than that for the Λ's due to the background because the background under the Λ peak is negligible and no correction is needed which is not the case for the Σ^0's. Due to the low statistics and the inherent uncertainties in the LG detector there is substantial background under the Σ^0 peak. Since this arises due to Λ's pairing up with uncorrelated γ's, we must subtract this background to calculate the Σ^0 results independent of Λ's produced directly or from sources other than Σ^0 decay. The analyzing power of the Σ^0's is measured by calculating the asymmetry of Σ^0 production. This relates in practice to counting the number of Σ^0's for beam spin up and spin down. The calculation is essentially identical to the one given for Λ's except that the raw asymmetry has to be corrected for background Λ's. The asymmetry is defined as before,

$$\epsilon = \frac{N^+ - N^-}{N^+ + N^-}$$  \hspace{1cm} (4.16)
The asymmetry we have calculated contains the average result of all the $\Sigma^0$'s under the mass peak. As we can see, this peak rests on a background due to uncorrelated photons which fortuitously give a correct mass when coupled with the $\Lambda$. These photons can come from the primary interaction, from showers initiated elsewhere in the magnet, due to decay of $\pi^0$'s or due to the decay of massive resonances. After estimating the background we must subtract the contribution due to these accidental $\Sigma^0$'s.

If $N_{\Sigma}$ and $N_{BG}$ are the number of actual $\Sigma^0$ and background events, which we obtain by fitting the background to an exponential for $m < m_\Sigma - \Delta m_\Sigma$ and a polynomial for $m > m_\Sigma + \Delta m_\Sigma$, then the measured asymmetry is given by

$$\epsilon = \frac{N_{\Sigma}}{N_{tot}} \epsilon_\Sigma + \frac{N_{BG}}{N_{tot}} \epsilon_{BG}$$

(4.17)

Here $\epsilon_\Sigma$ and $\epsilon_{BG}$ represent the asymmetries of the $\Sigma^0$'s and the background events respectively. The background parameters are calculated by taking all the events which pass the $\Sigma^0$ event cut and fall in the mass range of 1.10 to 1.18 GeV/c. The $\Sigma^0$ peak consists of all the $\Sigma^0$ events which lie within 1.18 and 1.23 GeV/c. This division of events for calculating the $BG$ and peak parameters is common for the whole analysis.

Rearranging the above equation we get

$$\epsilon_\Sigma = S \epsilon - (S - 1) \epsilon_{BG}$$

(4.18)

where $S = N_{tot}/N_{\Sigma}$ is a measure of the background. The results of the background ratio calculations are shown in the table below.
Table 4.2

Estimate Of The Background Content In The $\Sigma^0$ Peak

<table>
<thead>
<tr>
<th>$x_F$</th>
<th>$p_T$</th>
<th>$N_{tot}$</th>
<th>$N_\Sigma$</th>
<th>$S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>all</td>
<td>all</td>
<td></td>
<td>2.3 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>all</td>
<td>0.4-0.8</td>
<td>1076</td>
<td>169</td>
<td>6.3 ± 0.3</td>
</tr>
<tr>
<td>0.0-0.2</td>
<td>0.8-2.0</td>
<td>4295</td>
<td>1475</td>
<td>2.91 ± 0.3</td>
</tr>
<tr>
<td>0.2-0.35</td>
<td>0.8-2.0</td>
<td>7407</td>
<td>3450</td>
<td>2.14 ± 0.2</td>
</tr>
<tr>
<td>0.35-1.0</td>
<td>0.8-2.0</td>
<td>6732</td>
<td>3951</td>
<td>1.70 ± 0.1</td>
</tr>
<tr>
<td>0.2-1.0</td>
<td>all</td>
<td>14139</td>
<td>7401</td>
<td>1.91 ± 0.1</td>
</tr>
</tbody>
</table>

Following the argument adopted for the $\Lambda$ we find similarly for the $\Sigma^0$ that

\[
A_\Sigma = \frac{1}{p_B < \cos \phi >_\Sigma - p_x E_\Sigma} \epsilon_\Sigma
\]  

(4.19)

where $E_\Sigma$ is the detector asymmetry for measuring $\Sigma^0$'s. We expect this number to be different for $\Lambda$'s and $\Sigma^0$'s due to the asymmetric placement of the LG calorimeter. In the table below we see how they compare. We have calculated $E$ for $\Sigma^0$'s which have been corrected for background contamination according to the now familiar relation

\[
E_\Sigma = S E - (S - 1) E_{BG}
\]  

(4.20)

We assume that $E_{BG} = E_{\Lambda}$. 
Table 4.3
Detector Asymmetry Correction For $\Sigma^0$ Measurements

<table>
<thead>
<tr>
<th>$x_F$</th>
<th>$p_T$</th>
<th>$E$</th>
<th>$E_A$</th>
<th>$E_\Sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>all</td>
<td>all</td>
<td>0.248</td>
<td>0.249</td>
<td>0.246</td>
</tr>
<tr>
<td>all</td>
<td>0.4-0.8</td>
<td>0.186</td>
<td>0.113</td>
<td>0.569</td>
</tr>
<tr>
<td>0.0-0.2</td>
<td>0.8-2.0</td>
<td>0.309</td>
<td>0.337</td>
<td>0.256</td>
</tr>
<tr>
<td>0.2-0.35</td>
<td>0.8-2.0</td>
<td>0.257</td>
<td>0.261</td>
<td>0.253</td>
</tr>
<tr>
<td>0.35-1.0</td>
<td>0.8-2.0</td>
<td>0.201</td>
<td>0.192</td>
<td>0.207</td>
</tr>
<tr>
<td>0.2-1.0</td>
<td>all</td>
<td>0.240</td>
<td>0.230</td>
<td>0.249</td>
</tr>
</tbody>
</table>

On examining the mass bins to the left of the mass peak we find that $\epsilon_{BG} = \epsilon_A$.

This implies that

$$A_{BG} = A_A = \frac{1}{P_B < \cos \phi>_A - P_x E_A} \epsilon_A$$ (4.21)

Similarly our measurements include $< \cos \phi>$ for the whole peak. This is separated into $< \cos \phi>_\Sigma$ and $< \cos \phi>_A$ using

$$< \cos \phi>_\Sigma = S < \cos \phi> - (S-1) < \cos \phi>_A$$ (4.22)

We have tabulated below the results of the calculations for $< \cos \phi>_\Sigma$. 
Table 4.4

Background Corrected Values For $< \cos \phi >_\Sigma$

<table>
<thead>
<tr>
<th>$x_F$</th>
<th>$p_T$</th>
<th>$&lt; \cos \phi &gt;$</th>
<th>$&lt; \cos \phi &gt;_{BG}$</th>
<th>$&lt; \cos \phi &gt;_{\Lambda}$</th>
<th>$&lt; \cos \phi &gt;_{\Sigma}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>all</td>
<td>all</td>
<td>0.843</td>
<td>0.839</td>
<td>0.841</td>
<td>0.848</td>
</tr>
<tr>
<td>all</td>
<td>0.4-0.8</td>
<td>0.848</td>
<td>0.853</td>
<td>0.857</td>
<td>0.821</td>
</tr>
<tr>
<td>0.0-0.2</td>
<td>0.8-2.0</td>
<td>0.846</td>
<td>0.838</td>
<td>0.840</td>
<td>0.861</td>
</tr>
<tr>
<td>0.2-0.35</td>
<td>0.8-2.0</td>
<td>0.842</td>
<td>0.838</td>
<td>0.839</td>
<td>0.846</td>
</tr>
<tr>
<td>.35-1.0</td>
<td>0.8-2.0</td>
<td>0.841</td>
<td>0.839</td>
<td>0.840</td>
<td>0.842</td>
</tr>
<tr>
<td>0.2-1.0</td>
<td>all</td>
<td>0.841</td>
<td>0.839</td>
<td>0.839</td>
<td>0.843</td>
</tr>
</tbody>
</table>

The kinematic variables for $\Sigma^0$ are also subject to changes due to the $\Lambda$ background. We correct for this using relations for $x_F$ and $p_T$ similar to those used for $< \cos \phi >$ and $E$. In Table 4.5 we have listed the calculation for these two parameters.

Table 4.5

Background Corrected Values Of $x_F$ and $p_T$

<table>
<thead>
<tr>
<th>$x_F$</th>
<th>$&lt; x_F &gt;$</th>
<th>$&lt; x_F &gt;_{\Lambda}$</th>
<th>$&lt; x_F &gt;_{\Sigma}$</th>
<th>$p_T$</th>
<th>$&lt; p_T &gt;$</th>
<th>$&lt; p_T &gt;_{\Lambda}$</th>
<th>$&lt; p_T &gt;_{\Sigma}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>all</td>
<td>0.292</td>
<td>0.130</td>
<td>0.30</td>
<td>all</td>
<td>1.176</td>
<td>1.187</td>
<td>1.16</td>
</tr>
<tr>
<td>all</td>
<td>0.107</td>
<td>0.080</td>
<td>0.25</td>
<td>0.4-0.8</td>
<td>0.719</td>
<td>0.700</td>
<td>0.82</td>
</tr>
<tr>
<td>0.0-0.2</td>
<td>0.131</td>
<td>0.133</td>
<td>0.13</td>
<td>0.8-2.0</td>
<td>1.076</td>
<td>1.066</td>
<td>1.10</td>
</tr>
<tr>
<td>0.2-0.35</td>
<td>0.277</td>
<td>0.276</td>
<td>0.28</td>
<td>0.8-2.0</td>
<td>1.176</td>
<td>1.187</td>
<td>1.16</td>
</tr>
<tr>
<td>.35-1.0</td>
<td>0.449</td>
<td>0.447</td>
<td>0.45</td>
<td>0.8-2.0</td>
<td>1.317</td>
<td>1.351</td>
<td>1.30</td>
</tr>
<tr>
<td>0.2-1.0</td>
<td>0.357</td>
<td>0.35</td>
<td>0.36</td>
<td>all</td>
<td>1.236</td>
<td>1.255</td>
<td>1.22</td>
</tr>
</tbody>
</table>
Thus we have the final expression for the $\Sigma^0$ analyzing power

$$A_{\Sigma} = S \frac{1}{P_B < \cos \phi >_{\Sigma} - P_x E_{\Sigma} \epsilon - (S - 1)} \frac{P_B < \cos \phi >_{\Lambda} - P_x E_{\Lambda}}{P_B < \cos \phi >_{\Sigma} - P_x E_{\Sigma}} A_{\Lambda}$$  \hspace{1cm} (4.23)

We know $< \cos \phi >_{\Lambda}$ and $A_{\Lambda}$ from the previous analysis. Thus by measuring the raw asymmetry, $\epsilon$, for the $\Sigma^0$ peak we can calculate the analyzing power for the $\Sigma^0$, $A_{\Sigma}$.

We have the final results for $\Sigma^0$ analyzing power listed in Table 4.6. In fig 4.4 we show the $x_F$ and $p_T$ dependence of the analyzing power. We see that as we approach higher $x_F$ the analyzing power approaches zero. This is more pronounced than for the $\Lambda$ case.

The data in this case consists of separate $x_F$ and $p_T$ bins, so we cannot assign any mean values for the whole plot.
Table 4.6

Results Of Analyzing Power For Inclusively Produced $\Sigma^0$'s.

<table>
<thead>
<tr>
<th>$x_F$</th>
<th>$P_T$</th>
<th>$&lt;x_F&gt;_{\Sigma}$</th>
<th>$&lt;P_T&gt;_{\Sigma}$</th>
<th>$E$</th>
<th>$&lt;\cos \phi&gt;_{\Sigma}$</th>
<th>$\epsilon 10^{-3}$</th>
<th>$A_\Lambda$</th>
<th>$A_\Sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>all</td>
<td>all</td>
<td>0.300</td>
<td>1.16</td>
<td>.249</td>
<td>.848</td>
<td>-6.22</td>
<td>-.024</td>
<td>-.014</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\pm 7.00$</td>
<td>$\pm .007$</td>
<td>$\pm .051$</td>
</tr>
<tr>
<td>all</td>
<td>.4-.8</td>
<td>0.25</td>
<td>0.82</td>
<td>.113</td>
<td>.821</td>
<td>-14.39</td>
<td>-.004</td>
<td>-.245</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\pm 30.34$</td>
<td>$\pm .002$</td>
<td>$\pm .563$</td>
</tr>
<tr>
<td>.0-.2</td>
<td>.8-.2</td>
<td>0.13</td>
<td>1.10</td>
<td>.337</td>
<td>.861</td>
<td>-28.79</td>
<td>-.054</td>
<td>-.171</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\pm 15.17$</td>
<td>$\pm .016$</td>
<td>$\pm .146$</td>
</tr>
<tr>
<td>.2-.35</td>
<td>.8-.2</td>
<td>0.28</td>
<td>1.16</td>
<td>.261</td>
<td>.846</td>
<td>-10.89</td>
<td>-.025</td>
<td>-.045</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\pm 11.28$</td>
<td>$\pm .012$</td>
<td>$\pm .077$</td>
</tr>
<tr>
<td>.35-1.</td>
<td>.8-.2</td>
<td>0.45</td>
<td>1.30</td>
<td>.192</td>
<td>.842</td>
<td>+11.67</td>
<td>-.009</td>
<td>+.066</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\pm 12.06$</td>
<td>$\pm .014$</td>
<td>$\pm .063$</td>
</tr>
<tr>
<td>.2-1.</td>
<td>all</td>
<td>0.35</td>
<td>1.22</td>
<td>.230</td>
<td>.842</td>
<td>+.389</td>
<td>-.017</td>
<td>+.018</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\pm 8.17$</td>
<td>$\pm .009$</td>
<td>$\pm .055$</td>
</tr>
</tbody>
</table>

$$
\epsilon = \frac{N^+ - N^-}{N^+ + N^-}
$$

$$
A_\Lambda = \frac{1}{P_B < \cos \phi>_{\Lambda}} \frac{N^+ - N^-}{N^+ + N^-}
$$

$$
A_\Sigma = S \frac{1}{P_B < \cos \phi>_{\Sigma} - P_x E} \frac{N^+ - N^-}{N^+ + N^-} - (S - 1) \frac{P_B < \cos \phi>_{\Lambda} - P_x E}{P_B < \cos \phi>_{\Sigma} - P_x E} A_\Lambda
$$
Fig 4.4 Variation of the Analyzing Power for $\Sigma^0$'s w.r.t. 
(a) $p_T$ and (b) $x_F$. ○ : all data.
4.3 Analyzing Power For $K_s$

The calculations for $K_s$ are identical to those of the $\Lambda$. We list in Table 4.7 the analyzing power results for $K_s$.

Table 4.7

<table>
<thead>
<tr>
<th>$x_F$</th>
<th>$p_T$</th>
<th>$&lt;x_F&gt;_{K_s}$</th>
<th>$&lt;p_T&gt;_{K_s}$</th>
<th>$E$</th>
<th>$&lt;\cos \phi&gt;_{K_s}$</th>
<th>$\epsilon 10^{-3}$</th>
<th>$A_{K_s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>all</td>
<td>all</td>
<td>.052</td>
<td>.943</td>
<td>.249</td>
<td>.837</td>
<td>-45.12</td>
<td>- .142</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>± 4.67</td>
<td>± .016</td>
</tr>
<tr>
<td>all</td>
<td>.4-.8</td>
<td>-.15</td>
<td>.770</td>
<td>.113</td>
<td>.831</td>
<td>-35.01</td>
<td>-.107</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>± 7.39</td>
<td>± .023</td>
</tr>
<tr>
<td>.0-.2</td>
<td>.8-2</td>
<td>.077</td>
<td>.958</td>
<td>.337</td>
<td>.839</td>
<td>-38.12</td>
<td>-.134</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>± 8.17</td>
<td>± .029</td>
</tr>
<tr>
<td>.2-.35</td>
<td>.8-2</td>
<td>.197</td>
<td>1.07</td>
<td>.261</td>
<td>.843</td>
<td>-49.01</td>
<td>-.160</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>± 10.50</td>
<td>± .034</td>
</tr>
<tr>
<td>.35-1</td>
<td>.8-2</td>
<td>.336</td>
<td>1.195</td>
<td>.192</td>
<td>.843</td>
<td>-77.41</td>
<td>-.242</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>± 11.28</td>
<td>± .035</td>
</tr>
</tbody>
</table>

The $x_F$ and $p_T$ distribution of the analyzing power is shown in fig 4.5. The data indicates that the analyzing power is increasing with $x_F$ and $p_T$. This behaviour is contrary to that of the $\Lambda$ and $\Sigma^0$ which are quite small and tend towards zero. This feature of the data cannot be reconciled with an explanation which works for the baryons. We have discussed this point later on in the conclusions.
Fig 4.5 Variation of the Analyzing Power for $K_a$'s w.r.t. (a) $p_T$ and (b) $x_F$. ○ : all data.
4.4 Polarization

The weak decay of the \( \Lambda \) implies parity violation (due to interference of \( l = 0 \) and \( l = 1 \) final angular momentum states) and leads to an asymmetry in the angular distribution of its decay products. If the proton momentum makes an angle \( \Theta^\prime \) w.r.t. the \( \Lambda \) spin, \( P_\Lambda \), then the angular distribution is given by

\[
\frac{dN}{d\cos \Theta^\prime} \propto (1 + \alpha P_\Lambda \cos \Theta^\prime)
\]

The parameter \( \alpha \) is by conventional definition the helicity of the decay protons in the unpolarized \( \Lambda \) rest frame and is a measure of the parity violating interference. [LEE57].

