

NEGATIVE HYPERON PRODUCTION
IN K^- - PROTON COLLISIONS
AT 3.5 GEV/C INCIDENT K^-
MOMENTUM

by

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ABSTRACT

The results from a study of the production of negative hyperons in K^-P interactions at 3.5 GeV/c in hydrogen bubble chamber are presented in this thesis. Chapter 1 deals with introduction and the object of the work presented in the thesis. In chapters 2 and 3 details of the experimental apparatus and experimental procedure are given. Chapter 4 discusses the different programs used in the data analysis. Chapter 5 describes the 'Eightfold' way in detail. In chapter 6 different biases in the results are discussed. Discussions on the Σ channels together with the production of Y_1^{*-} (1385) and $N_{3/2}^{*-}$ (1238) are made in chapter 7. Chapter 8 deals with the results in the Ξ^- channels. In chapter 9 comparisons of the results at 3.5 GeV/c with those at other energies are made followed by the conclusion.

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PREFACE

The author joined the High Energy Physics Group at the Imperial College in October 1961. Since then, he has been working in the Bubble chamber Film Analysis Group under the supervision of Prof. C.C. Butler. He spent the first year studying the basic theory of elementary particles. He also took part in the film analysis for the 4 GeV/c π^-p ⁽¹⁾ experiment in which the Imperial College Group was a collaborator. These 4 GeV/c π^- films were taken in CERN (Centre Europeenne pour la Recherche Nucleaire) using the 81 cm. Hydrogen Bubble chamber⁽²⁾ of Saclay and Ecole polytechnique. Mr. F. Campayne and the author set up the bubble counting device which was vital for the event analysis in the π^- experiment. The device consisted of a projection microscope for projecting the picture of a bubble chamber event on to a screen which was calibrated in suitable intervals. The distribution of the gaps is measured and the mean gap length is calculated (For details see reference 3).

In February 1963 Imperial College joined three other groups - the University of Oxford, the University of Glasgow and NIRNS (National Institute of Research in Nuclear Science) to form a collaboration with the object of studying the 3.5 GeV/c K^-p interactions. This was the highest incident energy of the K^- particles in a hydrogen bubble chamber

experiment used so far. Some 120,000 pictures were taken in CERN using the 81 cm. hydrogen bubble chamber.⁽²⁾ The scanning of the films was started in March, 1963. Soon after, the measurement of the events with two or more vees ('Vee' in our terminology means a charged or neutral strange particle decay) started. The measurements of the "common" events (events with one vee only) were started subsequently. In October 1963, another 120,000 K^- pictures at the same energy were taken. Subsequently another short run of K^- was done during Christmas time in 1963. The author went to Cern to help in the run. 60,000 pictures were taken this time.

In this experiment the author was exclusively responsible for the compilation and analysis of the Ξ^- data.

CHAPTER I.

INTRODUCTION

Section 1.1: SU_3 and I, U and V Spins:

The interest in the study of the strange particles dates back to the discovery of the K^0 (neutral K meson) particle by Rochester and Butler⁽⁴⁾ in 1947 using the cloud chamber technique. In recent years a large number of new particles and resonances have been discovered using the bubble chamber technique which was first developed by Glaser⁽⁵⁻⁸⁾ and was improved considerably in the last few years. The principle of working of a bubble chamber has been described in the references (5-8).

Side by side with the experimental development the theoretical physicists tried to find laws describing the production and the decay of these particles and to group them according to their properties. The Japanese physicists, Sakata, Ikeda, Ogawa and Ohnuki followed by Gell-Mann, Ne'eman, Salam, Ward, Okubo and others⁽⁹⁻²⁰⁾ formulated a new symmetry principle in grouping the particles and resonances, known as Unitary Symmetry or SU_3 . An alternative description of SU_3 was that of Levinson et al⁽¹⁸⁻²⁰⁾ who generalised the I-spin concept and invoked two other 'spins' namely the U-spin and the V-spin. All these three quantities are required to be conserved simultaneously.

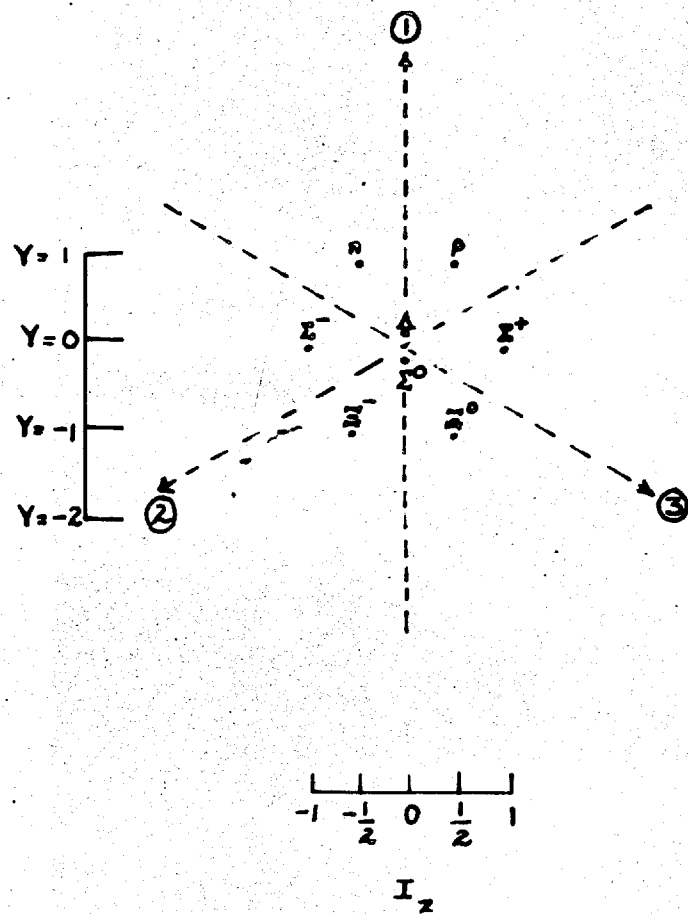
Some predictions about the cross-sections and the decay modes could be made considering the symmetry about the three axes of the above mentioned "spins" which are at an angle of 120° to each other.

In the diagram of the Baryon octet, figure 1.1a where I_z (z component of the I-spin) is plotted against the hypercharge $Y(Y=S+B, S$ is the strangeness quantum number and B is the baryon number) a 120° rotational symmetry can be seen. The particles which appear in the same horizontal line form I-spin multiplet. Likewise particles might be grouped along lines at $\pm 120^\circ$ forming U-spin and V-spin multiplets.

Section 1.2: The object of the work presented in this thesis:

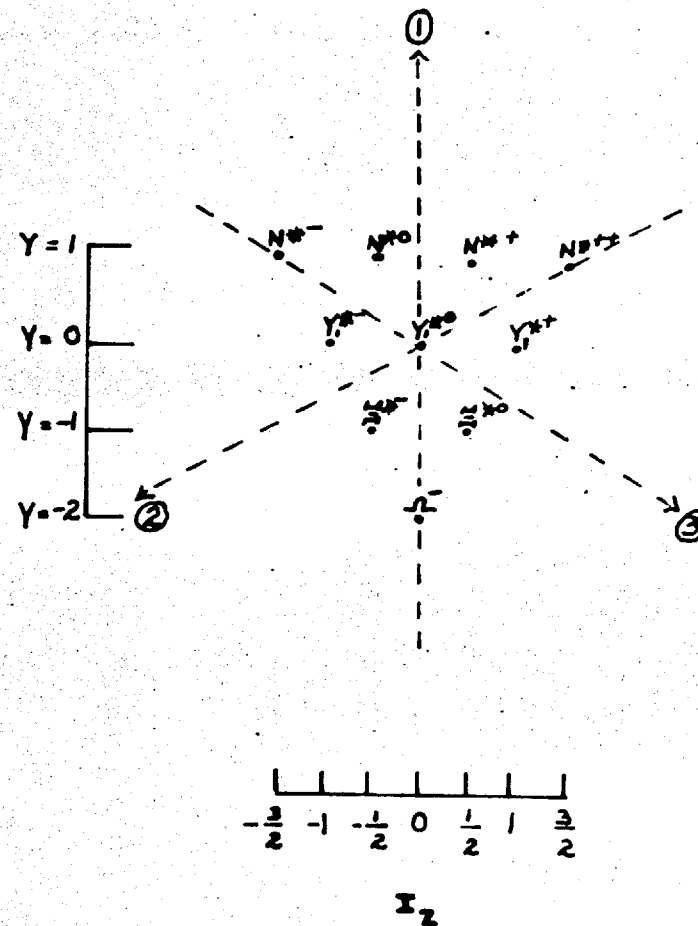
In a U-spin multiplet the strangeness is not the same but the electric charge is the same. Consequently Σ^- and Ξ^- form a U-spin doublet. Similarly in the decuplet of Baryon resonances, figure 1.1b, the well known $3/2-3/2$ resonance, $N_{3/2}^{*-}$ (1238 Mev), Y_1^{*-} (1385 Mev) (31,32 and 35-41), Ξ^{*-} (1530 Mev) (35,42-45) and Ω^- (1680 Mev) (26,48,49) form a U-spin quartet with $U = 3/2$.

The object of the work presented in this thesis was to study the properties and the correlations of different cross-sections of production and angular distributions of the



Baryon Octet

FIG 1-1a



Baryon Decuplet

FIG 1-1b

hyperons and hyperonic resonances belonging to the $U = \frac{1}{2}$ and $U = 3/2$ multiplets.

From the U-spin conservation some interesting predictions about experimental cross-sections can be made such as,

$$\frac{K^- P \rightarrow K^+ \Xi^{*-}}{K^- P \rightarrow \pi^+ Y^{*-}} = 1$$

or

$$\frac{\pi^- P \rightarrow K^+ Y_1^{*-}}{K^- P \rightarrow K^+ \Xi^{*-}} = 1$$

Predictions can also be made about the decay of the resonances. Since rotations in U-spin space do not alter the electric charge U-spin multiplets consist of particles or resonances which have the same coupling to the electromagnetic field. Therefore, the electromagnetic interaction conserves U-spin and the photon can be regarded as having U-spin zero. Hence,

$$\begin{aligned} \Xi^{*-} &\rightarrow \Xi^- + \gamma \\ Y_1^{*-} &\rightarrow \Sigma^- + \gamma \\ U &= 3/2 \quad \frac{1}{2} \quad 0 \end{aligned}$$

are forbidden but

$$\begin{aligned} Y_1^{*+} &\rightarrow \Sigma^+ + \gamma \\ N^{*+} &\rightarrow P + \gamma \\ U &= \frac{1}{2} \quad \frac{1}{2} \quad 0 \end{aligned}$$

are allowed since U is conserved.

CHAPTER 2.

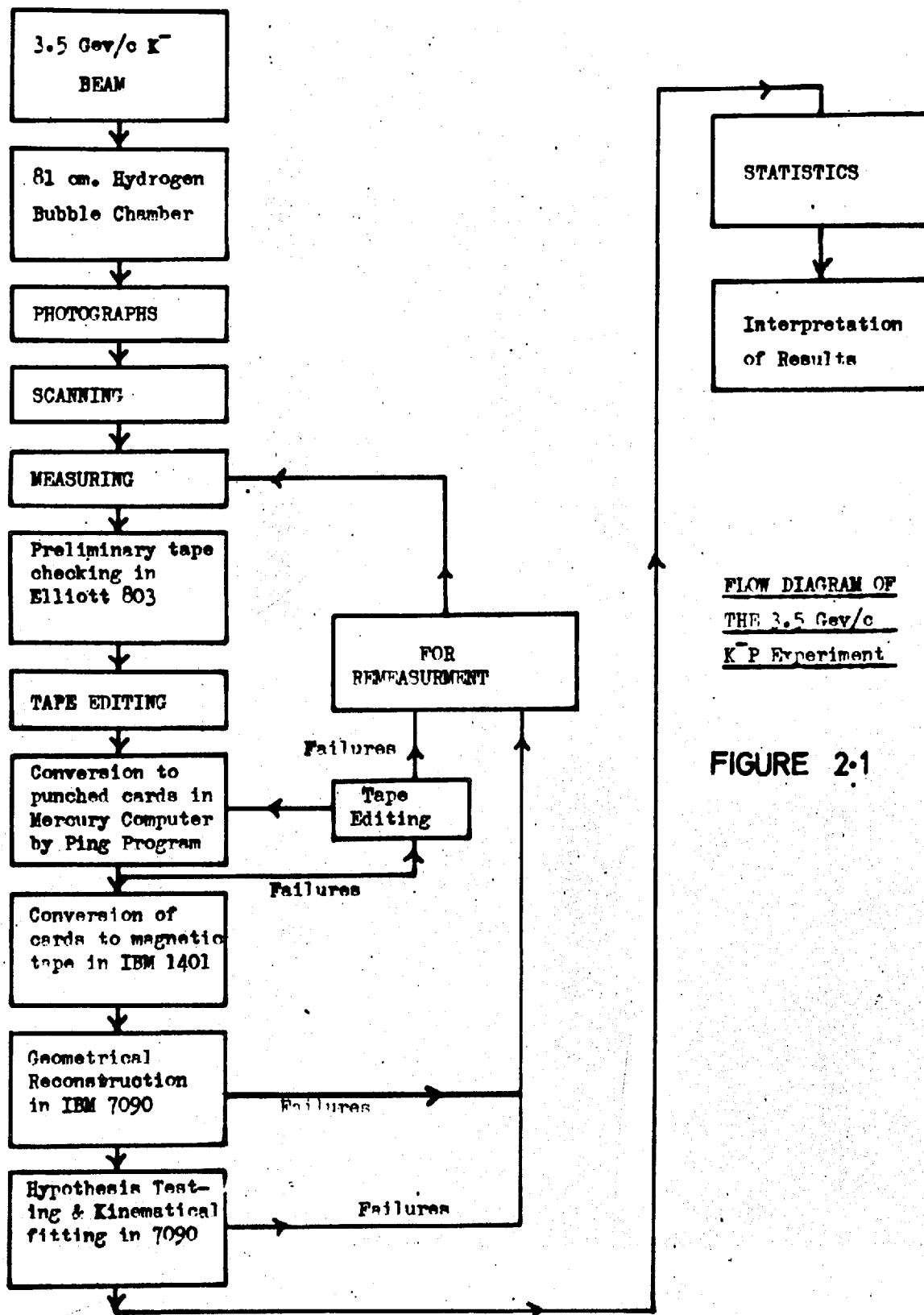
THE EXPERIMENTAL APPARATUS

Section 2.1: 3.5 GeV/c K^- ⁽⁷⁸⁾ beam and the 81 cm bubble chamber:

Figure 2.1 shows the flow diagram of the whole 3.5 GeV/c K^-P experiment. The layout of the K^- beam is shown in figure 2.2. The beam is produced by the collisions of a 19.4 GeV/c primary Proton beam with a beryllium target. The main characteristics of the beam are given in Table I.

Altogether 300,000 K^- pictures were taken at an incident K^- momentum of 3.5 GeV/c. The average number of K^- mesons per picture was nine with a contamination of about three additional particles mainly μ^- and π^- .

The 81 cm. hydrogen bubble chamber was used in this experiment. The description of this chamber is given in reference 2. Figure 2.3 gives the diagram of the geometrical layout of the chamber windows and the three stereoscopic cameras c_1 , c_2 and c_3 . The crosses with 2-digit numbers next to them are cross-marks on the inner surfaces of the front and back windows called as the fiducial marks and are used to define a frame of reference. The X direction is positive in the sense of the incident K^- beam direction. The Y direction is positive in the sense going from the fiducial 00 to the fiducial 99. The Z direction is positive in the sense going from the cameras towards the



FLOW DIAGRAM OF
THE 3.5 GeV/c
K⁻ Experiment

FIGURE 2-1

1) Beryllium target (25x4x1 mm³)

1a) Vertical and horizontal collimator.