There are no theoretical calculations for \( \alpha \) because there is no way to describe the hadrons at such low energies (confinement problem). It has been determined experimentally by measuring the proton polarization in associated production of \( \Lambda \) using 1.07 GeV/c \( \pi^- \) beam incident on a polyethylene target [OVE67]. The protons from \( \Lambda \) decay were then scattered in a Carbon-plate spark chamber and the left right asymmetry was determined. The polarization of the protons was evaluated by combining the asymmetry measurements with graphs on analyzing power for protons on Carbon determined in an earlier experiment [PET63]. The final result is \( \alpha = 0.65 \pm 0.02 \) for \( \Lambda \rightarrow p\pi^- \) decay.

The \( \Lambda \) polarization can be calculated by measuring the up-down asymmetry in the decay proton's distribution in the \( \Lambda \) rest frame. Our experimental setup was asymmetric about the \( x = 0 \) plane due to the asymmetric placement of the LG and subsequently its companion hodoscope which is a part of the proton trigger. The \( \Lambda \) polarization we observe is distorted due to this asymmetry.
4.4.1 The Σ⁰ Polarization

The polarization of Σ⁰'s was obtained by calculating the polarization of its daughter Λ's originating from Σ⁰ decay and using relation B.17 in appendix B. The Λ polarization was in turn obtained from the angular distribution of the decay protons in the Λ rest frame. To calculate the polarization, we start as usual from the weak decay distributions for the protons

\[ N = \frac{d\sigma}{d\Omega} (1 + \alpha P_\Lambda \cos \Theta^*) \]  \hspace{1cm} (4.24)

Looking at the expression for the distribution we see that \( \alpha P_\Lambda \) is the slope of a straight line when \( N \) is plotted as a function of \( \cos \Theta^* \) (fig 4.6). However, we could not use this method due to the \( \cos \Theta^* \) dependence in the efficiency. To extract the polarization, we determine the asymmetry of the \( + \cos \Theta^* \) (P) and \( - \cos \Theta^* \) (M) parts of the distribution. To reduce systematic errors we first calculated the polarization of the Λ's in small bins of \( \cos \Theta^* \) (0.04 bin size) and averaged over them later on to find the polarization for that kinematic bin. Since the polarization does not depend on the initial spin state of the beam we proceed with the analysis after adding the data for the two spin states.

\[ N_{P,i} = K \int_{x_i}^{x_i+\Delta x} (1 + \alpha P_i x_i) \, dx_i \]
\[ = K \left[ \Delta x + \frac{\alpha P_i}{2} (2x_i + \Delta x) \right] \Delta x \]  \hspace{1cm} (4.25)

\[ N_{M,i} = K \int_{x_i}^{x_i+\Delta x-1} (1 + \alpha P_i x_i) \, dx_i \]
\[ = K \left[ \Delta x + \frac{\alpha P_i}{2} (2x_i + \Delta x - 2) \right] \Delta x \]  \hspace{1cm} (4.26)
Fig 4.6 Angular distribution of protons in the rest frame of the $\Lambda$'s which are in the $\Sigma^0$ peak for (a) beam spin up and (b) beam spin down.
where $x$ denotes $\cos \Theta^*$ and $P$. $M$ indicates $\pm \cos \Theta^*$ and not the beam spin. The asymmetry for each bin is then given by

$$\epsilon_i = \frac{N_{P,i} - N_{M,i}}{N_{P,i} + N_{M,i}}$$

$$= -\frac{\alpha P_i/2}{1 + \frac{\alpha P_i}{2} (2x_i + \Delta x - 1)}$$

which can be rearranged to yield

$$P_i = -\frac{2\epsilon_i/\alpha}{(2x_i + \Delta x - 1) \epsilon_i + 1}$$

We computed $P_i$ for both the $\Lambda$ and $\Sigma^0$ data samples. We denote this polarization as $P_{\Lambda,\text{obs},i}$ and $P_{\Sigma,\text{obs},i}$ for $\Lambda$'s and $\Sigma^0$'s respectively, for further reference.

The polarization which we measure is also distorted due to the efficiency of our setup which is an effect of the size and position of the MPS magnet, momentum and production angle of the $\Lambda$ and the sophistication of the track reconstruction routines. The $\cos \Theta^*$ distributions for high $x_P$ and low $x_P$ regions are convex and concave respectively. The structure can be understood by looking at the $\Lambda$ decay in detail. $\cos \Theta^* = +1 (-1)$ implies that the decay proton is emitted along $\hat{N}$ ($-\hat{N}$). Due to the detector's acceptance, the $\Lambda$ momentum must lie within a half angle of 3.5° with respect to the horizontal. This implies that we can equate $\pm \hat{N}$, the normal to the production plane to $\pm \hat{y}$, the vertical axis in the lab frame. Thus, the decay protons are produced along $+\hat{y}$ ($-\hat{y}$) for $\cos \Theta^* = 0$, the decay protons are produced in the horizontal plane. For the high $x_P$ data the $\Lambda$ is produced at a small angle causing one of the decay products to pass close to the right edge of the chamber. Due to the large value of $x_P$ (large boost), the opening angle of the decay products is also small. As a result, for $\cos \Theta^* = 0$ one of the decay products
will either hit the wire chamber edges or get lost at the side causing the reconstruction program to discard the event. The $\cos \Theta^* = \pm 1$ events are in the vertical plane and due to the small opening angle are far away from the upper and lower edges and are not lost. Similarly, for the low $x_F$ region the $\Lambda$ is produced at larger angles and the decay products have a larger opening angle. Here the loss near $\cos \Theta^* = \pm 1$ dominates because the decay products are fairly far away from the side edges. Monte Carlo analysis showed that correcting for the efficiency changes the results by $\sim 1\%$ [TON88]. We have therefore ignored this effect here.

To correct for the asymmetry of the LG we have normalized the observed polarization in our run with the polarization observed in the previous run which did not have a LG. This is a reasonable approach because the setup for the two runs is similar and we are in the same kinematic range. If $P_\Lambda$ is the $\Lambda$ polarization from the last run, the correction for the distorted, $D$, for each $\cos \Theta^*$ bin is given by

$$D_i = \frac{P_\Lambda}{P_{\Lambda, \text{obs}, i}}\tag{4.29}$$

The true $\Lambda$ polarization of the $\Sigma^0$ peak is then given by,

$$P_{\Sigma, \text{peak}, i} = P_{\Sigma, \text{obs}, i} D_i\tag{4.30}$$

This is the polarization of the $\Lambda$'s in the whole $\Sigma^0$ mass peak. To account for the $\Lambda$'s which are not produced in the $\Sigma^0$ decay we apply a background correction as shown in the case for the analyzing power. Thus we get the following expression for the polarization of the $\Lambda$'s which originate from $\Sigma^0$ decay,

$$P_{\Sigma, \Lambda, i} = S P_{\Sigma, \text{peak}, i} D_i - (S - 1) P_{\Lambda, \text{obs}, i} D_i\tag{4.31}$$
We have taken the background polarization to be the same as the polarization of the $\Lambda$ sample, $P_{\Lambda,i}$, for the same kinematic bin under consideration.

To extract the $\Sigma^0$ polarization from the observed values of $\Lambda$ polarization, $P_{\Sigma,\Lambda,i}$, we start with the relation given in appendix B

$$P_\Lambda = - (P_{\Sigma} \cdot \hat{P}_\Lambda) \hat{P}_\Lambda$$  \hspace{1cm} (4.32)

where $P_{\Lambda,i}$ is the total polarization of the $\Lambda$'s produced in $\Sigma^0$ decay. The relative directions of $\Lambda$ and $\Sigma^0$ polarizations and $\Lambda$ momentum are shown in fig 4.7 below. Let us first consider the case when the $\Lambda$ and $\Sigma^0$ are in the same half plane. For this case the $\Lambda$ has negative helicity, which leads to

$$P_\Lambda = + P_\Sigma \cos \delta$$  \hspace{1cm} (4.33)

where $\delta$ is the angle between the $\Lambda$ momentum and the $\Sigma^0$ spin. Fig 4.8 shows the distribution for all the events in the $\Sigma^0$ mass peak. In the experiment we measure the normal component of the $\Lambda$ polarization, $P_{\Sigma,\Lambda}$. To relate the observed value of $\Lambda$ polarization to the polarization of the $\Sigma^0$, we take the normal component of $P_\Lambda$. Thus

$$P_{\Sigma,\Lambda} = P_\Lambda \cos \delta$$

$$= (P_\Sigma \cos(\pi - \delta)) \cos \delta$$

$$= - P_\Sigma \cos^2 \delta$$  \hspace{1cm} (4.34)

Thus we have a relation for $P_\Sigma$ in terms of the normal component of the decay $\Lambda$ polarization

$$P_{\Sigma,i} = - \frac{P_{\Sigma,\Lambda,i}}{<\cos^2 \delta >_{\Sigma,i}}$$  \hspace{1cm} (4.35)
Fig 4.7 $\Lambda$ helicity in $\Sigma^0$ restframe when $P_{\Sigma^0}$ and $P_{\Lambda}$ are in (a) different and (b) same half planes. $P_p$ indicate polarization and momentum respectively. $P_{\Lambda} = -(P_{\Sigma^0} \cdot P_{\Lambda}) P_{\Lambda}$
Fig 4.8 Angle Between $\Lambda$ Momentum And $\Sigma^0$ Spin in the $\Sigma^0$ rest frame.
Looking at fig 4.8a we see that the $\Lambda$ polarization is directed opposite to that of the $\Sigma^0$ polarization. This is true also for the other case in which the $\Lambda$ and $\Sigma^0$ are in different half planes. For this case the $\Lambda$'s have positive helicity, and we get

$$P_{\Sigma,\Lambda} = (-P_\Sigma \cos(\pi - \delta)) \cos(\pi - \delta)$$

$$= -P_\Sigma \cos^2 \delta$$  \hspace{1cm} (4.36)

Thus,

$$P_{\Sigma,i} = -\frac{P_{\Sigma,\Lambda,i}}{<\cos^2 \delta >_{\Sigma,i}}$$  \hspace{1cm} (4.37)

Summing over all the bins for the particular kinematic bin, we get

$$P_\Sigma = \sum_i P_{\Sigma,i}$$

$$= -\sum_i \frac{P_{\Sigma,\Lambda,i}}{<\cos^2 \delta >_{\Sigma,i}}$$  \hspace{1cm} (4.38)

The subscript $\Sigma$ indicates pure $\Sigma^0$ events. We have evaluated the values for $<\cos^2 \delta>$ in Table 4.8. The calculation is similar to that of $<\cos \phi>$, and gives

$$<\cos^2 \delta >_{\Sigma} = S <\cos^2 \delta > - (S - 1) <\cos^2 \delta >_{\Lambda}$$  \hspace{1cm} (4.39)
Table 4.8
Background Corrected Values For $<\cos^2\delta>_{\Sigma}$

<table>
<thead>
<tr>
<th>$x_F$</th>
<th>$p_T$</th>
<th>$&lt;\cos^2\delta&gt;$</th>
<th>$&lt;\cos^2\delta&gt;_{\Lambda}$</th>
<th>$&lt;\cos^2\delta&gt;_{\Sigma}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>all</td>
<td>all</td>
<td>2.3</td>
<td>0.144</td>
<td>0.067</td>
</tr>
<tr>
<td>all</td>
<td>0.4-0.8</td>
<td>6.3</td>
<td>0.076</td>
<td>0.071</td>
</tr>
<tr>
<td>0.0-0.2</td>
<td>0.8-2.0</td>
<td>2.91</td>
<td>0.088</td>
<td>0.061</td>
</tr>
<tr>
<td>0.2-0.35</td>
<td>0.8-2.0</td>
<td>2.14</td>
<td>0.141</td>
<td>0.069</td>
</tr>
<tr>
<td>0.35-1.0</td>
<td>0.8-2.0</td>
<td>1.7</td>
<td>0.200</td>
<td>0.071</td>
</tr>
<tr>
<td>0.2-1.0</td>
<td>all</td>
<td>1.91</td>
<td>0.166</td>
<td>0.070</td>
</tr>
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</table>

Thus by measuring the raw asymmetry $\epsilon$, we can arrive at the polarization of the $\Sigma^0$'s. We show the results for $\Sigma^0$ polarization in Table 4.9.

Table 4.9
Polarization Results For $\Sigma^0$ Production

<table>
<thead>
<tr>
<th>$&lt;x_F&gt;_{\Sigma}$</th>
<th>$&lt;p_T&gt;_{\Sigma}$</th>
<th>$S$</th>
<th>$&lt;\cos^2\phi&gt;_{\Sigma}$</th>
<th>$P_{\Lambda,\text{obs}}$</th>
<th>$P_{\Lambda}$</th>
<th>$P_{\Sigma,\Lambda}$</th>
<th>$P_{\Sigma}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.300</td>
<td>1.16</td>
<td>2.3 ± .2</td>
<td>0.243</td>
<td>-0.437</td>
<td>-0.096</td>
<td>-0.057</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>± 0.010</td>
<td>± 0.007</td>
<td>± 0.031</td>
<td>± 0.13</td>
</tr>
<tr>
<td>0.25</td>
<td>0.82</td>
<td>6.3 ± .3</td>
<td>0.099</td>
<td>-0.259</td>
<td>-0.032</td>
<td>-0.025</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>± 0.049</td>
<td>± 0.016</td>
<td>± 0.154</td>
<td>± 1.56</td>
</tr>
<tr>
<td>0.13</td>
<td>1.10</td>
<td>2.91 ± .2</td>
<td>0.140</td>
<td>-0.447</td>
<td>-0.037</td>
<td>-0.064</td>
<td>0.45</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td>± 0.021</td>
<td>± 0.012</td>
<td>± 0.040</td>
<td>± 0.29</td>
</tr>
<tr>
<td>0.28</td>
<td>1.16</td>
<td>2.14 ± .2</td>
<td>0.224</td>
<td>-0.452</td>
<td>-0.110</td>
<td>-0.059</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>± 0.016</td>
<td>± 0.010</td>
<td>± 0.053</td>
<td>± 0.24</td>
</tr>
<tr>
<td>0.45</td>
<td>1.30</td>
<td>1.71 ± .1</td>
<td>0.283</td>
<td>-0.442</td>
<td>-0.147</td>
<td>-0.031</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>± 0.018</td>
<td>± 0.010</td>
<td>± 0.058</td>
<td>± 0.20</td>
</tr>
<tr>
<td>0.35</td>
<td>1.22</td>
<td>1.91 ± .2</td>
<td>0.254</td>
<td>-0.446</td>
<td>-0.110</td>
<td>-0.043</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>± 0.012</td>
<td>± 0.010</td>
<td>± 0.042</td>
<td>± 0.17</td>
</tr>
</tbody>
</table>

Fig 4.9 shows the $x_F$ and $p_T$ distribution of $\Sigma^0$ polarization.
Fig 4.9 Variation of the Polarization for $\Sigma^0$'s w.r.t. (a) $p_T$ and (b) $x_F$. $\circ$: all data.
4.5 The \( \Sigma^0 \) Depolarization

The depolarization of the \( \Sigma^0 \)'s has been calculated from the angular distributions of the decay proton of the \( \Lambda \)'s coming from \( \Sigma^0 \) decay. Considering all the events in the \( \Sigma^0 \) mass peak, we can write

\[
\epsilon = \frac{N^{-} - N^{+}}{N^{-} + N^{+}}
\]

\[
= \frac{N_{\Sigma}^{-} - N_{\Sigma}^{+}}{N_{\Sigma}^{-} + N_{\Sigma}^{+}} + \frac{N_{\Lambda}^{-} - N_{\Lambda}^{+}}{N_{\Lambda}^{-} + N_{\Lambda}^{+}}
\]  

(4.40)

where \( N_{\Sigma} \) and \( N_{\Lambda} \) refer to the number of \( \Sigma^0 \)'s and \( \Lambda \)'s in the \( \Sigma^0 \) mass peak respectively.