2) Quadrupole Q₁
 3) " Q₂
 5) " Q₃
 11) " Q₄
 13) " Q₅
 15) " Q₆
 16) " Q₇
 17) " Q₈
 20) " Q₉

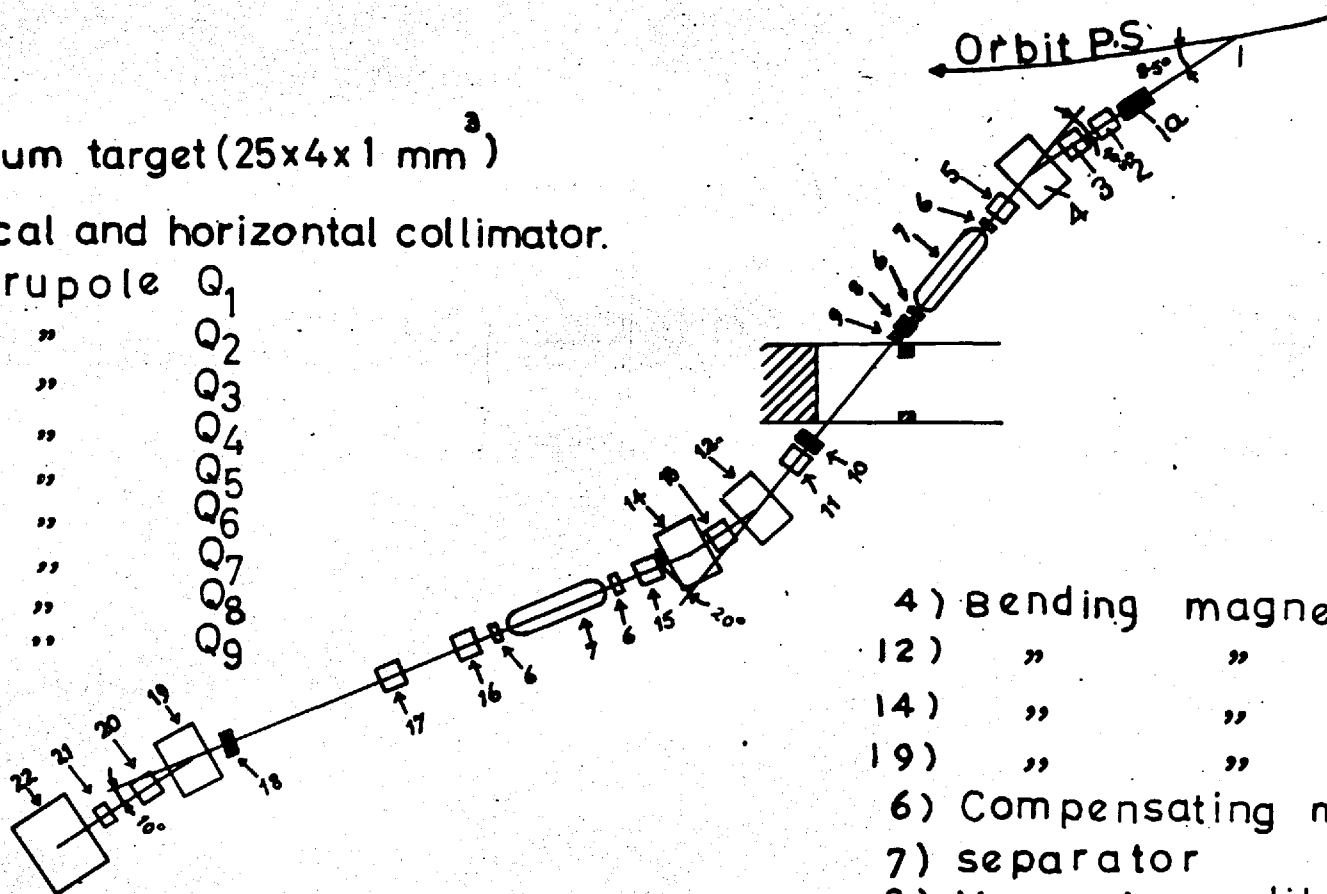


FIGURE 2-2

4) Bending magnet BM1
 12) " " BM2
 14) " " BM3
 19) " " BM4
 6) Compensating magnets
 7) separator
 8) Momentum slit F1
 10) Mass " F2
 18) " " F3
 9) sextupole
 21) Magnet at the entrance of bub-cham.
 22) Bubble chamber.

TABLE I

Initial Proton Beam Momentum	Target Size			Method of Separation	$\frac{\Delta P}{P}$ in %	Ω $\times 10^{-4}$ sterad
	Height	Width	Length			
19.4 Gev/c	1 mm	4 mm	25 mm	Steel Plate Separator	0.5	0.61

where

$\frac{\Delta P}{P}$ is the momentum bite

Ω is the solid angle of acceptance

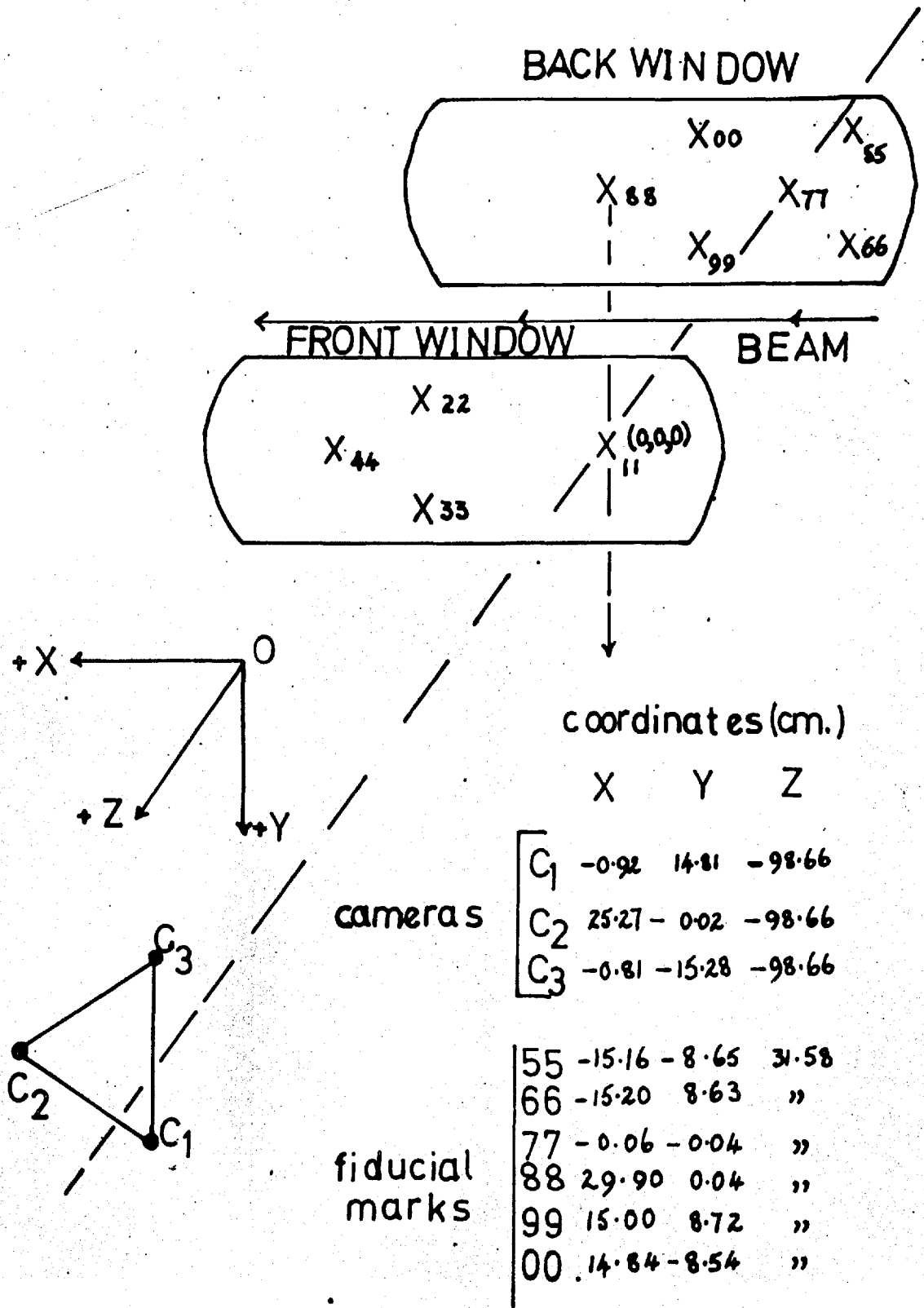


FIGURE 2.3

chamber . $X = Y = 0$ at the fiducial 77 on the back window. Z is equal to zero at the plane of the front glass. Figure 2.3 also gives the coordinates of the three cameras and the fiducial marks.