Considering the \( \Sigma^0 \) events, we can write for spin up and spin down

\[
N_{\Sigma}^{\pm} = K \left[ \frac{N_{\Sigma}^{-} + N_{\Sigma}^{+}}{N_{\Sigma}^{-} + N_{\Sigma}^{+}} \right] (1 \pm A_{\Sigma PB} < \cos \phi > \Sigma) \left(1 + P_{\Sigma,\Lambda}^{\pm} \cos \Theta_{\Sigma} \right)
\]  

(4.41)

Substituting for \( P_{\Sigma,\Lambda} \) in terms of \( P_{\Sigma} \), we get

\[
N_{\Sigma}^{\pm} = K \left[ \frac{N_{\Sigma}^{-} + N_{\Sigma}^{+}}{N_{\Sigma}^{-} + N_{\Sigma}^{+}} \right] (1 \pm A_{\Sigma PB} < \cos \phi > \Sigma) \left(1 - P_{\Sigma}^{\pm} \alpha \cos \Theta_{\Sigma} \cos \delta \right)
\]  

(4.42)

where \( \delta \) is the angle between the \( \Sigma^0 \) polarization and the \( \Lambda \) momentum direction. Using relation 4.1 for \( P_{\Sigma}^{\pm} \), we obtain

\[
N_{\Sigma}^{\pm} = K (1 \pm A_{\Sigma PB} < \cos \phi > \Sigma) \left(1 - \frac{P_{\Sigma}^{\pm} PB_{\Sigma}}{1 \pm A_{\Sigma PB} < \cos \phi > \Sigma} \alpha \cos \Theta_{\Sigma} \right)
\]  

(4.43)

The acceptance of the detector changes not only for \( \Theta \) but it is also a function of \( \delta \). If we integrate over \( \delta \) we will obtain terms which are independent of \( \delta \) and some which depend on \( \delta \) through the acceptance which don't cancel out when we calculate the asymmetry. Thus we are forced to take data bins of both \( \Theta \) and \( \delta \).
Consider a phase space element \( d(\cos \Theta') d(\cos \delta) \). We have

\[
N^\pm_S = K \frac{1}{S} \left( 1 \pm A_{\Sigma} P_B < \cos \phi >_{\Sigma} \right) \left( 1 - \frac{P_\Sigma \pm P_B D_{\Sigma,ij}}{1 \pm A_\Sigma P_B < \cos \phi >_{\Sigma}} \alpha \cos \Theta_i \cos \delta_j \right)
\]

\[
= K \frac{1}{S} \left( 1 \pm A_{\Sigma} P_B < \cos \phi >_{\Sigma} - (P_\Sigma \pm p_B D_{\Sigma,ij}) \alpha \cos \Theta_i \cos \delta_j \right) \quad (4.44)
\]

Similarly for the \( \Lambda \) events we have

\[
N^\pm_\Lambda = K \left[ \frac{N^\pm_\Lambda}{N_{\text{tot}} + N^\pm_\Lambda} \right] \left( 1 \pm A_{\Lambda} P_B < \cos \phi >_\Lambda \right) \left( 1 + p_A^\pm \alpha \cos \Theta_i \right)
\]

\[
= K \left[ \frac{N^\pm_\Lambda}{N_{\text{tot}} + N^\pm_\Lambda} \right] \left( 1 \pm A_{\Lambda} P_B < \cos \phi >_\Lambda + (P_\Lambda \pm p_B D_\Lambda) \alpha \cos \Theta_i \right) \quad (4.45)
\]

The fractions in square brackets are more familiar as \( S \) and \( (S - 1) \) for the \( \Sigma^0 \) and \( \Lambda \) events respectively.

The asymmetry can be calculated to yield,

\[
\epsilon_{ij} = p_B \frac{-A_\Sigma < \cos \phi >_{\Sigma} + D_{\Sigma,ij} \alpha \cos \Theta_i \cos \delta_j - (S - 1) [A_{\Lambda} < \cos \phi >_\Lambda + D_\Lambda \alpha \cos \Theta_i]}{1 - P_\Sigma \alpha \cos \Theta_i \cos \delta_j + (S - 1) \left[ 1 + \alpha P_\Lambda \cos \Theta_i \right]} \quad (4.46)
\]

Rearranging the above expression leads to an expression for \( D_{ij} \).

\[
D_{\Sigma,ij} = \frac{1}{p_B \alpha \cos \Theta_i \cos \delta_j} \left( \epsilon_{ij} \left[ 1 - P_\Sigma \alpha \cos \Theta_i \cos \delta_j + (S - 1) \left( 1 + P_\Lambda \alpha \cos \Theta_i \right) \right] \right.
\]

\[
+ A_\Sigma P_B < \cos \phi >_{\Sigma} + (S - 1) \left[ P_\Lambda A_{\Lambda} < \cos \phi >_\Lambda + p_B D_\Lambda \alpha \cos \Theta_i \right] \quad (4.47)
\]

We could correct the above expression by taking the background corrected values for \( < \cos \delta >_\Sigma,ij \) and \( P_{\Sigma,ij} \). This is not possible here because we have taken very small bins of \( \cos \Theta_i \) and \( \cos \delta_j \) which makes it impossible to evaluate the background factor \( S \) for each bin due to low statistics. We have evaluated the asymmetry for each small bin and used it in the calculation. We find that there is negligible difference. The correction for the background under the \( \Sigma^0 \) peak is applied as usual and leads to the final expression
for the depolarization,

\[ D_{\Sigma} = S \left( \sum_{ij} D_{\Sigma,ij} \right) \]

We do not have any \( D_{\Lambda} \) term in the above expression because it is zero as determined earlier [BON88].

To calculate \( D \), we subdivided the scatter plots of the data for each kinematic bin into 40 bins on each axis. We calculated the depolarization by taking the sum of 4 bins at a time. Thus we had 100 values of depolarization for each set of histograms. The results for the depolarization are shown in the table below.

**Table 4.9**

Depolarization Results For \( \Sigma^0 \) Production

<table>
<thead>
<tr>
<th>( &lt; x_F &gt;_{\Sigma} )</th>
<th>( &lt; p_T &gt;_{\Sigma} )</th>
<th>( P_{\Lambda} )</th>
<th>( \sum D_{\Sigma,ij} )</th>
<th>( D_{\Sigma} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.30</td>
<td>1.16</td>
<td>(-0.084 \pm 0.007)</td>
<td>(0.169 \pm 0.115)</td>
<td>(0.34 \pm 0.15)</td>
</tr>
<tr>
<td>0.25</td>
<td>0.82</td>
<td>(-0.032 \pm 0.016)</td>
<td>(0.521 \pm 0.604)</td>
<td>(2.90 \pm 1.30)</td>
</tr>
<tr>
<td>0.13</td>
<td>1.10</td>
<td>(-0.037 \pm 0.012)</td>
<td>(0.174 \pm 0.302)</td>
<td>(0.44 \pm 0.45)</td>
</tr>
<tr>
<td>0.28</td>
<td>1.16</td>
<td>(-0.110 \pm 0.010)</td>
<td>(0.091 \pm 0.192)</td>
<td>(0.17 \pm 0.24)</td>
</tr>
<tr>
<td>0.45</td>
<td>1.30</td>
<td>(-0.150 \pm 0.010)</td>
<td>(0.141 \pm 0.172)</td>
<td>(0.21 \pm 0.20)</td>
</tr>
<tr>
<td>0.35</td>
<td>1.22</td>
<td>(-0.131 \pm 0.009)</td>
<td>(0.154 \pm 0.127)</td>
<td>(0.26 \pm 0.16)</td>
</tr>
</tbody>
</table>

Fig 4.10 shows the \( x_F \) and \( p_T \) distribution of the \( \Sigma^0 \) depolarization.
Fig 4.10 Variation of the Depolarization parameter for $\Sigma^0$'s w.r.t. (a) $p_T$ and (b) $x_F$
Chapter 5

Theoretical Model

In an effort to explain the large values of polarization observed in inclusive hadron production DeGrand and Miettinen [DGM77] have proposed a phenomenological model which we discuss here. They have adopted the framework of the parton fragmentation-recombination model [HWA80] along with static SU(6) wavefunctions to predict the spin parameters in any reaction. The recombination model was chosen because of the observation that polarization is independent of energy. In this model the short range order of the parton forces implies that the distribution of slow quarks in the target is independent of energy. If the model is applied to say Λ production, the ud diquark fragment from the incident proton combines with a slow strange sea quark to give a Λ. The beam fragment which is transferred to the Λ is in a spin singlet state (assumption of SU(6) wavefunctions) and so does not contribute to the Λ polarization. The mechanism of Thomas precession preferentially selects a slow strange sea quark to combine with its spin down. Since the slow sea quark distribution is independent of energy, this leads to an energy independent polarization for Λ. The model incorporates the following
assumptions:

1. The final state must be a recombination of a beam fragment and sea quark for non-zero spin effects.

2. Thomas precession of the quarks during recombination is perceived to be the mechanism for preferential recombination of the beam fragment with spin up and sea quarks with spin down.

3. Static SU(6) wavefunctions are used to describe the hadrons.

The process of recombination involves a valence quark (diquark) transfer from the beam projectile and a sea diquark (quark) pickup to form the final baryon as shown in fig 5.1. The different amplitudes are parametrized to allow a preferential recombination for a fast quark with spin up and a slow quark with spin down. The spin parameters are calculated using the forms for polarization, $P$, analyzing power, $A$, and depolarization, $D$ given in chapter 4 which we reproduce here for clarity.

\[
\begin{align*}
P &= \frac{(W_{||} - W_{\|}) + (W_{\|} - W_{||})}{W_{||} + W_{\|} + W_{\|} + W_{||}} \\
P_B A &= \frac{(W_{||} - W_{\|}) + (W_{\|} - W_{||})}{W_{||} + W_{\|} + W_{\|} + W_{||}} \\
P_B D &= \frac{(W_{||} - W_{\|}) + (W_{\|} - W_{||})}{W_{||} + W_{\|} + W_{\|} + W_{||}}
\end{align*}
\]

$W_{fi}$ denotes the probability of scattering from initial spin state $i$ to final spin state $f$ and $P_B$ is the beam polarization. In the model, the transition rate $W_{fi}$ is assumed to be the incoherent sum of the squares of the amplitudes. This assumption is made because we are considering inclusive processes. A further assumption breaks up each amplitude into a
Fig 5.1 Parametrization of the various recombination processes in the DGM model. The solid lines indicate the quarks taking part in that process.
product of a valence term and a sea term. Before we can calculate any of the parameters we have to recast the quark model wavefunctions into a diquark-quark combination, $|D_{SM},q_{1}(i)>$. $D_{SM}$ represents the diquark with total spin $S$ and magnetic quantum number $M$. $q_{1}(i)$ represents the third quark with spin up (down). The procedure for deriving the quark model wavefunctions and recasting them into a diquark-quark form is given in appendix A. The wavefunctions are listed in Tables A-1 & A-2 for spin up and spin down baryons respectively. The spin down wavefunctions can be obtained from their spin up version by making the following changes:

\[ |i\rightarrow i, \\
M\rightarrow-M\]

reversing the sign of coefficient of $(S=0,M=0)$ singlet term

5.1 Predictions for $\Sigma^0$: An illustrative example of DGM model

To illustrate how calculations are done in the DGM model let us examine the production of $\Sigma^0$ from an incident proton beam. To calculate the spin parameters we need the transition rates, $W_{fi}$, for the different spin combinations. Let us first calculate the rate $W_{\uparrow\uparrow}$ i.e. a spin up proton leading to a spin up $\Sigma^0$. Looking at the wavefunctions for the proton and $\Sigma^0$ we can see that the process can occur in the following different ways:

- Transfer of $|ud\,11>$ diquark + pickup of strange sea quark with spin down (spin up $s$ quark would not give a spin $1/2$ baryon)
• Transfer of $|ud\,10\rangle$ diquark + pickup of strange sea quark with spin up

• Transfer of $|d\,\downarrow\rangle$ quark + pickup of $|us\,11\rangle$ diquark from the sea

• Transfer of $|d\,\uparrow\rangle$ quark + pickup of $|us\,10\rangle$ diquark from the sea

• Transfer of $|d\,\uparrow\rangle$ quark + pickup of $|us\,00\rangle$ diquark from the sea

• Transfer of $|u\,\downarrow\rangle$ quark + pickup of $|ds\,11\rangle$ diquark from the sea

• Transfer of $|u\,\uparrow\rangle$ quark + pickup of $|ds\,10\rangle$ diquark from the sea

• Transfer of $|u\,\uparrow\rangle$ quark + pickup of $|ds\,00\rangle$ diquark from the sea

The $T$ matrix amplitude can then be written as the sum of the various amplitudes each of which is a product of a valence term and a sea term.

\[
< \Sigma^0 | T | p > = \left( \frac{-1}{\sqrt{3}} \right) \left( \frac{\sqrt{2}}{\sqrt{3}} \right) A_{11} B_\downarrow + \left( \frac{1}{\sqrt{18}} \right) \left( \frac{-1}{3} \right) A_{10} B_\downarrow + \\
\left( \frac{\sqrt{2}}{\sqrt{3}} \right) \left( \frac{-1}{\sqrt{18}} \right) A'_{11} B'_{\downarrow} + \left( \frac{-1}{3} \right) \left( \frac{1}{6} \right) A'_{10} B'_{\downarrow} + \left( \frac{-1}{3} \right) \left( \frac{1}{2} \right) A'_{00} B'_{\downarrow} + \\
\left( \frac{1}{\sqrt{2}} \right) \left( \frac{1}{6} \right) A'_{10} B'_{\downarrow} + \left( \frac{1}{\sqrt{18}} \right) \left( \frac{-1}{2} \right) A'_{00} B'_{\downarrow}
\]

Squaring the amplitudes separately and adding them incoherently we get the transition rate $W$

\[
W_{\downarrow\downarrow} = \frac{AB}{162} \left[ 5 + 3\epsilon + 4\delta + 4\epsilon\delta \right] + \frac{A'B'}{216} \left[ 5 - 3\epsilon' - 4\delta' + 4\epsilon'\delta' \right]
\]
Similarly, for a spin down proton fragmenting into a spin up $\Sigma^0$, we get for the amplitude

$$< \Sigma^0|T|p> =$$

$$\left( \frac{1}{\sqrt{18}} \right) \left( \frac{-3}{3} \right) A_{10}B_{\perp} +$$

$$\left( \frac{x}{3} \right) \left( \frac{i}{6} \right) A'_{10}B_{\perp} + \left( \frac{x}{3} \right) \left( \frac{i}{6} \right) A'_{00}B_{\perp} + \left( \frac{-1}{3} \right) \left( \frac{-1}{\sqrt{18}} \right) A'_{11}B_{\perp} +$$

$$\left( \frac{-1}{3} \right) \left( \frac{1}{6} \right) A'_{10}B_{\perp} + \left( \frac{-1}{3} \right) \left( \frac{1}{6} \right) A'_{00}B_{\perp} +$$

$$\left( \frac{1}{\sqrt{18}} \right) \left( \frac{-3}{3} \right) A'_{11}B_{\perp} + \left( \frac{1}{2} \right) \left( \frac{-3}{\sqrt{18}} \right) A'_{11}B_{\perp} \right)$$

(5.3)

and for the transition rate

$$W_{\perp} = \frac{AB}{162} \left[ 1 - \epsilon \right] + \frac{A'B'}{54} \left[ 7 + 3\epsilon' - 2\epsilon' + 2\epsilon' \right]$$

(5.4)

The rates for the other two combinations $W_{\perp}$ ($W_{\parallel}$) can be obtained by reversing the signs of all the parameters $\epsilon$, $\delta$ etc. in $W_{\perp}$ ($W_{\parallel}$) respectively. The production of $\Sigma^0$ (also $\Lambda$ and $\Sigma^+$) from incident protons occurs primarily due to a ud valence diquark transfer (VVS process). Another source could be due to a single valence quark transfer (VSS process) which is not necessarily negligible and should be taken into account. The rates for the various reactions are listed in Table 5.1a for a single valence quark transfer and Table 5.1b for a valence diquark transfer. These can be told apart by the co-efficient multiplying each rate. The single valence quark transfer rate has $A'B'$ while the valence diquark rate comes with AB.

Prior to this time the calculations using the model were done assuming that the VSS processes were negligible compared to the VVS processes when both types were present. While this holds for the case of $\Lambda$ production, it is not true for the other cases. The key factor for ignoring the VSS effects is the value of the ratio of the co-coefficients $A'B'/AB$. 
### Table 5.1a
Transition Rates For SINGLE QUARK Transfer

| Reaction | Co-eff | $W_{||}$ | $W_{\perp}$ |
|----------|--------|----------|-------------|
| $p \rightarrow \Lambda$ | $A_{B'}$ | $3 + \epsilon' - \delta' + \epsilon' \delta'$ | $3 - \epsilon' - 2\delta' + 2 \epsilon' \delta'$ |
| $p \rightarrow \Sigma^+$ | $A_{B'}^{13}$ | $26 + 24 \epsilon' - \delta' + \epsilon' \delta'$ | $10 - 5 \delta' + 5 \epsilon' \delta'$ |
| $p \rightarrow \Sigma^0$ | $A_{B'}^{54}$ | $11 + 9 \epsilon' - \delta' + \epsilon' \delta'$ | $7 + 3 \epsilon' - 2 \delta' + 2 \epsilon' \delta'$ |
| $p \rightarrow \Sigma^-$ | $A_{B'}^{81}$ | $7 + 3 \epsilon' - 2 \delta' + 2 \epsilon' \delta'$ | $11 - 9 \epsilon' - 10 \delta' + 10 \epsilon' \delta'$ |
| $p \rightarrow \Xi^0$ | $A_{B'}^{81}$ | $7 + 3 \epsilon' - 2 \delta' + 2 \epsilon' \delta'$ | $11 - 9 \epsilon' - 10 \delta' + 10 \epsilon' \delta'$ |
| $p \rightarrow \Xi^-$ | $A_{B'}^{81}$ | $5 - 3 \epsilon' - 4 \delta' + 4 \epsilon' \delta'$ | $4 - 2 \delta' + 2 \epsilon' \delta'$ |

### Table 5.1b
Transition Rates For DIQUARK Transfer

| Reaction | Co-eff | $W_{||}$ | $W_{\perp}$ |
|----------|--------|----------|-------------|
| $p \rightarrow \Lambda$ | $\bar{A}_{B}$ | $1 - \epsilon$ | $1 - \epsilon$ |
| $p \rightarrow \Sigma^+$ | $A_{B}$ | $5 + 3 \epsilon + 4 \delta + 4 \epsilon \delta$ | $1 - \epsilon$ |
| $p \rightarrow \Sigma^0$ | $A_{102}$ | $5 + 3 \epsilon + 4 \delta + 4 \epsilon \delta$ | $1 - \epsilon$ |
We have used the value 1/12 for this ratio which was estimated using the production cross section ratio of $\Sigma^+$ and $\Sigma^-$ [TON88]. If we neglect the VSS processes the spin parameters would be those given in Table 5.2. In particular the spin parameters for $\Sigma^0$ are

$$P = -\epsilon$$

$$A = \frac{1}{3}\epsilon + \frac{2}{3}\delta$$

$$D = \frac{2}{3}\delta$$

To compare the predictions of the model with experimental results we have to assign numerical values to the parameters $\epsilon$, $\delta$, $\epsilon'$, and $\delta'$. This is the phenomenological input to the model. We have chosen the following parametrization

**Table 5.3**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon$</td>
<td>0.15</td>
<td>Poln of $\Lambda$ from $p$</td>
</tr>
<tr>
<td>$\epsilon'$</td>
<td>0.35</td>
<td>Poln of $\Lambda$ from $K^-$</td>
</tr>
<tr>
<td>$\delta$</td>
<td>0.15</td>
<td>Poln of $\Lambda = \Sigma^0 \Rightarrow \epsilon = \delta$</td>
</tr>
<tr>
<td>$\delta'$</td>
<td>0.0</td>
<td>Poln of $\Lambda$ from $\pi^-$</td>
</tr>
</tbody>
</table>

Comparing the predictions with the experimental values we obtain
Table 5.2

DGM Model Predictions In Leading Order For P, A And D.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>P</th>
<th>A</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>p → Λ</td>
<td>-ε</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>p → Σ⁺</td>
<td>$\frac{1}{3} \epsilon + \frac{2}{3} \delta$</td>
<td>$\frac{2}{3} (\epsilon + \delta)$</td>
<td>$\frac{2}{3}$</td>
</tr>
<tr>
<td>p → Σ⁰</td>
<td>$\frac{1}{3} \epsilon + \frac{2}{3} \delta$</td>
<td>$\frac{2}{3} (\epsilon + \delta)$</td>
<td>$\frac{2}{3}$</td>
</tr>
<tr>
<td>p → Σ⁻</td>
<td>$\frac{2}{3} \epsilon' - \frac{1}{3} \delta'$</td>
<td>$-\frac{1}{3} \epsilon' - \frac{1}{18} \delta'$</td>
<td>$-\frac{2}{5}$</td>
</tr>
<tr>
<td>p → Ξ⁰</td>
<td>$-\frac{1}{3} \epsilon' - \frac{2}{3} \delta'$</td>
<td>$\frac{2}{3} \epsilon' + \frac{4}{3} \delta'$</td>
<td>$-\frac{2}{5}$</td>
</tr>
<tr>
<td>p → Ξ⁻</td>
<td>$-\frac{2}{3} \epsilon' - \frac{3}{3} \delta'$</td>
<td>$-\frac{1}{3} \epsilon' - \frac{2}{3} \delta'$</td>
<td>$\frac{1}{5}$</td>
</tr>
<tr>
<td>p → π⁰</td>
<td>$\frac{1}{3} (\epsilon' + \epsilon')$</td>
<td>$\frac{2}{3} (\epsilon' + \epsilon')$</td>
<td>$\frac{1}{3} (\epsilon' + \epsilon')$</td>
</tr>
<tr>
<td>p → π⁺</td>
<td>$\frac{2}{3} (\epsilon' + \epsilon')$</td>
<td>$\frac{2}{3} (\epsilon' + \epsilon')$</td>
<td>$\frac{1}{3} (\epsilon' + \epsilon')$</td>
</tr>
<tr>
<td>p → π⁻</td>
<td>$-\frac{1}{3} (\epsilon' + \epsilon')$</td>
<td>$-\frac{1}{3} (\epsilon' + \epsilon')$</td>
<td>$-\frac{1}{3} (\epsilon' + \epsilon')$</td>
</tr>
<tr>
<td>p → K⁺</td>
<td>$\frac{2}{3} (\epsilon' + \epsilon')$</td>
<td>$\frac{2}{3} (\epsilon' + \epsilon')$</td>
<td>$\frac{2}{3} (\epsilon' + \epsilon')$</td>
</tr>
<tr>
<td>π⁺ → p</td>
<td>$\frac{2}{3} \epsilon' + \frac{1}{6} \delta'$</td>
<td>$\frac{2}{3} \epsilon' + \frac{1}{6} \delta'$</td>
<td>$\frac{2}{3} \epsilon' + \frac{1}{6} \delta'$</td>
</tr>
<tr>
<td>π⁺ → Λ</td>
<td>$-\frac{1}{2} \delta'$</td>
<td>$-\frac{1}{2} \delta'$</td>
<td>$-\frac{1}{2} \delta'$</td>
</tr>
<tr>
<td>π⁻ → p</td>
<td>$-\frac{1}{3} \epsilon' - \frac{2}{3} \delta'$</td>
<td>$-\frac{1}{3} \epsilon' - \frac{2}{3} \delta'$</td>
<td>$-\frac{1}{3} \epsilon' - \frac{2}{3} \delta'$</td>
</tr>
<tr>
<td>π⁻ → Λ</td>
<td>$-\frac{1}{2} \delta'$</td>
<td>$-\frac{1}{2} \delta'$</td>
<td>$-\frac{1}{2} \delta'$</td>
</tr>
<tr>
<td>K⁺ → Λ</td>
<td>$-\frac{1}{2} \delta'$</td>
<td>$-\frac{1}{2} \delta'$</td>
<td>$-\frac{1}{2} \delta'$</td>
</tr>
<tr>
<td>K⁺ → Σ⁰</td>
<td>$\frac{2}{3} \epsilon' - \frac{1}{3} \delta'$</td>
<td>$\epsilon'$</td>
<td>$\epsilon'$</td>
</tr>
<tr>
<td>K⁻ → Λ</td>
<td>$\epsilon'$</td>
<td>$\epsilon'$</td>
<td>$\epsilon'$</td>
</tr>
</tbody>
</table>
The first column refers to the predictions of the model without any VSS contribution, the second column gives the results from our experiment and the last column gives the predictions when the VSS terms are included. We can see that the predictions are in agreement for the polarization but not for A and D even when the VSS contribution is included. This brings us to the second improvement in the model, namely, transversity spin flip, which is the subject of the next section. In Table 5.4 we have given the predictions for the various reactions including VSS and VVS processes where applicable.

5.2 Transversity Spin Flips In The DGM Model

Comparing the predictions of the model with the observed results, we see that there is a large disagreement between the two for $\Sigma^0$. Like the parton fragmentation recombination model from which it is descended, the DGM model assumes that the beam fragments pass through to the final state without any change. This works well for the hadronization processes which the recombination model describes where all the spins are summed over. It may not necessarily be true for the kind of effects we see here. One of the possibilities is that there is a finite probability for transversity spin flips during the quark or diquark transfer from the beam projectile to the final hadron. Notice that we are not talking about the helicity (longitudinal spin flips) flips which must be conserved in a strong
Table 5.4

DGM Model Predictions For P, A And D Including VSS.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>P</th>
<th>A</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p \rightarrow \Lambda$</td>
<td>$-\frac{12}{13} \epsilon - \frac{1}{26} \delta'$</td>
<td>$\frac{3}{39} \epsilon' + \frac{1}{78} \delta'$</td>
<td>0.00</td>
</tr>
<tr>
<td>$p \rightarrow \Sigma^+$</td>
<td>$\frac{3}{6} (\epsilon + 2 \delta) + \frac{1}{18} (4 \epsilon' - \delta')$</td>
<td>$\frac{6}{6} (\epsilon + \delta) + \frac{9}{6} (6 \epsilon' + \delta)$</td>
<td>$\frac{10}{21}$</td>
</tr>
<tr>
<td>$p \rightarrow \Sigma^0$</td>
<td>$\frac{4}{21} (\epsilon + 2 \delta + \frac{1}{14} (4 \epsilon' - \delta'))$</td>
<td>$\frac{5}{21} (\epsilon + \delta) + \frac{7}{42} (6 \epsilon' + \delta')$</td>
<td>$\frac{10}{21}$</td>
</tr>
<tr>
<td>$p \rightarrow \Sigma^-$</td>
<td>$\frac{3}{5} \epsilon' - \frac{1}{5} \delta'$</td>
<td>$-\frac{1}{3} \epsilon' - \frac{1}{18} \delta'$</td>
<td>$\frac{2}{6}$</td>
</tr>
<tr>
<td>$p \rightarrow \Xi^0$</td>
<td>$-\frac{1}{3} \epsilon' - \frac{2}{3} \delta'$</td>
<td>$\frac{2}{3} \epsilon' + \frac{2}{3} \delta'$</td>
<td>$\frac{2}{6}$</td>
</tr>
<tr>
<td>$p \rightarrow \Xi^-$</td>
<td>$-\frac{1}{3} \epsilon' - \frac{2}{3} \delta'$</td>
<td>$-\frac{1}{3} \epsilon' - \frac{2}{9} \delta'$</td>
<td>$\frac{1}{9}$</td>
</tr>
<tr>
<td>$p \rightarrow \pi^0$</td>
<td>$\frac{1}{3} (\epsilon + \epsilon')$</td>
<td>$\frac{1}{3} (\epsilon + \epsilon')$</td>
<td>$\frac{1}{3} (\epsilon + \epsilon')$</td>
</tr>
<tr>
<td>$p \rightarrow \pi^+$</td>
<td>$\frac{2}{3} (\epsilon + \epsilon')$</td>
<td>$\frac{2}{3} (\epsilon + \epsilon')$</td>
<td>$\frac{2}{3} (\epsilon + \epsilon')$</td>
</tr>
<tr>
<td>$p \rightarrow \pi^-$</td>
<td>$-\frac{1}{3} (\epsilon + \epsilon')$</td>
<td>$-\frac{1}{3} (\epsilon + \epsilon')$</td>
<td>$-\frac{1}{3} (\epsilon + \epsilon')$</td>
</tr>
<tr>
<td>$p \rightarrow K_0$</td>
<td>$-\frac{1}{3} (\epsilon + \epsilon')$</td>
<td>$-\frac{1}{3} (\epsilon + \epsilon')$</td>
<td>$-\frac{1}{3} (\epsilon + \epsilon')$</td>
</tr>
<tr>
<td>$\pi^+ \rightarrow p$</td>
<td>$\frac{2}{3} \epsilon' + \frac{1}{6} \delta'$</td>
<td>$\frac{2}{3} \epsilon' + \frac{1}{6} \delta'$</td>
<td>$\frac{2}{3} \epsilon' + \frac{1}{6} \delta'$</td>
</tr>
<tr>
<td>$\pi^+ \rightarrow \Lambda$</td>
<td>$-\frac{1}{2} \delta'$</td>
<td>$-\frac{1}{2} \delta'$</td>
<td>$-\frac{1}{2} \delta'$</td>
</tr>
<tr>
<td>$\pi^- \rightarrow p$</td>
<td>$-\frac{1}{3} \epsilon' - \frac{2}{3} \delta'$</td>
<td>$-\frac{1}{3} \epsilon' - \frac{2}{3} \delta'$</td>
<td>$-\frac{1}{3} \epsilon' - \frac{2}{3} \delta'$</td>
</tr>
<tr>
<td>$\pi^- \rightarrow \Lambda$</td>
<td>$-\frac{1}{2} \delta'$</td>
<td>$-\frac{1}{2} \delta'$</td>
<td>$-\frac{1}{2} \delta'$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \Lambda$</td>
<td>$-\frac{1}{2} \delta'$</td>
<td>$-\frac{1}{2} \delta'$</td>
<td>$-\frac{1}{2} \delta'$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \Sigma^0$</td>
<td>$\frac{2}{3} \epsilon' - \frac{1}{3} \delta'$</td>
<td>$\frac{2}{3} \epsilon' - \frac{1}{3} \delta'$</td>
<td>$\frac{2}{3} \epsilon' - \frac{1}{3} \delta'$</td>
</tr>
<tr>
<td>$K^- \rightarrow \Lambda$</td>
<td>$\epsilon'$</td>
<td>$\epsilon'$</td>
<td>$\epsilon'$</td>
</tr>
</tbody>
</table>
interaction process (Origin of small poln values in "QCD" calculations). The same does not apply to transversity flips. We include additional amplitudes, which are shown in fig 5.2, to take this into account. In writing the amplitudes we have mimicked the form for the non-flip processes. This procedure involves four more arbitrary parameters, $\epsilon''$, $\Delta$, $\tau_1$ and $\tau_2$ which have to be put in by hand. There is a strong prejudice to take $\epsilon'' = \epsilon'$ and $\Delta \equiv \delta$ because they express the enhancement of transferring a fast valence quark and diquark with spin up respectively. There is no reason to believe this enhancement will be different for transversity spin flip and non-flip transitions. $\tau_1$ ($\tau_2$) is the ratio of the spin flip amplitude and the spin non-flip amplitude in a valence quark (diquark) transfer. If $\wp$ is the probability for a single spin flip, then

\[
\begin{align*}
\tau_1 &= \frac{\wp}{1 - \wp} \\
\tau_2 &= \frac{\wp(1 - \wp)}{1 - \wp(1 - \wp)}
\end{align*}
\]  

(5.5)

(5.6)

This brings to one the number of additional parameters needed viz; $\wp$.

The form of the amplitudes express the fact that a certain fraction of the time recombination occurs with transversity spin flips (expressed by $\tau$). This flip is favored or disfavored to get a fast quark with spin up or a slow quark with spin down according to the mechanism suggested by Thomas precession.