Section 2.2: Scanning Machines:

The first stage of the analysis consists of scanning and measuring the bubble chamber events. The purpose of scanning is to provide a catalogue of the events of interest.

At present there are five scanning machines available in this college. The photographs of the bubble chamber events taken simultaneously from three cameras are mounted on three channels of the scanning machine which is fitted with a lens and mirror system to project the picture on the scanning table. The picture thus projected is about life size. The scanning table is also provided with a film transport mechanism. All three views can be moved together or individually. There is also the provision for projecting the pictures on the two extreme channels side by side. It is also possible to make two views overlap. This becomes necessary to check for stopping tracks in the chamber.

Section 2.3: Measuring Machines and their Accuracy:

After scanning comes the measurement process. The physicist defines the categories of events that he wishes

to be measured. The locations of these events in the film are obtained from the scanning cards made during the scanning (the procedure of scanning will be discussed in section 3.1 in detail).

It is well known that a charged particle in a magnetic field moves in a curved trajectory. The momentum P of the particle is related to the magnetic field H and the radius of curvature R of the trajectory by the following relation,

$$P = 300 HR$$

with P in ev/c , H in gauss and R in centimetres. The purpose of the measuring machines is to measure approximately equally spaced points along the track on the film. This is done in three views. Some fixed fiducials are also measured. With the help of these measurements the tracks are reconstructed in space i.e. in the bubble chamber (For detailed discussion see reference 21 and also section 4.1).

At present there are three measuring machines in the Imperial College. One of them was built in the college, the other two are typical British National Measuring machines (Description of these machines is given in reference 22). In the homemade machine the film moves both in the X and the Y directions. The picture is projected on a screen through a lens system. The projected picture is three times the life size. In the other two big machines the film moves on

a carriage parallel to its length in the X-direction and the lens system moves along the Y-direction. There are three separate lens systems and photoelectric detectors, (in one of these two big machines there is only one detector and there is no high magnification screen). Figure 2.4 shows the optical layout of the system. A stationary view of the whole frame is projected in tungsten light by the 9X lens. The measuring channel is illuminated by a high pressure mercury lamp shared by all three channels. The small beam surrounding the measured point selected by the beam splitting patch is divided into two parts by a beam splitter. The reflected part containing the mercury green and yellow lines is projected 30X on a screen. The transmitted part containing the blue and violet lines goes to the photoelectric detector. The screen on which the 30X magnification is displayed has got a cross marked on it which can be rotated to line up with the direction of the track. The X and Y movements are done by hydraulic rams. Moiré fringe digitizers are used for digitization. The big machine with only one photoelectric detector is provided with an automatic track-following device.

After the two big machines were installed the author investigated the accuracy with which the measurements were made by these machines. The random error is due to the setting on a point to be measured. The r.m.s. setting error

OPTICAL LAYOUT OF THE MEASURING MACHINE (one channel only)

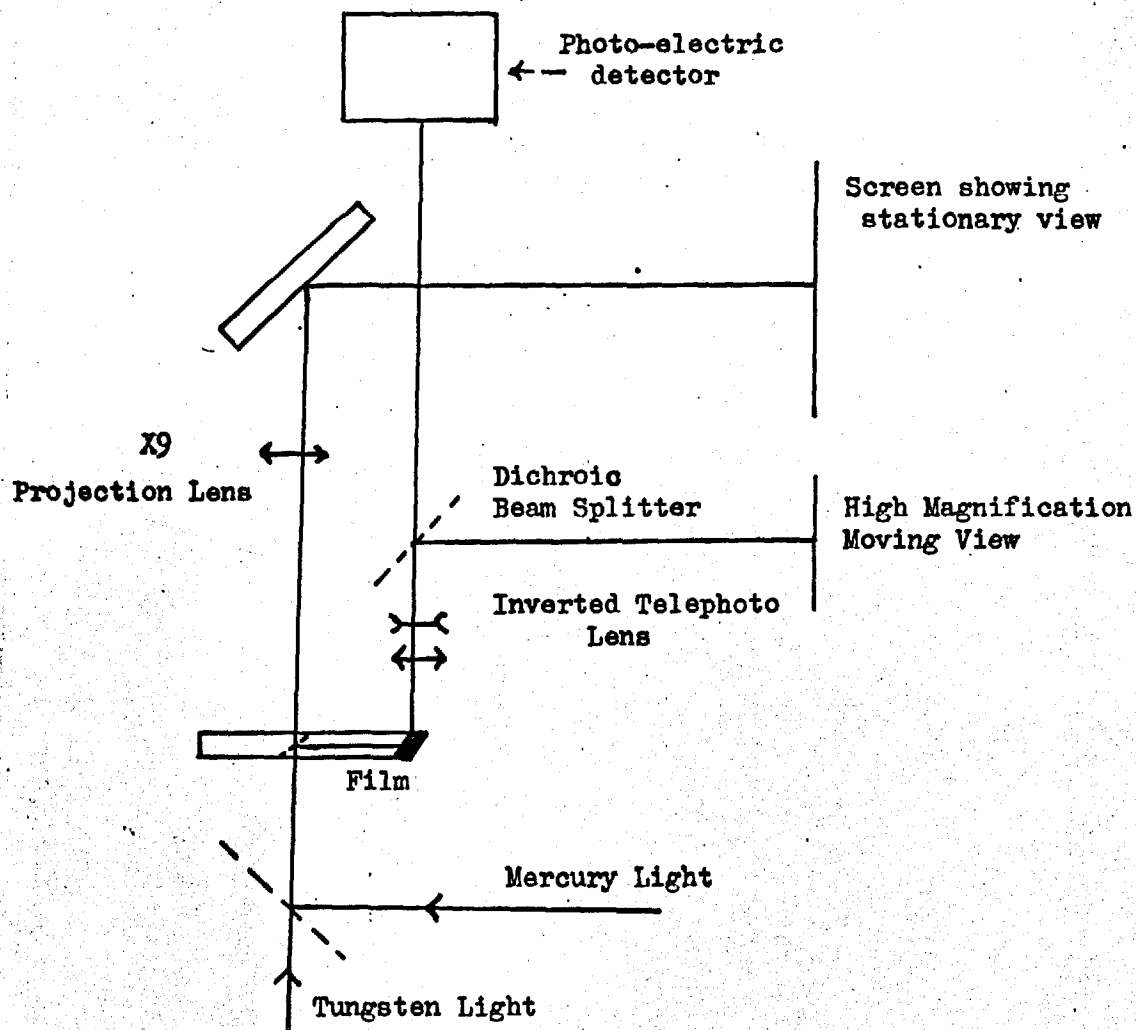


FIGURE 2.4

was of the order of ± 3 microns in both the machines. The inaccuracy in the movement of the stage of the machine might introduce some systematic error in the measurement. This was found out in the following way.

A contact print was made on a piece of film from the image of a thin stretched glass fibre on a photographic plate. This 9 cm straight line which was very nearly parallel to the x-axis of the machine was measured several times. It was then reversed through 180° and was measured again several times. Each time about 30 measurements were taken along the whole length. If there were no error introduced by the movement of the stages then the two curvatures from these two different sets of measurements should have the same numerical value but would differ in sign. A very small systematic error was found which could safely be ignored.

CHAPTER 3

THE EXPERIMENTAL PROCEDURE

Out of the 300,000 K^- pictures taken over three runs the Imperial College received 40,000 pictures. The purpose of scanning has already been described in section 2.2. In section 3.1 the scanning procedure and the different criteria used in the scanning will be discussed. In section 3.2 the measurement procedure and the preliminary stage of the data processing will be described.

Section 3.1: Scanning Procedure:

The pictures of the bubble chamber events were mounted in three different channels of the scanning machines. Every picture was searched for an event with at least one strange particle decay. The topological characteristics of an event were denoted by three digits ABC, A,B,C being the number of charged secondaries from the primary vertex, number of charged decays and number of neutral decays respectively. For example, in this terminology a 421 type of event would look like figures 3.1a and 3.1b, the difference between 3.1a and 3.1b being that the neutral vee could either come from the primary vertex or from one of the decay vertices. Events with two or more V's (henceforth to be called the top priority events) were noted down irrespective of the region in which they occurred

AN EVENT OF 421 TYPE

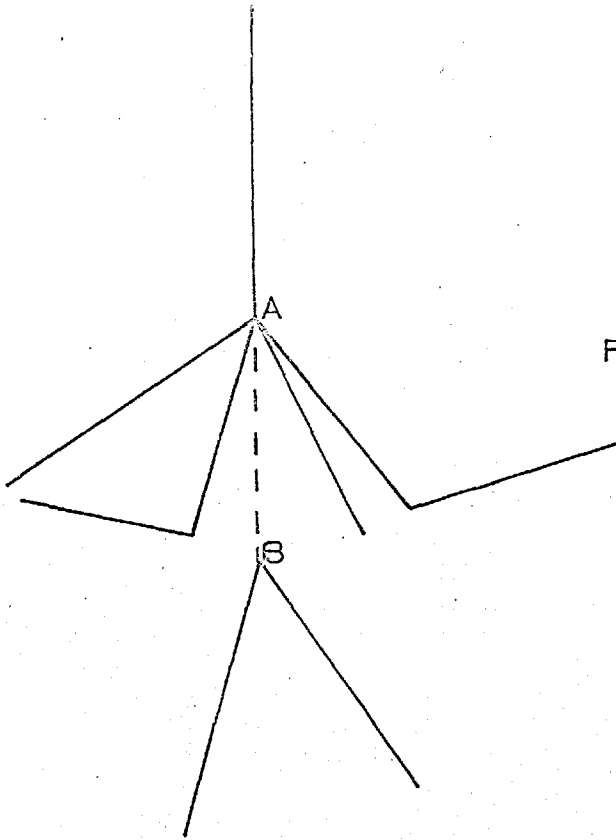
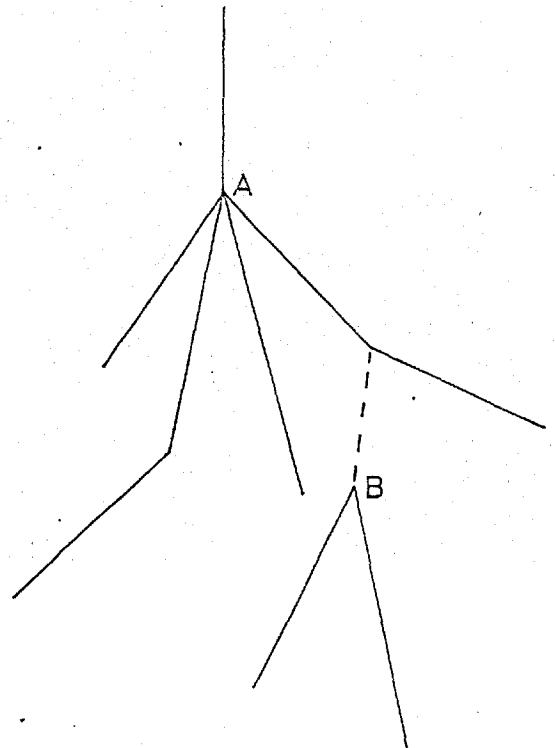


FIGURE 3.1a

FIGURE 3.1b



But for the common events a fiducial region was defined. Events were noted down only if they occurred inside a rectangular box of dimensions 39 cms x 15.5 cms., figure 3.2. This fiducial volume is defined in the second view since the camera axis on the second view is most normal to the centre of the tracks. For the same reason, for visual estimation of the ionisation of the tracks the second view is used. τ decays ($K^- \rightarrow \pi^+ \pi^- \pi^-$) were also noted down. These τ counts were used later on to calculate the cross-sections of different channels. A note was also made of any blank or overlapping frames. The information which was put down in the scanning card was:

1. The Frame Number
2. The topology of the event.
3. A code number to describe the topology.
4. The event number (if there were more than one event in a frame, then the event numbers were put down as 1,2,3,... the numbers increasing as the length of the incident K^- track increases).
5. The Scanner's number
6. Information about the origin of a neutral V.
7. A small drawing of the bubble chamber to locate the positions of the different apices.

A sketch of the event was also drawn on the space provided in the scan card. Additional information can also

FIDUCIAL VOLUME

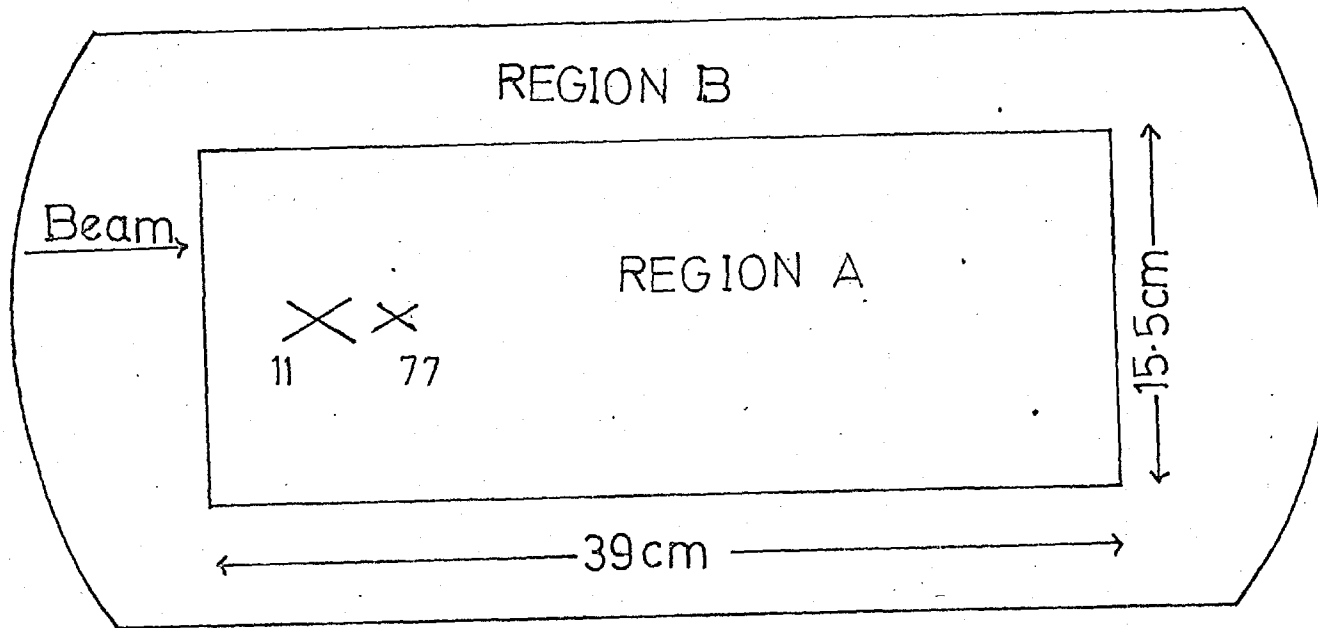


FIGURE 3.2

be put down in the remaining space of the card. Two scans were made independently. A check scan list was then prepared containing the events which were found only in one scan but not in the other and also other discrepancies such as region, frame numbers or wrong interpretation of the event. The check scan was carried out by two physicists. A master list of 'good' events was then prepared.