In writing down the amplitudes for a single transversity spin flip (referred to as XSF in short in future) in a diquark we have summed incoherently over the various spin terms. This is arbitrary and has nothing more in its favour than a coherent sum except that it gives the "correct" results. To see how this is done, consider a spin flip in the diquark
Valence Diquark Transfer

\[ |A_{1M}|^2 = \tau_2 A (1 + M \Delta) \]
\[ |A_{00}|^2 = \tau_2 A \]

Valence Quark Transfer

\[ |B'^\uparrow|^2 = \tau_1 B' (1 + \varepsilon'') \]
\[ |B'^\downarrow|^2 = \tau_1 B' (1 - \varepsilon'') \]

Fig 5.2 Parametrization of the transversity spin flip processes. \( \tau_1 \) and \( \tau_2 \) are the probabilities for spin flip in a valence diquark and a quark.
\[ |00 > \text{ which can undergo XSF through either of its two quarks.} \]

\[ |00 > = \frac{\frac{1}{\sqrt{2}}}{\frac{1}{\sqrt{2}}} \]

\[ \text{flip1} = \frac{\frac{1}{\sqrt{2}}}{\frac{1}{\sqrt{2}}} \]

\[ \text{flip2} = \frac{\frac{1}{\sqrt{2}}}{\frac{1}{\sqrt{2}}} \]

Since we are considering a single XSF we need to normalize the amplitude properly, which gives

\[ |00 > = \frac{\text{single flip}}{\sqrt{2}} \frac{\text{flip1} + \text{flip2}}{\sqrt{2}} \]

Summing incoherently over the various terms, we get

\[ |11 > + |1 - 1 > \]

Thus, we have the various single XSF terms in a diquark

\[ |11 > = \rho(1 - \rho)[|10 > + |00 >] \]

\[ |10 > = \rho(1 - \rho)[|11 > + |1 - 1 >] \]

\[ |1 - 1 > = \rho(1 - \rho)[|10 > + |00 >] \]

\[ |00 > = \rho(1 - \rho)[|11 > + |1 - 1 >] \]

This way of calculating the spin flip implies that we are treating the diquark not as a composite object but as two quarks which happen to be travelling together. So, when one quark undergoes a XSF it is not bound by the spin state of its partner. At this point we have neglected double XSFs which would take state \[ |11 > \text{ to } |1 - 1 > \text{ etc. .} \]
5.3 Estimate Of Spin Flip Probability, \( \rho \)

To estimate the value of \( \rho \) we use the production cross section ratio of \( \Sigma^0 \) and \( \Lambda \) and fit it to the observed value of 0.393. The model gives the ratio to be 0.18 when we include the VSS terms and 0.11 when they are not included.

\[
\frac{\sigma(\Sigma^0)}{\sigma(\Lambda)} = \frac{A' B'}{A B} \left\{ \frac{[6 + \epsilon' \delta'] - \rho [\epsilon' \delta' - \epsilon'' \delta'']}{[2 + \epsilon' \delta'] - \rho [\epsilon' \delta' - \epsilon'' \delta']} \right\} + \frac{A_B}{A} \left\{ \frac{[6 + 4 \epsilon] + \rho (1 - \rho) [38 + 20 \epsilon \Delta + 16 \epsilon \delta]}{[18] - \rho (1 - \rho) [14]} \right\}
\]

\[= x \text{ (say)} \quad (5.16)\]

Taking the following values

\[
\frac{A' B'}{A B} = \frac{1}{12}
\]
\[\epsilon = \delta = \Delta = 0.15\]
\[\epsilon' = \epsilon'' = 0.35\]
\[\delta' = 0.0\]

we get

\[
\rho^2 - \rho + \frac{117 \pi - 21.118}{64 \pi + 77.02} = 0 \quad (5.17)
\]

Solving this equation we get

\[\rho = 0.66, 0.34 \text{ for } x = 0.393\]

\[
\tau_1 = 0.52, \tau_2 = 0.29 \quad (5.18)
\]

Now we have all the ingredients to make a final prediction of the spin parameters. In Table 5.5a and 5.5b we have listed the various XSF rates for a single quark and a diquark...
Table 5.5a
SINGLE QUARK Transfer Rates For Transversity Flip

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Co-eff</th>
<th>( W_1 )</th>
<th>( W_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p \rightarrow \Lambda )</td>
<td>( AB ) ( 18 )</td>
<td>( 3 - \epsilon'' - 2 \delta' + 2 \epsilon'' \delta' )</td>
<td>( 3 + \epsilon'' - \delta' + \epsilon'' \delta' )</td>
</tr>
<tr>
<td>( p \rightarrow \Sigma^+ )</td>
<td>( AB ) ( 21 )</td>
<td>( 10 - 5 \delta + 5 \epsilon \delta' )</td>
<td>( 26 + 24 \epsilon'' - \delta' + \epsilon'' \delta' )</td>
</tr>
<tr>
<td>( p \rightarrow \Sigma^0 )</td>
<td>( AB ) ( 54 )</td>
<td>( 7 + 3 \epsilon'' - 2 \delta' + 2 \epsilon'' \delta' )</td>
<td>( 11 + 9 \epsilon'' - \delta' + \epsilon'' \delta' )</td>
</tr>
<tr>
<td>( p \rightarrow \Sigma^- )</td>
<td>( AB ) ( 87 )</td>
<td>( 11 + 9 \epsilon'' - \delta' + \epsilon'' \delta' )</td>
<td>( 7 + 3 \epsilon'' - 2 \delta' + 2 \epsilon'' \delta' )</td>
</tr>
<tr>
<td>( p \rightarrow \Xi^0 )</td>
<td>( AB ) ( 87 )</td>
<td>( 11 - 9 \epsilon'' - 10 \delta' + 10 \epsilon'' \delta' )</td>
<td>( 7 + 3 \epsilon'' - 2 \delta' + 2 \epsilon'' \delta' )</td>
</tr>
</tbody>
</table>

| \( p \rightarrow \Xi^- \) | \( AB \) \( 87 \) | \( 4 - 2 \delta' + 2 \epsilon'' \delta' \) | \( 5 - 3 \epsilon'' - 4 \delta' + 4 \epsilon'' \delta' \) |

| \( p \rightarrow \pi^0 \) | \( BB \) \( 18 \) | \( 3 - \epsilon'' - \epsilon + 3 \epsilon'' \epsilon \) | \( 3 + \epsilon'' + \epsilon + 3 \epsilon'' \epsilon \) |
| \( p \rightarrow \pi^+ \) | \( BB \) \( 21 \) | \( 3 - 2 \epsilon'' - 2 \epsilon + 3 \epsilon'' \epsilon \) | \( 3 + 2 \epsilon'' + 2 \epsilon + 3 \epsilon'' \epsilon \) |
| \( p \rightarrow \pi^- \) | \( BB \) \( 87 \) | \( 3 + \epsilon'' + \epsilon + 3 \epsilon'' \epsilon \) | \( 3 - \epsilon'' - \epsilon + 3 \epsilon'' \epsilon \) |
| \( p \rightarrow K^+ \) | \( BB \) \( 36 \) | \( 3 + \epsilon'' + \epsilon + 3 \epsilon'' \epsilon \) | \( 3 - \epsilon'' - \epsilon + 3 \epsilon'' \epsilon \) |

| \( p \rightarrow \Lambda \) | \( AB \) \( 18 \) | \( 6 + 4 \epsilon'' - \delta' + \epsilon'' \delta' \) | \( 6 - 4 \epsilon'' + \delta' + \epsilon'' \delta' \) |
| \( p \rightarrow \Lambda \) | \( AB \) \( 12 \) | \( 2 - \delta' + \epsilon'' \delta' \) | \( 2 + \delta' + \epsilon'' \delta' \) |
| \( \pi^- \rightarrow p \) | \( AB \) \( 18 \) | \( 3 - \epsilon'' - 2 \delta' + 2 \epsilon'' \delta' \) | \( 3 + \epsilon'' + 2 \delta' + 2 \epsilon'' \delta' \) |
| \( \pi^- \rightarrow \Lambda \) | \( AB \) \( 12 \) | \( 2 - \delta' + \epsilon'' \delta' \) | \( 2 + \delta' + \epsilon'' \delta' \) |
| \( \pi^- \rightarrow \Lambda \) | \( AB \) \( 12 \) | \( 2 - \delta' + \epsilon'' \delta' \) | \( 2 + \delta' + \epsilon'' \delta' \) |
| \( K^+ \rightarrow \Sigma^0 \) | \( AB \) \( 36 \) | \( 6 + 4 \epsilon'' - \delta' + \epsilon'' \delta' \) | \( 6 - 4 \epsilon'' + \delta' + \epsilon'' \delta' \) |
| \( K^- \rightarrow \Lambda \) | \( AB \) \( 87 \) | \( 1 + \epsilon'' \) | \( 1 - \epsilon'' \) |

Table 5.5b
DIQUARK Transfer Rates For Transversity Flip

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Co-eff</th>
<th>( W_1 )</th>
<th>( W_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p \rightarrow \Lambda )</td>
<td>( AB ) ( 27 )</td>
<td>( 1 - \epsilon )</td>
<td>( 1 - \epsilon )</td>
</tr>
<tr>
<td>( p \rightarrow \Sigma^+ )</td>
<td>( 2 AB ) ( 87 )</td>
<td>( 2 + \Delta + \epsilon \Delta )</td>
<td>( 2 + \Delta + \epsilon \Delta )</td>
</tr>
<tr>
<td>( p \rightarrow \Sigma^0 )</td>
<td>( AB ) ( 87 )</td>
<td>( 11 + 9 \epsilon + 10 \Delta + 10 \epsilon \Delta )</td>
<td>( 11 - 9 \epsilon - 10 \Delta + 10 \epsilon \Delta )</td>
</tr>
</tbody>
</table>
transfer. The combined effects of VSS and XSF have been tabulated in Tables 5.6a, b, and c for the analyzing power A, polarization P, and the depolarization D respectively. \( \sigma \) is proportional to the production cross section and is given in Table 5.6d. With the numerical values of the parameters given above and taking the smaller value of \( \varphi \) of 0.34 we can calculate the predictions. For \( \Sigma^0 \), we get

<table>
<thead>
<tr>
<th></th>
<th>VVS</th>
<th>VSS + VVS</th>
<th>Expt.</th>
<th>VSS + VVS + XSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P )</td>
<td>15.0</td>
<td>18.5</td>
<td>23.0 ± 13.0</td>
<td>19.1</td>
</tr>
<tr>
<td>( A )</td>
<td>20.0</td>
<td>16.2</td>
<td>1.8 ± 5.5</td>
<td>5.6</td>
</tr>
<tr>
<td>( D )</td>
<td>66.7</td>
<td>48.5</td>
<td>26.0 ± 16.0</td>
<td>33.1</td>
</tr>
</tbody>
</table>

We see that the new predictions are in very good agreement with the model. In tables 5.7a and b we have calculated the spin parameters for the various reactions. The first line for each reaction shows the model’s prediction with VSS and VVS but without XSF and the second line with the XSF included.

**5.4 Discussion Of The Model**

The model incorporates a number of assumptions

- The physical origin of spin effects is attributed to Thomas precession of the quarks during recombination.

- Flavor SU(6) wavefunctions describe the baryons and mesons.

- The sea and valence quark amplitudes can be separated in the T matrix and all the amplitudes can be added incoherently.
Table 5.6a  

Expressions For Product Of Cross-Section And Analyzing Power ($\sigma A$)

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\sigma A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p \rightarrow \Lambda$</td>
<td>$\frac{A' B'}{g'} \cdot { [2\epsilon' + \delta'] - \rho[2\epsilon' + 2\epsilon'' + 2\delta'] } + { 0 }$</td>
</tr>
<tr>
<td>$p \rightarrow \Sigma^+$</td>
<td>$8 \frac{A B}{g_1} \cdot { [6\epsilon' + \delta'] - \rho[6\epsilon' + 6\epsilon'' + 2\delta'] } + 8 \frac{AB}{g_1} \cdot { [\epsilon' + \delta] + \rho(1 - \rho)[0] }$</td>
</tr>
<tr>
<td>$p \rightarrow \Sigma^0$</td>
<td>$\frac{A B}{g_1} \cdot { [6\epsilon' + \delta'] - \rho[6\epsilon' + 6\epsilon'' + \delta' + \Delta] } + \frac{AB}{g_1} \cdot { 4\epsilon + 4\delta - \rho(1 - \rho)[4\epsilon + 4\delta] }$</td>
</tr>
<tr>
<td>$p \rightarrow \Sigma^-$</td>
<td>$\frac{A B'}{g_1'} \cdot { -12\epsilon' - 2\delta' } + \rho[12\epsilon' + 12\epsilon'' + 4\delta'] }$</td>
</tr>
<tr>
<td>$p \rightarrow \Xi^0$</td>
<td>$\frac{A B}{g_1} \cdot { 24\epsilon' + 16\delta' } - \rho[24\epsilon' + 24\epsilon'' - 32\delta'] }$</td>
</tr>
<tr>
<td>$p \rightarrow \Xi^-$</td>
<td>$\frac{A B}{g_1} \cdot { -6\epsilon' - 4\delta' } + \rho[6\epsilon' + 6\epsilon'' + 3\delta'] }$</td>
</tr>
<tr>
<td>$p \rightarrow \pi^0$</td>
<td>$\frac{BB'}{g} \cdot { \epsilon' + \epsilon'' } + \rho[2\epsilon' + \epsilon' + \epsilon'' }$</td>
</tr>
<tr>
<td>$p \rightarrow \pi^+$</td>
<td>$\frac{BB'}{g} \cdot { 4\epsilon + 4\epsilon' } - \rho[8\epsilon + 4\epsilon' + 4\epsilon'' }$</td>
</tr>
<tr>
<td>$p \rightarrow \pi^-$</td>
<td>$\frac{BB'}{g} \cdot { -\epsilon - \epsilon' } + \rho[2\epsilon + \epsilon' + \epsilon'' }$</td>
</tr>
<tr>
<td>$p \rightarrow K^+$</td>
<td>$\frac{BB'}{g} \cdot { -\epsilon - 8\epsilon' } + \rho[2\epsilon + \epsilon' + \epsilon'' }$</td>
</tr>
<tr>
<td>$p \rightarrow \Lambda$</td>
<td>$\frac{BB'}{g} \cdot { -\epsilon - \epsilon' } + \rho[2\epsilon + \epsilon' + \epsilon'' }$</td>
</tr>
<tr>
<td>$p \rightarrow \Xi^0$</td>
<td>$\frac{BB'}{g} \cdot { -\epsilon - \epsilon' } + \rho[2\epsilon + \epsilon' + \epsilon'' }$</td>
</tr>
<tr>
<td>$p \rightarrow \Xi^-$</td>
<td>$\frac{BB'}{g} \cdot { -\epsilon - \epsilon' } + \rho[2\epsilon + \epsilon' + \epsilon'' }$</td>
</tr>
</tbody>
</table>
### Table 5.6b

Expressions For Product Of Cross-Section And Polarization (\(\sigma P\))

<table>
<thead>
<tr>
<th>Reaction</th>
<th>(\sigma P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p (\rightarrow) n</td>
<td>(A'B') (\frac{18}{18}) ({[-6\delta'] + \varphi[0]} + \frac{AB}{27} {[-18\varepsilon] + \varphi(1 - \varphi)[14\varepsilon]})</td>
</tr>
<tr>
<td>p (\rightarrow) (\Lambda)</td>
<td>(4A'B') (\frac{27}{27}) ({[4\varepsilon' - \delta'] - \varphi[4\varepsilon' - 4\varepsilon'']} + \frac{4AB}{81} {[\varepsilon + 2\delta] - \varphi(1 - \varphi)[\varepsilon + 2\delta - 2\Delta]})</td>
</tr>
<tr>
<td>p (\rightarrow) (\Sigma^+)</td>
<td>(A'B') (\frac{27}{27}) ({[4\varepsilon' - \delta'] - \varphi[4\varepsilon' - 4\varepsilon'']} + \frac{AB}{81} {[2\varepsilon + 4\delta] + \varphi(1 - \varphi)[34\varepsilon + 40\Delta - 4\delta]})</td>
</tr>
<tr>
<td>p (\rightarrow) (\Sigma^-)</td>
<td>(A'B') (\frac{27}{27}) ({[8\varepsilon' - 2\delta'] - \varphi[8\varepsilon' - 8\varepsilon'']})</td>
</tr>
<tr>
<td>p (\rightarrow) (\Xi^0)</td>
<td>(A'B') (\frac{27}{27}) ({[-4\varepsilon' - 8\delta'] + \varphi[4\varepsilon' - 4\varepsilon'']})</td>
</tr>
<tr>
<td>p (\rightarrow) (\Xi^+)</td>
<td>(A'B') (\frac{27}{27}) ({[-2\varepsilon' - 4\delta'] + \varphi[6\varepsilon' - 6\varepsilon'']})</td>
</tr>
<tr>
<td>p (\rightarrow) (\pi^0)</td>
<td>(A'B') (\frac{27}{27}) ({[-\varepsilon' - 8\delta'] + \varphi[6\varepsilon' - 6\varepsilon'']})</td>
</tr>
<tr>
<td>p (\rightarrow) (\pi^+)</td>
<td>(A'B') (\frac{27}{27}) ({[-\varepsilon' + 2\delta'] + \varphi[6\varepsilon' - 6\varepsilon'']})</td>
</tr>
<tr>
<td>p (\rightarrow) (\pi^-)</td>
<td>(A'B') (\frac{27}{27}) ({[-\varepsilon' - 2\delta'] + \varphi[6\varepsilon' - 6\varepsilon'']})</td>
</tr>
<tr>
<td>p (\rightarrow) (K_0)</td>
<td>(A'B') (\frac{27}{27}) ({[-\varepsilon' + 2\delta'] + \varphi[6\varepsilon' - 6\varepsilon'']})</td>
</tr>
<tr>
<td>(\pi^+) (\rightarrow) p</td>
<td>(A'B') (\frac{18}{18}) ({[4\varepsilon' - \delta'] - \varphi[4\varepsilon' - 4\varepsilon'']})</td>
</tr>
<tr>
<td>(\pi^+) (\rightarrow) (\Lambda)</td>
<td>(A'B') (\frac{27}{27}) ({-\delta'] + \varphi[0]})</td>
</tr>
<tr>
<td>(\pi^-) (\rightarrow) p</td>
<td>(A'B') (\frac{27}{27}) ({-\varepsilon' - 2\delta'] + \varphi[\varepsilon' - \varepsilon'']})</td>
</tr>
<tr>
<td>(\pi^-) (\rightarrow) (\Lambda)</td>
<td>(A'B') (\frac{27}{27}) ({-\delta'] + \varphi[0]})</td>
</tr>
<tr>
<td>K(^+) (\rightarrow) (\Lambda)</td>
<td>(A'B') (\frac{27}{27}) ({-\delta'] + \varphi[0]})</td>
</tr>
<tr>
<td>K(^+) (\rightarrow) (\Sigma^0)</td>
<td>(A'B') (\frac{18}{18}) ({[4\varepsilon' - 2\delta'] - \varphi[4\varepsilon' - \varepsilon'']})</td>
</tr>
<tr>
<td>K(^-) (\rightarrow) (\Lambda)</td>
<td>(A'B') (\frac{3}{3}) ({[\varepsilon'] - \varphi[\varepsilon' - \varepsilon'']})</td>
</tr>
</tbody>
</table>
Table 5.6c