To separate electron pairs from V^0 's a restriction was imposed not to accept any event with a V^0 which had an opening angle $< 3^\circ$. In this way certainly some Λ^0 's and K^0 's would be lost (loss was about 1%) but quite a clean sample of V^0 's was thus obtained. The required minimum length of a charged decay was 1 mm. Any decay length less than that was classified as unmeasurable. Extreme care was also taken not to confuse a scatter with a charged decay.

The criterion of association of a neutral V to a vertex was quite straightforward. If the line joining the production vertex and the neutral decay vertex went through the two tracks of the V^0 , the V^0 was regarded to be associated, figure 3.3.

An effort was also made to distinguish the $\pi \rightarrow \mu$ decays in flight from the $K \rightarrow \mu$ decays from the knowledge of the maximum transverse momentum of the decay product in these two decays.

The off-beam criterion was not very well defined.

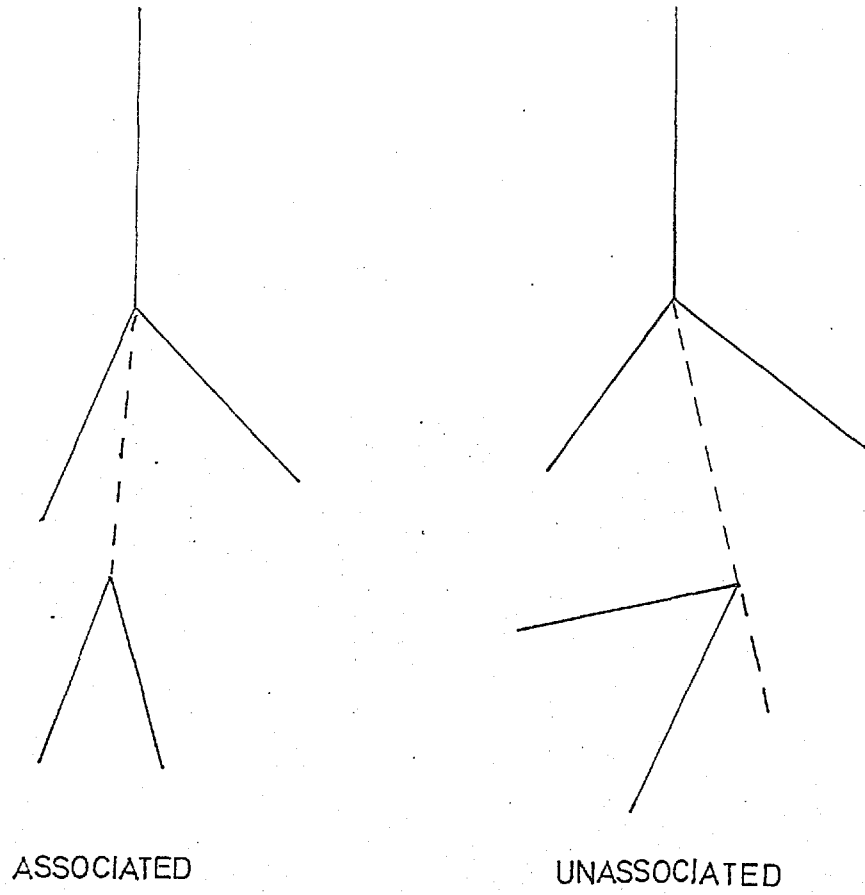


FIGURE 3.3

A beam which was obviously not parallel to the main bunch of the beams was regarded as off-beam and any interaction coming from that beam was ignored.

The overall scanning efficiency was of the order of 95%.

Section 3.2: Measurement of the events and Preliminary Data Processing:

The measurement of the top priority events was started first followed by the measurement of the common events. The object of measuring and the details of the measuring machines have been described in section 2.3. An event was measured only when all three views were seen. The output of the measuring machines is punched on 5-hole paper tape.

A preliminary check of this paper tape was made on the Elliot 803 computer for trivial faults in labelling of the items, punching of the holes and the sequence of measurements (which was indicated on the scan card). Some of the faults at this stage were removed by hand editing the tape.

These corrected tapes were then passed through a Program which would convert the paper tapes to punched cards in a format compatible with the Geometry Program.⁽²¹⁾ This job is done by a Mercury computer. The information in these cards for the successful events was then transferred to a

magnetic tape via a 1401 computer. The information on the tape passed through the Geoentry Program followed by the Hypothesis Testing and the Kinematical Fitting Program. (23) Figure 2.1 gives an idea of the different steps in the Data Processing system. The events which failed at the Mercury stage were corrected for editable faults otherwise they were sent for remeasurement. The failure at this stage was about 10% .

CHAPTER 4

PROGRAMS USED IN THE ANALYSIS OF THE DATA

Section 4.1: The Geometrical Reconstruction Program: ⁽²¹⁾

As was stated earlier in this thesis the purpose of the Geometry Program is to find the positions in space of the different measured vertices with their errors and also to calculate the momentum p , the azimuthal angle ϕ and the dip angle λ of the tracks with their errors. All these parameters are given at the centre of the track.

The coordinates of the vertices and of different tracks measured in all three views are presented in a form compatible with the input format of the Geometry Program. The transformation of all the measurements on film for each view to a standard frame for that view, defined as having the point where the optic axis cuts the film plane as origin

and X and Y axes parallel to the X and Y axes of the coordinate system of the chamber, is done as follows:

For each view a set of expected fiducial position in the standard frame is supplied. A particular fiducial on each view is always measured first and a translation is made on the measured fiducials so that this first fiducial is in its correct position. Then, assuming that the axes of the measurement frame and the axes of the standard frame are only inclined at a small angle, the measured fiducials can be identified with the standard fiducials. From these two corresponding sets of measured fiducials and the standard fiducials, the transformation coefficients are found for each view.

Assuming parallel glasses and film plane and no lens distortion for the bubble chamber optics, all the measured film coordinates are transformed into ray coordinates using suitable optical formulas. A ray is defined by a coordinate pair of the point where the ray cuts the front glass-hydrogen interface and by the direction ratios of the ray.

The vertex coordinates are reconstructed in the following way:

For each vertex there are three rays (if no view is missing) and we wish to find the point (x,y,z) in the chamber which is the point of nearest intersection of these rays. This is done by minimising $\sum d_i^2$ where d_i is the distance

between the projection of the point (x,y,z) on the film for view i and the point where the ray cuts the film.

The space points for tracks are found by the corresponding points method. A 'best' view is defined for each track and for each ray on this view corresponding rays on each of the other 'subviews' are found. These are then used to find a weighted mean for the space point. To find the corresponding rays between two views the ray coordinates are rotated in a system with x-axis along the direction between the two cameras. This is called the stereo-axis. For each track, the view for which

$$\frac{L}{L_{\max}} + W \left[\frac{\sin^2 \theta_1 + \sin^2 \theta_2}{\max (\sin^2 \theta_1 + \sin^2 \theta_2)} \right]$$

is a maximum is called the 'best view'. In this expression, L is the length of the image of the track, $L_{\max}$ is the maximum value of L for the three views, $\sin^2 \theta_1$ and $\sin^2 \theta_2$ are the average values of $\sin^2 \theta$ for the two subviews. θ is the angle that the tangent to the track on the subview makes with the stereo-axis. W is a specified weighting factor.

If (X_B, Y_B, U_B, V_B) be the coordinates of the 'best' view ray, then, ignoring optical constraints the corresponding ray (X_S, Y_S, U_S, V_S) on the subview can be found from the relation $Y_S = Y_B$. This would be done by finding the two

rays on the subview with Y coordinates nearest to the value $Y_S = Y_B$ and then interpolating. From these two rays the z-coordinate of the space point on the best view ray can be calculated

$$Z = \frac{X_B - X_S}{U_S - U_B}$$

The weighted mean value of the z-coordinate of the space point is given by

$$Z = \frac{\sin^2 \theta_1 Z_1 + \sin^2 \theta_2 Z_2}{\sin^2 \theta_1 + \sin^2 \theta_2}$$

But, in practice, because of the optical distortions, it is necessary to iterate to find corresponding rays and also to take account of the curvature of the track by interpolation.

A first approximation curve fitting is done on these space points. First, the x, y projection of the track are fitted, then the fitting of the z-coordinates is done. For tracks turning through a large angle a circle fit is made for the x, y coordinates while for tracks turning through a small angle a parabolic fit is made. To decide between a circle or parabolic fit a check is done on the value of

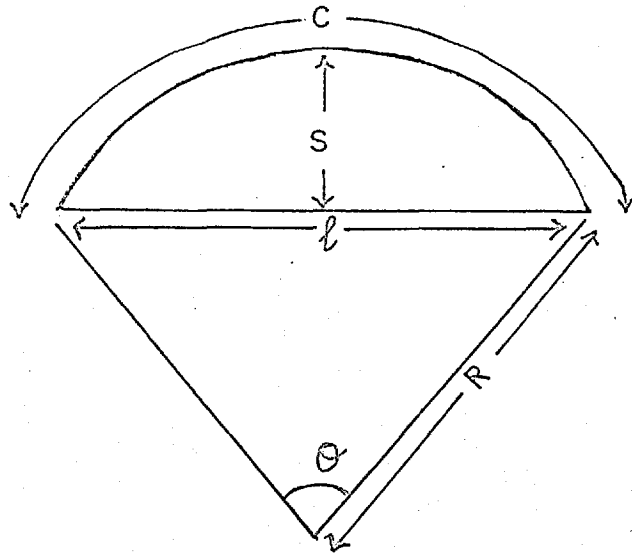
$$\theta = \frac{1}{R} \sim \frac{c}{R} \sim \frac{8s}{c}$$

where θ is the angle turned through, l is the length of the track, R is the radius of curvature, c is the length of the chord and s is the sagitta, see figure 4.1. To do a circle fit $\frac{8s}{c}$ and c must be greater than some specified values. For tracks which are straight to the accuracy of the points a straight line fit is made.

The beam track is then identified by comparing the first approximation values of the angles and momentum of these fitted tracks with the known beam track direction and momentum. Checks are also made to see that the identified track has also the charge and coordinates at the entrance of the chamber appropriate to a beam track.

The method of reconstructing tracks by corresponding points method has got several disadvantages. In the first place there is no entirely satisfactory way of doing the interpolations in finding the corresponding points. Moreover, as the fits are made to space points, the errors on the coordinates of these points must be known to be able to calculate the errors on the fitted quantities. The space points are, however, related in a very complicated way to the measurements, thus the errors on space points are difficult to calculate and are also correlated. Finally the measurements from the three views cannot be treated symmetrically.

CRITERION FOR SELECTING BETWEEN
CIRCLE AND PARABOLA FIT



$$\theta = \frac{l}{R} \sim \frac{C}{R} \sim \frac{8S}{C}$$

FIGURE 4.1

The method of fitting a helix overcomes these difficulties. In this method the parameters of the helix which lies closest to the rays corresponding to the image points on the three views are found by iteration.

For each of the three views of the track we have a set of rays defined by coordinates (X, Y, U, V) where X, Y are coordinates on the front class of the chamber and U, V are direction ratios for the ray. The best fit helix to these rays is then found out by projecting both the rays and the helix back onto a nominal film plane and then minimising $\sum d_i^2$ where d_i is the perpendicular distance from the point where the i^{th} ray cuts the film plane to the projected image of the helix. The helix fit uses the values of the helix parameters found from the first (corresponding points) fit as starting values for the iteration. Three fits are made for each track assuming the masses of K, π and proton for the track.

From the parameters of the fitted helix the momentum P is found out from the expression

$$P = \frac{0.3 HR}{\cos \lambda} \times 10^{-3} \text{ GeV/c}$$

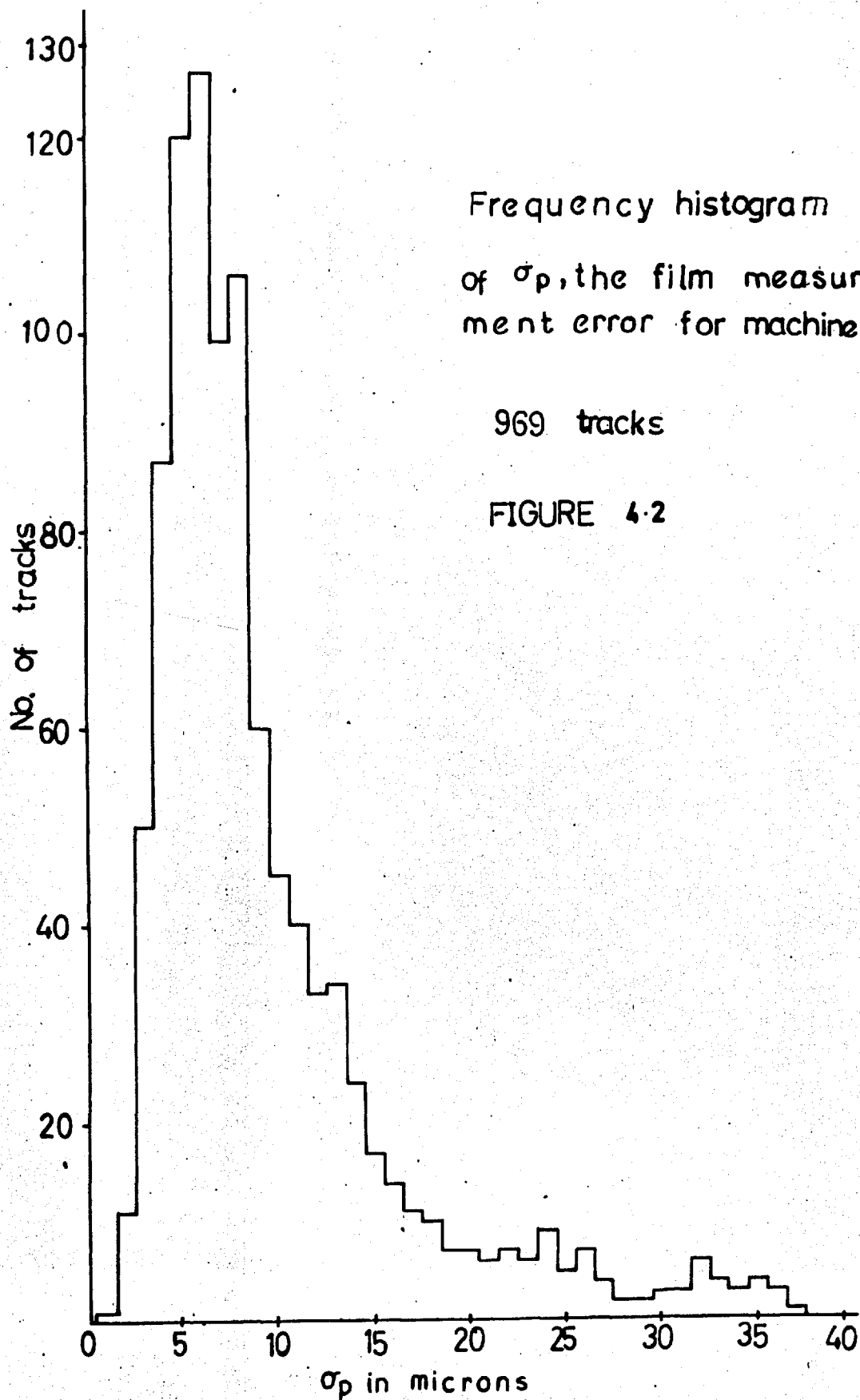
where H is the z -component of the magnetic field in Kilogauss, R is the radius of curvature of the helix and λ is the dip angle.

The corresponding azimuth ϕ will be

$$\phi = \theta_R \pm \frac{\pi}{2}$$

where θ_R is the angle that the measurements have been rotated through and the sign is taken according to the sense in which the particle is moving round the helix. The ϕ and $1/p$ of the track are altered so that they apply to the centre of the track. The errors on these three parameters are also calculated. The errors for each fitted track for the mass of K, π and proton are also found. Figure 4.2 is a histogram of the film measurement errors for 969 tracks. The Geometry Program also calculates the multiple Coulomb scattering errors and adds these to the measurement errors. The program has also provisions for dealing with stopping tracks and elastic scatters.