Expressions For Product Of Cross-Section And Depolarization ($\sigma$ D)

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\sigma$ D</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p \rightarrow n$</td>
<td>$\frac{A'B'}{g}$, ${[-e' \delta'] + \varphi[e' \delta' + e'' \delta'] }$ +</td>
</tr>
<tr>
<td>$p \rightarrow \Lambda$</td>
<td>$\frac{AB}{s}$, ${[32 - 8e' \delta'] - \varphi[64 - 8e' \delta' - 8e'' \delta'] }$ +</td>
</tr>
<tr>
<td>$p \rightarrow \Sigma^+$</td>
<td>$\frac{AB}{s}$, ${[4 - e' \delta'] - \varphi[8 - e' \delta' - e'' \delta'] }$ + $\frac{AB}{s}$, ${[8 + 8e\delta] - \varphi(1 - \varphi)[8 + 8e\delta] }$</td>
</tr>
<tr>
<td>$p \rightarrow \Sigma^0$</td>
<td>$\frac{AB}{s}$, ${[4 + 4e\delta] - \varphi(1 - \varphi)[4 + 4e\delta] }$</td>
</tr>
<tr>
<td>$p \rightarrow \Sigma^-$</td>
<td>$\frac{B}{s}$, ${[-8 + 2e' \delta'] + \varphi[16 - 2e' \delta' - 2e'' \delta'] }$</td>
</tr>
<tr>
<td>$p \rightarrow \Xi^0$</td>
<td>$\frac{B}{s}$, ${[-8 - 16e' \delta'] + \varphi[16 + 16e' \delta' + 16e'' \delta'] }$</td>
</tr>
<tr>
<td>$p \rightarrow \Xi^-$</td>
<td>$\frac{B}{s}$, ${[2 + 4e' \delta'] + \varphi[4 + 4e' \delta' + 4e'' \delta'] }$</td>
</tr>
<tr>
<td>$p \rightarrow \pi^0$, $p \rightarrow \pi^+$, $p \rightarrow \pi^-$</td>
<td>$\rho$</td>
</tr>
<tr>
<td>$p \rightarrow K^+$, $\pi^+ \rightarrow p$, $\pi^+ \rightarrow \Lambda$, $\pi^+ \rightarrow \Sigma^+$</td>
<td>$\rho(1 - \varphi)[8 + 8e\delta]$, $\varphi[64 - 8e' \delta' - 8e'' \delta']$</td>
</tr>
<tr>
<td>$p \rightarrow K^+$, $\pi^- \rightarrow p$, $\pi^- \rightarrow \Lambda$, $\pi^- \rightarrow \Sigma^+$</td>
<td>$\rho(1 - \varphi)[4 + 4e\delta]$, $\varphi[8 - e' \delta' - e'' \delta']$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \Lambda$, $K^+ \rightarrow \Sigma^0$, $K^- \rightarrow \Lambda$</td>
<td>$\varphi[8 + 8e\delta]$, $\varphi[4 + 4e\delta]$</td>
</tr>
</tbody>
</table>

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Table 5.6d
Expressions For $\sigma = W_{\uparrow\uparrow} + W_{\downarrow\downarrow} + W_{\uparrow\downarrow} + W_{\downarrow\uparrow}$

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p \rightarrow n$</td>
<td>$A'B'$ ${ [2 + e'\delta'] - \rho[e'\delta' - e''\delta'] }$ + $AB_{\frac{27}{31}}$ ${ [18] - \rho(1 - \rho)[14] }$</td>
</tr>
<tr>
<td>$p \rightarrow \Sigma^+$</td>
<td>$A'B'<em>{\frac{27}{31}}$ ${ [24 + 4e'\delta'] - \rho[4e'\delta' - 4e''\delta'] }$ + $AB</em>{\frac{31}{31}}$ ${ [12 + 8\epsilon\delta] - \rho(4 - 4\rho)[4 + 8\epsilon\delta - \epsilon\Delta] }$</td>
</tr>
<tr>
<td>$p \rightarrow \Sigma^0$</td>
<td>$A'B'<em>{\frac{27}{31}}$ ${ [6 + e'\delta'] - \rho[e'\delta' - e''\delta'] }$ + $AB</em>{\frac{31}{31}}$ ${ [6 + 4\epsilon\delta] 2\rho(1 - \rho) + [19 + 20\epsilon\Delta - 2\epsilon\delta] }$</td>
</tr>
<tr>
<td>$p \rightarrow \Sigma^-$</td>
<td>$A'B'_{\frac{27}{31}}$ ${ [12 + 2e'\delta'] - \rho[2e'\delta' - 2e''\delta'] }$</td>
</tr>
<tr>
<td>$p \rightarrow \Xi^0$</td>
<td>$A'B'_{\frac{27}{31}}$ ${ [12 + 8e'\delta'] - 8\rho[e'\delta' - e''\delta'] }$</td>
</tr>
<tr>
<td>$p \rightarrow \Xi^-$</td>
<td>$A'B'_{\frac{27}{31}}$ ${ [6 + 4e'\delta'] - \rho[4e'\delta' - 4e''\delta'] }$</td>
</tr>
<tr>
<td>$p \rightarrow \pi^0$</td>
<td>$BB^b_{\frac{3}{2}}$ ${ [1 + e\epsilon'] - \rho[e\epsilon' - e\epsilon''] }$</td>
</tr>
<tr>
<td>$p \rightarrow \pi^+$</td>
<td>$BB^b_{\frac{3}{2}}$ ${ [2 + 2e\epsilon'] - \rho[2e\epsilon' - 2e\epsilon''] }$</td>
</tr>
<tr>
<td>$p \rightarrow \pi^-$</td>
<td>$BB^b_{\frac{3}{2}}$ ${ [1 + e\epsilon'] - \rho[e\epsilon' - e\epsilon''] }$</td>
</tr>
<tr>
<td>$p \rightarrow K_\pi$</td>
<td>$BB^b_{\frac{3}{2}}$ ${ [1 + e\epsilon'] - \rho[e\epsilon' - e\epsilon''] }$</td>
</tr>
<tr>
<td>$\pi^+ \rightarrow p$</td>
<td>$A'B'_{\frac{9}{3}}$ ${ [6 + e'\delta'] - \rho[e'\delta' - e''\delta'] }$</td>
</tr>
<tr>
<td>$\pi^+ \rightarrow \Lambda$</td>
<td>$A'B'_{\frac{9}{3}}$ ${ [2 + e'\delta'] - \rho[e'\delta' - e''\delta'] }$</td>
</tr>
<tr>
<td>$\pi^- \rightarrow p$</td>
<td>$A'B'_{\frac{9}{3}}$ ${ [3 + 2e'\delta'] - 2\rho[e'\delta' - e''\delta'] }$</td>
</tr>
<tr>
<td>$\pi^- \rightarrow \Lambda$</td>
<td>$A'B'_{\frac{9}{3}}$ ${ [2 + e'\delta'] - \rho[e'\delta' - e''\delta'] }$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \Lambda$</td>
<td>$A'B'_{\frac{9}{3}}$ ${ [2 + e'\delta'] - \rho[e'\delta' - e''\delta'] }$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \Sigma^0$</td>
<td>$A'B'_{\frac{18}{3}}$ ${ [6 + e'\delta'] - \rho[e'\delta' - e''\delta'] }$</td>
</tr>
<tr>
<td>$K^- \rightarrow \Lambda$</td>
<td>$A'B'_{\frac{3}{3}}$ ${ [1] }$</td>
</tr>
</tbody>
</table>
Table 5.7a

Predictions For $\sigma$, $\sigma P$, $\sigma A$ and $\sigma D$.

Top Line: VSS + VVS

Bottom Line: VSS + VVS + Transversity Flip

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\sigma$</th>
<th>$\sigma P$</th>
<th>$\sigma A$</th>
<th>$\sigma D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p \to \Lambda$</td>
<td>0.73</td>
<td>-0.10</td>
<td>0.019</td>
<td>0.00</td>
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<tr>
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<td>0.61</td>
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<td>$p \to \Sigma^+$</td>
<td>0.22</td>
<td>0.04</td>
<td>0.047</td>
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<td>0.21</td>
<td>0.038</td>
<td>0.035</td>
<td>0.089</td>
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<tr>
<td>$p \to \Sigma^0$</td>
<td>0.13</td>
<td>0.024</td>
<td>0.021</td>
<td>0.063</td>
</tr>
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<td>0.24</td>
<td>0.046</td>
<td>0.013</td>
<td>0.043</td>
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<tr>
<td>$p \to \Sigma^-$</td>
<td>0.44</td>
<td>0.104</td>
<td>-0.052</td>
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<td>0.44</td>
<td>0.104</td>
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<tr>
<td>$p \to \Xi^0$</td>
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<td>-0.052</td>
<td>0.104</td>
<td>-0.099</td>
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<td>0.44</td>
<td>-0.052</td>
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<td>-0.032</td>
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<td>$p \to \Xi^-$</td>
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<td>-0.026</td>
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<td>-0.026</td>
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<tr>
<td>$p \to \pi^0$</td>
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<td></td>
<td>0.70</td>
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<td>0.071</td>
<td></td>
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<tr>
<td>$p \to \pi^-$</td>
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<td></td>
<td>-0.056</td>
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<td></td>
<td>0.35</td>
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<td>-0.018</td>
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<td>$p \to K^+$</td>
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<td>0.18</td>
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<td>$\pi^+ \to p$</td>
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<tr>
<td></td>
<td>0.67</td>
<td>0.156</td>
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<td></td>
</tr>
<tr>
<td>$\pi^+ \to \Lambda$</td>
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<td>0.00</td>
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</tr>
<tr>
<td></td>
<td>0.33</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\pi^- \to p$</td>
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<td>-0.039</td>
<td></td>
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<tr>
<td></td>
<td>0.33</td>
<td>-0.039</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\pi^- \to \Lambda$</td>
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<td>0.00</td>
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<tr>
<td></td>
<td>0.33</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K^+ \to \Lambda$</td>
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<td>0.00</td>
<td></td>
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<td></td>
<td>0.33</td>
<td>0.00</td>
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</tr>
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<td>$K^+ \to \Sigma^0$</td>
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<td>0.33</td>
<td>0.078</td>
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</tr>
<tr>
<td>$K^- \to \Lambda$</td>
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<tr>
<td></td>
<td>0.33</td>
<td>0.117</td>
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</table>
Table 5.7b

Predictions (%) For P, A and D

Top Line: VSS + VVS
Bottom Line: VSS + VVS + Transversity Flip

<table>
<thead>
<tr>
<th>Reaction</th>
<th>P</th>
<th>A</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>p → λ</td>
<td>-13.7</td>
<td>2.6</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>-13.1</td>
<td>0.3</td>
<td>0.00</td>
</tr>
<tr>
<td>p → Σ⁺</td>
<td>18.2</td>
<td>21.4</td>
<td>60.9</td>
</tr>
<tr>
<td></td>
<td>18.0</td>
<td>16.7</td>
<td>42.4</td>
</tr>
<tr>
<td>p → Σ⁰</td>
<td>18.5</td>
<td>16.2</td>
<td>48.5</td>
</tr>
<tr>
<td></td>
<td>19.1</td>
<td>5.6</td>
<td>33.1</td>
</tr>
<tr>
<td>p → Σ⁻</td>
<td>23.7</td>
<td>-11.8</td>
<td>-22.5</td>
</tr>
<tr>
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<td>23.7</td>
<td>-3.6</td>
<td>-7.3</td>
</tr>
<tr>
<td>p → Ξ⁺</td>
<td>-11.8</td>
<td>23.6</td>
<td>-22.5</td>
</tr>
<tr>
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<td>-11.8</td>
<td>7.5</td>
<td>-7.3</td>
</tr>
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<td>-11.8</td>
<td>11.4</td>
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<tr>
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<td>3.6</td>
</tr>
<tr>
<td>p → π⁰</td>
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<td>15.7</td>
<td>5.1</td>
</tr>
<tr>
<td>p → π⁺</td>
<td></td>
<td>31.7</td>
<td>10.1</td>
</tr>
<tr>
<td>p → π⁻</td>
<td></td>
<td>-16.0</td>
<td>-5.1</td>
</tr>
<tr>
<td>p → K⁺</td>
<td></td>
<td>-15.6</td>
<td>-5.0</td>
</tr>
<tr>
<td>π⁺ → p</td>
<td></td>
<td>23.3</td>
<td>23.3</td>
</tr>
<tr>
<td>π⁺ → λ</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>π⁻ → p</td>
<td>-11.8</td>
<td>-11.8</td>
<td></td>
</tr>
<tr>
<td>π⁻ → λ</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>K⁺ → λ</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>K⁺ → Σ⁰</td>
<td>23.6</td>
<td>23.6</td>
<td></td>
</tr>
<tr>
<td>K⁻ → λ</td>
<td>35.5</td>
<td>35.5</td>
<td></td>
</tr>
</tbody>
</table>
• The target projectiles have high $x_F$.

With the addition of XSF amplitudes the model is successful in predicting $P$, $\Lambda$ and $D$ for $\Lambda$ and $\Sigma^0$, and $P$ for $\Sigma^+$, $\Sigma^-$, $\Xi^0$ and $\Xi^-$ in proton induced inclusive production. (The $A$ and $D$ parameters have not been measured for the other baryons.) It works reasonably well in the pion sector where the predictions for $A$ agree in sign and are close in magnitude. For $\pi^+$ the addition of XSF improves the agreement considerably. For pions we observe the following

<table>
<thead>
<tr>
<th>Expt.</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>VSS</td>
<td>VSS + XSF</td>
</tr>
<tr>
<td>$p \rightarrow \pi^0$</td>
<td>10.0 ± 3.0</td>
</tr>
<tr>
<td>$p \rightarrow \pi^-$</td>
<td>-0.5 ± 3.0</td>
</tr>
<tr>
<td>$p \rightarrow \pi^+$</td>
<td>7.9 ± 1.3</td>
</tr>
</tbody>
</table>

The model fails in the kaon sector where we observe that

<table>
<thead>
<tr>
<th>Expt.</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>VSS</td>
<td>VSS + XSF</td>
</tr>
<tr>
<td>$p \rightarrow K^0$</td>
<td>-14.2 ± 1.6</td>
</tr>
<tr>
<td>$K^- \rightarrow \Lambda$</td>
<td>35.0 ± 2.0</td>
</tr>
</tbody>
</table>

With the addition of XSF the predictions for the pion sector are closer to the observed values while the reverse is true for the kaon sector. The situation is summarized in table 5.8 where we show the model’s predictions along with the experimental values. The numbers quoted are as close to $x_F \sim 0.5$ and $p_T \sim 1.0$ as was possible. For $\Lambda$ production there is a lot of data. The result quoted represents the average value with the error spanning the central value of all the measurements.
Table 5.8

Predictions Compared With Available Experimental Values

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Baryon Polarization (%)</th>
<th></th>
<th></th>
<th></th>
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<tr>
<td></td>
<td>VVS</td>
<td>VSS</td>
<td>VVS+VSS</td>
<td>Epxt.</td>
<td>VVS+VSS+XSF</td>
<td>Ref</td>
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<tr>
<td>p → p</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.3 ± 0.6</td>
<td>0.0</td>
<td>[YAM81]</td>
</tr>
<tr>
<td>p → Λ</td>
<td>−ε</td>
<td></td>
<td>-14.9 ± 2.0</td>
<td></td>
<td></td>
<td>[PON85]</td>
</tr>
<tr>
<td>p → Σ⁺</td>
<td>1/3ε + 2/3δ</td>
<td>18.2</td>
<td>22.0 ± 4.0</td>
<td>18.0</td>
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<td>[WIL81]</td>
</tr>
<tr>
<td>p → Σ₀</td>
<td>15.0</td>
<td>18.5</td>
<td>25.5 ± 9.2</td>
<td>19.1</td>
<td></td>
<td>[DUK87]</td>
</tr>
<tr>
<td>p → Σ⁻</td>
<td>23.7</td>
<td>23.7</td>
<td>15.5 ± 3.6</td>
<td>23.7</td>
<td></td>
<td>[DEC83]</td>
</tr>
<tr>
<td>p → Σ⁺</td>
<td>-11.8</td>
<td>-11.8</td>
<td>-12.0 ± 2.5</td>
<td>-11.8</td>
<td></td>
<td>[HEL83]</td>
</tr>
<tr>
<td>p → Σ⁻</td>
<td>-11.8</td>
<td>-11.8</td>
<td>-10.2 ± 1.7</td>
<td>-11.8</td>
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<td>[RAM86]</td>
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<tr>
<td>π⁺ → Σ⁺</td>
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<tr>
<td>π⁻ → Λ</td>
<td>−1/2γ '</td>
<td>-5.1 ± 1.2</td>
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<td>[BEN83]</td>
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<td>K⁻ → Σ⁺</td>
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<td>K⁺ → Σ₀</td>
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<tr>
<td>K⁻ → Λ</td>
<td>γ '</td>
<td>35.0 ± 2.0</td>
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<td>[ARM85]</td>
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Analyzing Power (%)

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</thead>
<tbody>
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<td>-1.1 ± 0.7</td>
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<tr>
<td>p → Σ₀</td>
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<td>1.8 ± 5.5</td>
<td>5.6</td>
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<tr>
<td>p → π₀</td>
<td>15.7</td>
<td>15.7</td>
<td>10.0 ± 3.0</td>
<td>5.1</td>
<td></td>
<td>[BON88]</td>
</tr>
<tr>
<td>p → π⁺</td>
<td>31.7</td>
<td>31.7</td>
<td>7.9 ± 1.3</td>
<td>10.1</td>
<td></td>
<td>[BON88]</td>
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<tr>
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<td>-16.0</td>
<td>-0.5 ± 3.0</td>
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<td></td>
<td>[BON88]</td>
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<tr>
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<td>-15.6</td>
<td>-14.2 ± 1.6</td>
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Depolarization (%)

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<tbody>
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<td>-2.7 ± 2.4</td>
<td>0.0</td>
<td></td>
<td>[BON88]</td>
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<tr>
<td>p → Σ₀</td>
<td>66.7</td>
<td>48.5</td>
<td>26.0 ± 16.0</td>
<td>33.1</td>
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<td>this expt</td>
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</tbody>
</table>
In figure 5.3 we have shown the analyzing power for $K^+$ production in different $x_F$ bins. The data reproduces the feature of the model that spin effects should be prominent at high $x_F$ but the values are too large and still increasing. The analyzing power for the low $x_F$ ($< 0.2$) data is flat and does not approach zero, while at high $x_F$ ($> 0.2$) it seems to get bigger. It is possible that in the $K^+$ production we have two mechanisms, one contributing at low $x_F$ and the other at high $x_F$. More data on this variable is welcome and will hopefully shed light on the production mechanism.

The model has five free parameters which are fixed by experiment. We are forced to choose $\epsilon' = 0.35$ because of the large value of polarization observed for $\Lambda$'s produced by a $K^-$ beam. One can rationalize this by looking at the different degrees of spin precession undergone by a valence quark coming from a meson and a baryon. In $K^-$ — $\Lambda$ production the valence quark carries at least half of the initial momentum, which leads to a precession $\propto \frac{1}{2}(\frac{1}{m_s} + \frac{1}{m_d})$ whereas in $p$ — $\Lambda$ production the strange quark carries at most one third of the $\Lambda$ momentum which is less than one third of the proton's momentum. This leads to a precession $\propto \frac{1}{3m_L}$. Thus we have the ratio for the two parameters

$$\frac{\epsilon'}{\epsilon} = \frac{3 \cdot 25(m_s + m_d)}{m_d}$$

Thus we expect that $\epsilon'$ is at least twice as big as $\epsilon$. The parameters $\delta$ and $\delta'$ are related to their single quark partners $\epsilon'$ and $\epsilon$ in a very curious way ($\delta = \epsilon'^2$, and $\delta' = \epsilon^2$) which may just be a coincidence.

It would be worthwhile to measure some more parameters e.g. $P$ for $\Sigma^0$ production using a $K^+$ beam. Although there is no data for inclusive production of $\Sigma^+$ from $\pi^+$ and
Fig 5.3 $K_s$ analyzing power from E817/TON88 and this run as a function of $x_F$. $x_T = 2p_T/\sqrt{s}$
$K^-$ beams, exclusive reaction measurements give polarization values which agree with the predictions. Other spin parameter measurements that could shed light on this puzzle would be A and D for the other hyperons. To verify how good the SU(6) wavefunctions are in this regime, we can look at the agreement in the results for D.

The free parameters must have an $x_p$ and $p_T$ dependence (as seen in the results) which must be built into them, as has been done for $\epsilon$ from the $\Lambda$ polarization results, and then compare predictions with experimental values.
Chapter 6

Conclusions

We have measured the analyzing power A, polarization P and depolarization parameter D for inclusive $\Sigma^0$ production. We used the polarized beam at the AGS which accelerated protons to 18.5 GeV/c with an average polarization of 43%. This was also the energy at which we had measured the P, A and D for inclusive $\Lambda$ production in an earlier run. The original idea was to extract the beam at a higher energy but the accelerator faced a serious setback when the Siemens power supply used to power the ring magnets broke down. The polarized proton run was rescued from a postponement of a few years by the resourceful AGS staff who retrieved the old Westinghouse power supply from its resting place for the last 18 years. The Westinghouse power supply limited the energy to which the beam could be accelerated and so we ran with 18.5 Gev/c polarized protons. Since the experimental setup detects both lambdas and photons we could have made another set of measurements for $\Lambda$ production. As it turned out we were only able to verify the earlier results.

A large fraction of the time allocated for the polarized proton running at the AGS
was spent in tuning the machine to cross all the depolarizing resonances without losing the polarization. During running we faced a lot of problems with the spill structure which had a large rf modulation which reduced the duty cycle considerably. This limited the amount of data we could collect in the already short time available.

6.1 Discussion Of The Results

We have verified that the analyzing power for inclusive $\Lambda$ production yields $A \approx 0$. We have a measurement of polarization for $\Sigma^0$'s which agrees with an earlier experiment [DUK87]

<table>
<thead>
<tr>
<th></th>
<th>This expt.</th>
<th>[DUK87]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$</td>
<td>23.0 ± 13.0</td>
<td>28.0 ± 13.0</td>
</tr>
</tbody>
</table>

the error being due to the low statistics. We also measured, for the first time, the analyzing power $A$ and depolarization $D$ for $\Sigma^0$ production. The results along with theoretical predictions for these parameters are given below.

<table>
<thead>
<tr>
<th></th>
<th>VVS</th>
<th>VSS + VVS</th>
<th>Expt.</th>
<th>VSS + VVS + XSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$</td>
<td>15.0</td>
<td>18.5</td>
<td>23.0 ± 13.0</td>
<td>19.1</td>
</tr>
<tr>
<td>$A$</td>
<td>20.0</td>
<td>16.2</td>
<td>1.8 ± 5.5</td>
<td>5.6</td>
</tr>
<tr>
<td>$D$</td>
<td>66.7</td>
<td>48.5</td>
<td>26.0 ± 16.0</td>
<td>33.1</td>
</tr>
</tbody>
</table>

The VVS column is the original predictions of the model which neglected recombination due to single quark transfer and sea diquark pickup. The results are many standard deviations away from the predictions. On adding the VSS terms we see that the difference is still very large. The next step in the calculation required a modification of
the model. The model assumes that there is no transversity spin flip (XSF) during the transfer of quarks and/or diquarks. Since this process does not have to conserve helicity it is not disallowed by the symmetry of strong interaction. We included two new terms in the model to account for a XSF in a quark and diquark transfer to the final target projectile. The probability for a spin flip, $\rho$, was determined by fitting the ratio of cross sections of $\Lambda$ and $\Sigma^0$ production to the observed values. This yields $\rho = 0.34$, which changes the results for $\Sigma^0$ production as shown in the last column above. We see that the results are now in very good agreement with the extended model's predictions.

The analysis was complicated due to the large background under the $\Sigma^0$ peak. There are three main possibilities for this, which we list below.

- **Bad reconstruction of the decay particles $\Lambda$ and $\gamma$.**

  This would lead to a broadened mass peak and not to a background like we see. We have also reconstructed $\Lambda$'s and $K^+$'s and we do not notice any broadening which could be ascribed to bad reconstruction. Thus we can rule this possibility out.

- **Decays of higher mass resonances some of whose decay particles can be reconstructed to yield $\Sigma^0$'s.**

  The only baryon which has a significant probability is $\Xi^0$. It can decay to $\Lambda \pi^0$ in the first step. The $\pi^0$ can then decay to two photons one of which enters the lead glass array. We can safely rule out such processes from contributing to our $\Sigma^0$ data sample because they decay outside the target. By requiring the primary decay vertex to be in the target we can overcome this source of background.
- Uncorrelated $\Lambda$'s pairing up with neutral particles which shower in the lead glass to give a $\Sigma^0$ within the mass peak.

The background consists mostly of such events.

A further experiment to enhance statistics has been approved at BNL for the next polarized run at the AGS.

In conclusion, the physical origin of the spin effects in inclusive particle production still eludes us. The measurements we have made imply that the recombination is enhanced and is not a simple beam fragment transfer to the final state. We have parametrized it by a transversity spin flip and find good agreement with the existing data.
Appendix A

SU6 Wavefunctions Of Baryons

The SU(6) quark model wavefunctions of baryons are defined as \( \{SU(3)_{\text{flavor}}, SU(2)_{\text{spin}}\} \)
i.e. there are three flavors each of which has two spin components. The representations arising from this combination are:

\[
6 \otimes 6 \otimes 6 = 56 \oplus 70 \oplus 70 \oplus 20. \quad (A.1)
\]

These form the symmetric (S), mixed symmetric (M\(\_\)s), mixed antisymmetric (M\(\_s\)) and antisymmetric (A) states respectively. These can be written in a more transparent form as

\[
3 \otimes 3 \otimes 3 = 10_S \oplus 8_{M_s} \oplus 8_{M_a} \oplus 1_A \quad (A.2)
\]

and

\[
2 \otimes 2 \otimes 2 = 4_S \oplus 2_{M_s} \oplus 2_{M_a} \quad (A.3)
\]

for flavor and spin respectively. The combined representation looks like:

\[
S \ : \ (10,4) + (8,2)
\]
\( M_s : (10,2) + (8,4) + (8,2) + (1,2) \)

\( M_a : (10,2) + (8,4) + (8,2) + (1,2) \)

\( A : (8,2) + (1,4) \)

We are interested in the symmetric octet \((8,2)_s\) which is given by:

\[
(8,2)_s = \frac{\phi(M_s) \chi(M_s) + \phi(M_a) \chi(M_a)}{2}
\]  

(A.4)

where \(\phi\) and \(\chi\) are the flavor and spin wavefunctions respectively (refer to HM table 3.7).

The SU(6) wavefunctions for the spin up baryons are given by:

\[
|p> = -\frac{1}{\sqrt{18}} \left[ uud(||| + |1| + 2||) + udu(||| + |1| + 2||) \right] + duu(||| + |1| + 2||) \]  

(A.5)

\[
|n> = -|p> \rightarrow d, d, u \]  

(A.6)

\[
|\Lambda> = \frac{1}{\sqrt{12}} \left[ (uds - dus)(||| + |1| + 2||) + (dsu - uds)(||| + |1| + 2||) \right] + (sdv - uvd)(||| + |1| + 2||) \]  

(A.7)

\[
|\Sigma^0> = -\frac{1}{6} \left[ (uds + dus)(||| + |1| + 2||) + (dus + usd)(||| + |1| + 2||) \right] + (sdv + uvd)(||| + |1| + 2||) \]  

(A.8)

\[
|\Sigma^+> = |p> \rightarrow s \]  

(A.9)

\[
|\Sigma^-> = |\Sigma^+> \rightarrow d \]  

(A.10)

\[
|\Xi^0> = |n^0> \rightarrow s \]  

(A.11)

\[
|\Xi^-> = |n^0> \rightarrow s; u \rightarrow d \]  

(A.12)

We will rewrite the above wavefunctions as a diquark-quark pair. This is best seen by calculating for a specific baryon. Let us choose \(\Sigma^0\). Regrouping appropriate terms
we get

\[ |\Sigma^0\rangle = \frac{1}{6} \{ [ds(2\uparrow\downarrow) + sd(2\uparrow\downarrow)]u] - [ds(1\downarrow\downarrow) + sd(1\downarrow\downarrow)]u] - [ds(1\uparrow\downarrow) + sd(1\uparrow\downarrow)]u] \\
+ [us(2\uparrow\downarrow) + su(2\uparrow\downarrow)]d] - [us(1\downarrow\downarrow) + su(1\downarrow\downarrow)]d] - [us(1\uparrow\downarrow) + su(1\uparrow\downarrow)]d] \\
-[ud(1\uparrow\downarrow) + du(1\uparrow\downarrow)]s] - [ud(1\downarrow\downarrow) + du(1\downarrow\downarrow)]s] + [ud(2\uparrow\downarrow) + du(2\uparrow\downarrow)]s] \} (A.13)\]

Now

\[ |\uparrow\uparrow\rangle = (11) \]
\[ |\downarrow\rangle = \frac{1}{\sqrt{2}}[(10) + (00)] \]
\[ |\downarrow\uparrow\rangle = \frac{1}{\sqrt{2}}[(10) - (00)] \]

Note that we have \( q_a q_b (S_1 S_2) = q_b q_a (S_2 S_1) \) after the diquark has been formed. So

\[ \frac{[q_a q_b (S_1 S_2) + q_b q_a (S_2 S_1)]}{\sqrt{2}} = (q_a q_b)(S_1 S_2) \]  

(A.14)

e.g.

\[ [ds(1\downarrow\downarrow) + sd(1\downarrow\downarrow)] = \sqrt{2}(ds)(10) + (00) \]
\[ = (ds)[(10) + (00)] \]  

(A.15)

and

\[ ds(1\uparrow\downarrow) + sd(1\downarrow\downarrow) = \sqrt{2}(ds)(11) \]  

(A.16)

Thus we have

\[ |\Sigma^0\rangle = \frac{1}{6} \{ 2(ds)[(10) + (00)]u] - (ds)[(10) - (00)]u] - \sqrt{2}(ds)(11)u] \\
+ 2(us)[(10) + (00)]d] - (us)[(10) - (00)]d] - \sqrt{2}(us)(11)d] \\
-(ud)[(10) + (00)]s] - (ud)[(10) - (00)]s] + 2\sqrt{2}(ud)(11)]s] \} \]  

(A.17)
which gives

\[ |\Sigma^0| = \frac{\sqrt{2}}{3} |ud11 > |s| > - \frac{1}{3} |ud10 > |s| > - \frac{1}{\sqrt{18}} |us11 > |d| > + \frac{1}{6} |us10 > |d| > + \]
\[ \frac{1}{2} |us00 > |d| > - \frac{1}{\sqrt{18}} |ds11 > |u| > + \frac{1}{6} |ds10 > |u| > + \frac{1}{2} |ds00 > |u| > \]

Similarly the wavefunctions for the other baryons can be obtained. We have tabulated the expressions for the spin up and spin down baryons in the diquark-quark formalism in Tables A-1 and A-2.
## Table A-1

**SU(6) Wavefunctions For SPIN UP Baryons In Diquark-Quark Representation.**

<table>
<thead>
<tr>
<th>Wavefunction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>p\uparrow\rangle\rangle = \sqrt{\frac{5}{3}}</td>
</tr>
<tr>
<td>$</td>
<td>n\rangle\rangle = - \sqrt{\frac{5}{3}}</td>
</tr>
<tr>
<td>$</td>
<td>\Sigma^+\uparrow\rangle\rangle = \sqrt{\frac{5}{3}}</td>
</tr>
<tr>
<td>$</td>
<td>\Sigma^-\rangle\rangle = \sqrt{\frac{5}{3}}</td>
</tr>
<tr>
<td>$</td>
<td>\Xi^0\rangle\rangle = - \sqrt{\frac{5}{3}}</td>
</tr>
<tr>
<td>$</td>
<td>\Xi^-\rangle\rangle = - \sqrt{\frac{5}{3}}</td>
</tr>
<tr>
<td>$</td>
<td>\Lambda\rangle\rangle = \frac{1}{\sqrt{6}}</td>
</tr>
<tr>
<td>$</td>
<td>\Sigma^0\rangle\rangle = \frac{1}{\sqrt{6}}</td>
</tr>
<tr>
<td>$</td>
<td>\Sigma^0\rangle\rangle = - \frac{1}{\sqrt{3}}</td>
</tr>
<tr>
<td>$</td>
<td>\Sigma^0\rangle\rangle = \frac{1}{\sqrt{3}}</td>
</tr>
<tr>
<td>$\sqrt{\frac{2}{3}}</td>
<td>ud,11\rangle\rangle \frac{1}{\sqrt{18}}</td>
</tr>
</tbody>
</table>
TABLE A-2

SU(6) Wavefunctions For SPIN DOWN Baryons In Diquark-Quark Representation.

| |  
|---|---|
| | \[ |p \uparrow\rangle \] |  
| | \[ \pm \frac{\sqrt{3}}{3} | uu 1-1\rangle | d \uparrow+ \frac{1}{3} | uu 10\rangle | d \uparrow- \frac{1}{3} | ud 1-1\rangle | u \uparrow+ \frac{1}{\sqrt{18}} | ud 10\rangle | u \downarrow- \frac{1}{\sqrt{2}} | ud 00\rangle | u \downarrow  
| | \[ |u \uparrow\rangle \] |  
| | \[ - \frac{\sqrt{3}}{6} | dd 1-1\rangle | d \uparrow+ \frac{1}{3} | dd 10\rangle | u \uparrow+ \frac{1}{3} | ud 1-1\rangle | d \uparrow- \frac{1}{\sqrt{18}} | ud 10\rangle | d \downarrow- \frac{1}{\sqrt{2}} | ud 00\rangle | d \downarrow  
| | \[ |\Sigma^+ \downarrow\rangle \] |  
| | \[ \pm \frac{\sqrt{3}}{3} | uu 1-1\rangle | s \uparrow- \frac{1}{3} | uu 10\rangle | s \uparrow- \frac{1}{3} | us 1-1\rangle | u \uparrow+ \frac{1}{\sqrt{18}} | us 10\rangle | u \uparrow- \frac{1}{\sqrt{2}} | us 00\rangle | u \uparrow  
| | \[ |\Sigma^- \downarrow\rangle \] |  
| | \[ \pm \frac{\sqrt{3}}{3} | dd 1-1\rangle | s \uparrow- \frac{1}{3} | dd 10\rangle | s \uparrow- \frac{1}{3} | ds 1-1\rangle | d \uparrow+ \frac{1}{\sqrt{18}} | ds 10\rangle | d \uparrow- \frac{1}{\sqrt{2}} | ds 00\rangle | d \uparrow  
| | \[ |\Xi^0 \downarrow\rangle \] |  
| | \[ - \frac{\sqrt{3}}{6} | ss 1-1\rangle | u \uparrow+ \frac{1}{3} | ss 10\rangle | u \uparrow+ \frac{1}{3} | us 1-1\rangle | s \uparrow- \frac{1}{\sqrt{18}} | us 10\rangle | s \uparrow- \frac{1}{\sqrt{2}} | us 00\rangle | s \uparrow  
| | \[ |\Xi^- \downarrow\rangle \] |  
| | \[ - \frac{\sqrt{3}}{6} | ss 1-1\rangle | d \uparrow+ \frac{1}{3} | ss 10\rangle | d \uparrow+ \frac{1}{3} | ds 1-1\rangle | s \uparrow- \frac{1}{\sqrt{18}} | ds 10\rangle | s \uparrow- \frac{1}{\sqrt{2}} | ds 00\rangle | s \uparrow  
| | \[ |\Lambda \downarrow\rangle \] |  
| | \[ \pm \frac{\sqrt{12}}{3} | us 1-1\rangle | d \uparrow- \frac{1}{\sqrt{12}} | us 10\rangle | d \uparrow- \frac{1}{\sqrt{12}} | us 00\rangle | d \uparrow  
| | \[ - \frac{\sqrt{6}}{3} | ds 1-1\rangle | u \uparrow+ \frac{1}{\sqrt{12}} | ds 10\rangle | u \uparrow+ \frac{1}{\sqrt{12}} | ds 00\rangle | u \uparrow  
| | \[ - \frac{\sqrt{3}}{3} | ud 00\rangle | s \uparrow  
| | \[ |\Sigma^0 \downarrow\rangle \] |  
| | \[ - \frac{\sqrt{12}}{3} | us 1-1\rangle | d \uparrow+ \frac{1}{6} | us 10\rangle | d \uparrow- \frac{1}{6} | us 00\rangle | d \uparrow  
| | \[ - \frac{\sqrt{12}}{3} | ds 1-1\rangle | u \uparrow+ \frac{1}{6} | ds 10\rangle | u \uparrow- \frac{1}{6} | ds 00\rangle | u \uparrow  
| | \[ \frac{\sqrt{3}}{3} | ud 1-1\rangle | s \uparrow- \frac{1}{3} | ud 10\rangle | s \uparrow  


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Appendix B

Decay Characteristics Of $\Sigma^0$

Let us choose $|\uparrow\rangle$, $|\downarrow\rangle$ to be the spin of the $\Sigma^0$ in its rest frame along $\pm z$ axis. An arbitrary spin state of the $\Sigma^0$ can be written as

$$|\psi_i\rangle = \rho_+ |\uparrow\rangle + \rho_- |\downarrow\rangle$$

where $\rho_{\pm}$ are the probabilities for the $\Sigma^0$ to be in $|\uparrow\rangle$, and $|\downarrow\rangle$ states respectively. The polarization of $\Sigma^0$ is given by

$$P_{\Sigma^0} = \langle \psi_i | \sigma | \psi_i \rangle = \rho_+ < |\sigma| |\uparrow\rangle + \rho_- < |\sigma| |\downarrow\rangle$$

$$= (\rho_+ - \rho_-) z$$

The photon has a total angular momentum $j=1$ because $\Sigma^0$ decay proceeds via $M1$ transition which gives $\Delta l = \pm 1$ and $\Delta m = \pm 1$. So a $\Sigma^0$ can be decomposed into a $\Lambda$ and a $\gamma$ as

$$|\frac{1}{2}\frac{1}{2}\rangle_{\Sigma^0} = \alpha |\frac{1}{2}\frac{1}{2}\rangle_{\Lambda}|10\rangle_{\gamma} + \beta |\frac{1}{2}\frac{1}{2}\rangle_{\Lambda}|11\rangle_{\gamma}$$

$$= -\frac{1}{\sqrt{3}} |\frac{1}{2}\frac{1}{2}\rangle_{\Lambda}|10\rangle_{\gamma} + \sqrt{\frac{2}{3}} |\frac{1}{2}\frac{1}{2}\rangle_{\Lambda}|11\rangle_{\gamma}$$
\[ |\frac{1}{2} - \frac{1}{2} >_{\Sigma^n} = \frac{1}{\sqrt{3}} |\frac{1}{2} - \frac{1}{2} >_A |10 >_{\gamma} - \frac{\sqrt{2}}{3} |\frac{1}{2} \frac{1}{2} >_A |11 >_{\gamma} \]  

(B.4)

for spin up and down respectively. Here subscript \( \gamma \) refers to the \(|jm > \) state of the photon. We can decompose it further into an orbital angular momentum \( l \), and a spin angular momentum \( s \).

\[ 1_{\gamma} = l \times 1 \Rightarrow l = 0, 1, 2. \]

\( l = 0, 2 \) are ruled out because both \( \Sigma^0 \) and \( \Lambda \) are in the \( S \) state and \( \Delta l = \pm 1 \). If we then write the photon state as a product of \( Y_{lm} \) s and the spin states we get

\[ |10 >_{\gamma} = \frac{1}{\sqrt{2}} Y_{11} |1 - 1 >_{\gamma} - \frac{1}{\sqrt{2}} Y_{01} |11 >_{\gamma} \]  

(B.5)

\[ |11 >_{\gamma} = \frac{1}{\sqrt{2}} Y_{11} |10 >_{\gamma} - \frac{1}{\sqrt{2}} Y_{10} |11 >_{\gamma} \]  

(B.6)

\[ |1 - 1 >_{\gamma} = \frac{1}{\sqrt{2}} Y_{10} |1 - 1 >_{\gamma} - \frac{1}{\sqrt{2}} Y_{1-1} |10 >_{\gamma} \]  

(B.7)

Simplifying a little, we get

\[ |\frac{1}{2} \frac{1}{2} >_{\Sigma^n} = \left[ \frac{1}{\sqrt{6}} Y_{1-1} |\frac{1}{2} \frac{1}{2} >_A - \frac{1}{\sqrt{3}} Y_{10} |\frac{1}{2} - \frac{1}{2} >_A \right] |11 >_{\gamma} \]

\[ + \frac{1}{\sqrt{3}} Y_{11} |\frac{1}{2} - \frac{1}{2} >_A |10 >_{\gamma} - \frac{1}{\sqrt{6}} Y_{11} |\frac{1}{2} \frac{1}{2} >_A |1 - 1 >_{\gamma} \]  

(B.8)

\[ |\frac{1}{2} - \frac{1}{2} >_{\Sigma^n} = - \frac{1}{\sqrt{6}} Y_{1-1} |\frac{1}{2} - \frac{1}{2} >_A |11 >_{\gamma} + \frac{1}{\sqrt{3}} Y_{1-1} |\frac{1}{2} \frac{1}{2} >_A |10 >_{\gamma} \]

\[ + \left[ - \frac{1}{\sqrt{3}} Y_{10} |\frac{1}{2} \frac{1}{2} >_A + \frac{1}{\sqrt{6}} Y_{11} |\frac{1}{2} - \frac{1}{2} >_A \right] |1 - 1 >_{\gamma} \]  

(B.9)

There is no physical \( |10 >_{\gamma} \) state. We include it because we will shortly sum over the spin states of the photon. A correct analysis would have to take into consideration the relativistic nature of the photon.

After the decay the final state of the system can be written as

\[ |\psi_f > = \rho_+ |\psi^+ >_A + \rho_- |\psi^- >_A \]  

(B.10)
where $|\psi^+_{\Lambda\gamma}\rangle$ and $|\psi^-_{\Lambda\gamma}\rangle$ refer to the right hand sides of eqns B.3 and B.4. Since we do not observe the sign of the photon's spin we need to sum over them. This can be done by finding the density matrix for each photon spin and adding them.

\[
\rho = \sum_i \sum_{\alpha} w(\alpha) \rho_{ij}(\alpha, i) \tag{B.11}
\]

$i$ refers to the photon spin, $\alpha$ to the $\Sigma^0$ spin state, $w(\alpha)$ is the weight of state $\alpha$ and $\rho_{ij}(\alpha)$ is the density matrix of state $\alpha$. For $\Sigma^0$ spin up we get the following matrices

\[
\rho_{11} = \begin{pmatrix}
\frac{1}{6} |Y_{11}|^2 & -\frac{1}{\sqrt{15}} Y_{1-1} Y_{10} \\
\frac{1}{\sqrt{15}} Y_{10} Y_{11} & \frac{1}{3} |Y_{10}|^2
\end{pmatrix}
\]

\[
\rho_{10} = \begin{pmatrix}
0 & 0 \\
0 & \frac{1}{3} |Y_{11}|^2
\end{pmatrix}
\]

\[
\rho_{1-1} = \begin{pmatrix}
\frac{1}{6} |Y_{11}|^2 & 0 \\
0 & 0
\end{pmatrix}
\]

For $\Sigma^0$ spin down we get

\[
\rho_{11} = \begin{pmatrix}
0 & 0 \\
0 & \frac{1}{6} |Y_{11}|^2
\end{pmatrix}
\]

\[
\rho_{10} = \begin{pmatrix}
\frac{1}{4} |Y_{11}|^2 & 0 \\
0 & 0
\end{pmatrix}
\]

\[
\rho_{1-1} = \begin{pmatrix}
\frac{1}{3} |Y_{10}|^2 & \frac{1}{\sqrt{15}} Y_{1-1} Y_{10} \\
-\frac{1}{\sqrt{15}} Y_{10} Y_{11} & \frac{1}{6} |Y_{11}|^2
\end{pmatrix}
\]
Thus we get the total density matrix to be

$$\rho = \begin{pmatrix}
\rho_{+1} \frac{1}{2} |Y_{11}|^2 + \rho_{-1} \frac{1}{2} [|Y_{10}|^2 + |Y_{11}|^2] & (\rho_{-1} - \rho_{+1}) \frac{1}{\sqrt{18}} Y_{-1} Y_{10} \\
(\rho_{+1} - \rho_{-1}) \frac{1}{\sqrt{18}} Y_{10} Y_{11} & \rho_{+1} \frac{1}{2} [|Y_{10}|^2 + |Y_{11}|^2] + \rho_{-1} \frac{1}{2} |Y_{11}|^2
\end{pmatrix}$$

where we have used $Y_{lm}^* = (-)^m Y_{l-m}$.

### B.1 Polarization Of Λ's From $Σ^0$ Decay

The $\rho$ we have calculated is the density matrix for the $Λ$s. The polarization for the $Λ$s coming from $Σ^0$ decay is then defined by $\text{Tr}(σ \rho)$. On doing the calculation we get

$$\langle \sigma_x \rangle = -\frac{1}{4\pi} P_Σ \cos δ \sin δ \cos φ \quad (B.12)$$

$$\langle \sigma_y \rangle = -\frac{1}{4\pi} P_Σ \cos δ \sin δ \sin φ \quad (B.13)$$

$$\langle \sigma_z \rangle = -\frac{1}{4\pi} P_Σ \cos δ^2 \quad (B.14)$$

where we have used

$$Y_{11} = \sqrt{\frac{3}{8\pi}} \sin δ \exp(iφ)$$

$$Y_{10} = \sqrt{\frac{3}{4\pi}} \cos δ$$

$$Y_{1-1} = \sqrt{\frac{3}{8\pi}} \sin δ \exp(-iφ)$$

$δ$ and $φ$ are the angles of the photon's momentum with respect to the $+z$ axis. $P_Σ$ is as defined in eqn B.2. We get the same expressions for the spin components if we take the angles w.r.t the $Λ$ momentum. The direction of the $Λ$ momentum is given by

$$\vec{p}_Λ = -\left( i \sin δ \cos φ + j \sin δ \sin φ + k \cos δ \right) \quad (B.15)$$
Thus we get

\[ < \vartheta > = -\frac{1}{4\pi} P_{\Sigma} \cos \delta (-\vec{p}_\Lambda) \]  

(B.16)

which gives

\[ < \vartheta > \equiv < P_\Lambda > = -\frac{1}{4\pi} (P_{\Sigma} \cdot -\vec{p}_\Lambda) (-\vec{p}_\Lambda) \]

Finally, we get

\[ P_\Lambda = -(P_{\Sigma} \cdot \vec{p}_\Lambda) \vec{p}_\Lambda \]  

(B.17)

The average magnitude of the \( \Lambda \) polarization can be obtained by integrating eqn B.17 over \( \phi \) and \( \delta \). The result is

\[ | \overline{P}_\Lambda | = \frac{1}{2} | P_{\Sigma} | \]  

(B.18)

Similarly, the mean values of the \( \Lambda \) polarization along each component is given by

\[ \overline{P}_{\Lambda x} = 0, \overline{P}_{\Lambda y} = 0, \overline{P}_{\Lambda z} = -\frac{1}{3} P_{\Sigma} \]  

(B.19)

### B.2 Remarks

1. Maximum \( \Lambda \) polarization if \( \Lambda \) momentum is collinear with \( \Sigma^0 \) spin.

2. Minimum \( \Lambda \) polarization if \( \Lambda \) momentum is anti-collinear with \( \Sigma^0 \) spin.

3. The \( \Lambda \) spin is always opposite that of \( \Sigma^0 \) spin.

4. If \( \Sigma^0 \) and \( \Lambda \) are in the same half plane, the \( \Lambda \)s have negative helicity.

5. If \( \Sigma^0 \) and \( \Lambda \) are in the different half planes, the \( \Lambda \)s have positive helicity.
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