The failure at the geometrical reconstruction stage was about 10%. The events which are successful at this stage are passed on for further processing through the Hypothesis Testing and Kinematic Fitting program (discussed in the next section). The events which fail at this stage due to various faults are sent back for measurements (see the flow diagram of the 3.5 GeV/c K^+P experiment, figure 2.1).



Section 4.2: Hypothesis Testing and Kinematical Fitting

Program : (23)

The object of this program is to assign different masses to each reconstructed track and to try to vary the parameters of the event in order to obtain energy and momentum conservation at each vertex. The purpose of the fitting is to get the best estimate of the true values of the three parameters (p, λ, ϕ) for each track because due to the measurement errors the parameters will not satisfy energy-momentum conservation at a vertex.

The kinematical fitting program uses the values of $\tan \lambda, \phi$ and $1/p$ at the centre of the track obtained from the Geometrical Reconstruction Program as the starting values. Centre of track quantities are used because it is assumed that here the errors will be normally distributed (though $\tan \lambda$ is not normally distributed near $\lambda = \pm \pi/2$ but such cases are rare).

The goodness of the fit of the event to a particular hypothesis is done by the usual χ^2 test where χ^2 is defined as

$$\chi^2 = \sum_{i,j} (x_i - x_i^m) G_{ij}^x (x_j - x_j^m) + 2 \sum_{\lambda} a_{\lambda} f_{\lambda}(x)$$

where a_{λ} 's are Lagrangian multipliers and

$$\left(G_{ij}^x\right)^{-1} = \delta x_i^m \delta x_j^m$$

is the error matrix associated with the kinematical variables $\underline{x}^m$ which are subject to the L constraint equations

$$f_{\lambda}(x) = 0, \quad \lambda = 1, L$$

The histograms of the χ^2 for the four constraint case for the fitted Σ^- events is shown in figure 4.3. The solid curve represents the theoretical distribution normalised to the total number of events in the histograms. There is quite good agreement between the experimental distribution and the theoretical prediction. The figure also shows the probability distribution for Σ^- events. The probability of having a value of $\chi^2 \geq \chi_o^2$ is given by

$$P_n(\chi^2 \geq \chi_o^2) = \int_{\chi_o^2}^{\infty} \frac{1}{2^{n/2} \Gamma(\frac{n}{2})} (\chi^2)^{\frac{n-2}{2}} e^{-\frac{\chi^2}{2}} d\chi^2$$

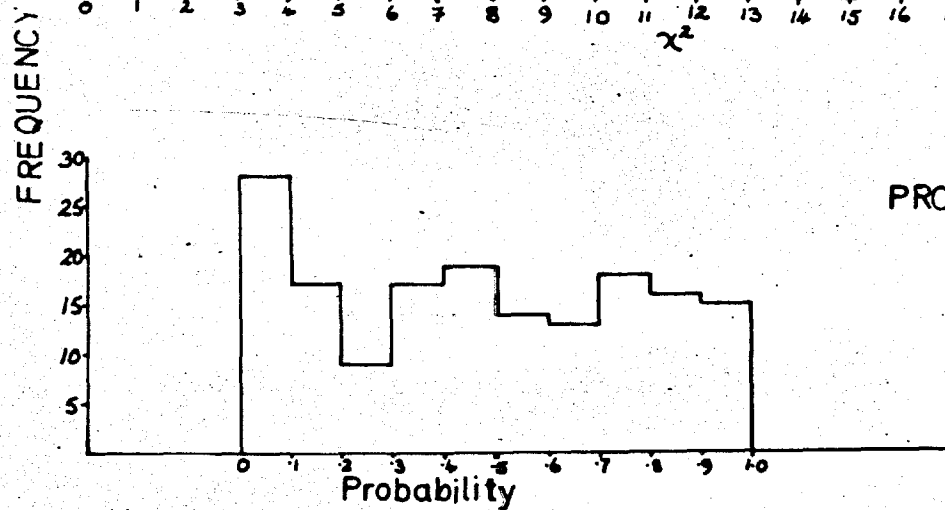
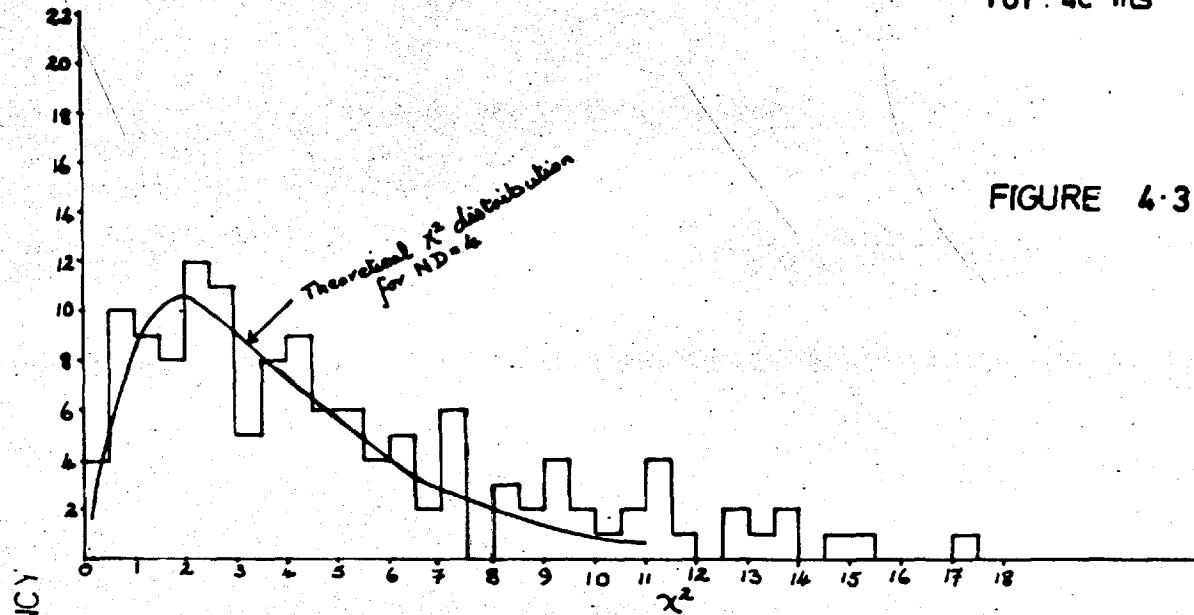
where n is the number of degrees of freedom. This distribution is normalised so that

$$\int_0^{\infty} P_n(\chi^2) d\chi^2 = 1$$

The distribution shown in figure 4.3 is flat as it should be when the χ^2 distribution is proper.

χ^2 DISTRIBUTION for 4c fits

FIGURE 4.3



PROBABILITY DISTRIBUTION

The program also calculates the normalised stretch functions defined as

$$S_i = \frac{x_i - x_i^m}{\sqrt{\langle \delta(x_i - x_i^m) \delta(x_i - x_i^m) \rangle^{\frac{1}{2}}}}$$

for the three parameters of a track namely p , λ and ϕ . This quantity would be distributed normally about 0 with standard deviation of 1 if there are no systematic errors in x_i^m and the measurement errors are correctly estimated. The stretch functions for p , λ and ϕ of the nondecaying secondary tracks of the four-pronged Σ events are plotted in figure 4.4. The solid curves represent the normal distributions with mean of 0 and standard deviation of 1.

The kinematics program outputs the fitted values of p , λ and ϕ with their errors and also the missing mass, missing energy and the three components of the missing momentum at a vertex. The missing mass is defined by

$$(\text{Missing Mass})^2 = (E_I - \sum_{i=1}^n E_i)^2 - (\vec{P}_I - \sum_{i=1}^n \vec{P}_i)^2$$

where E_I and $\vec{P}_I$ are respectively the energy and vector momentum of the initial state and E_i and $\vec{P}_i$ are the corresponding quantities for the i^{th} final state particle and n is the total number of the observed final state particles.

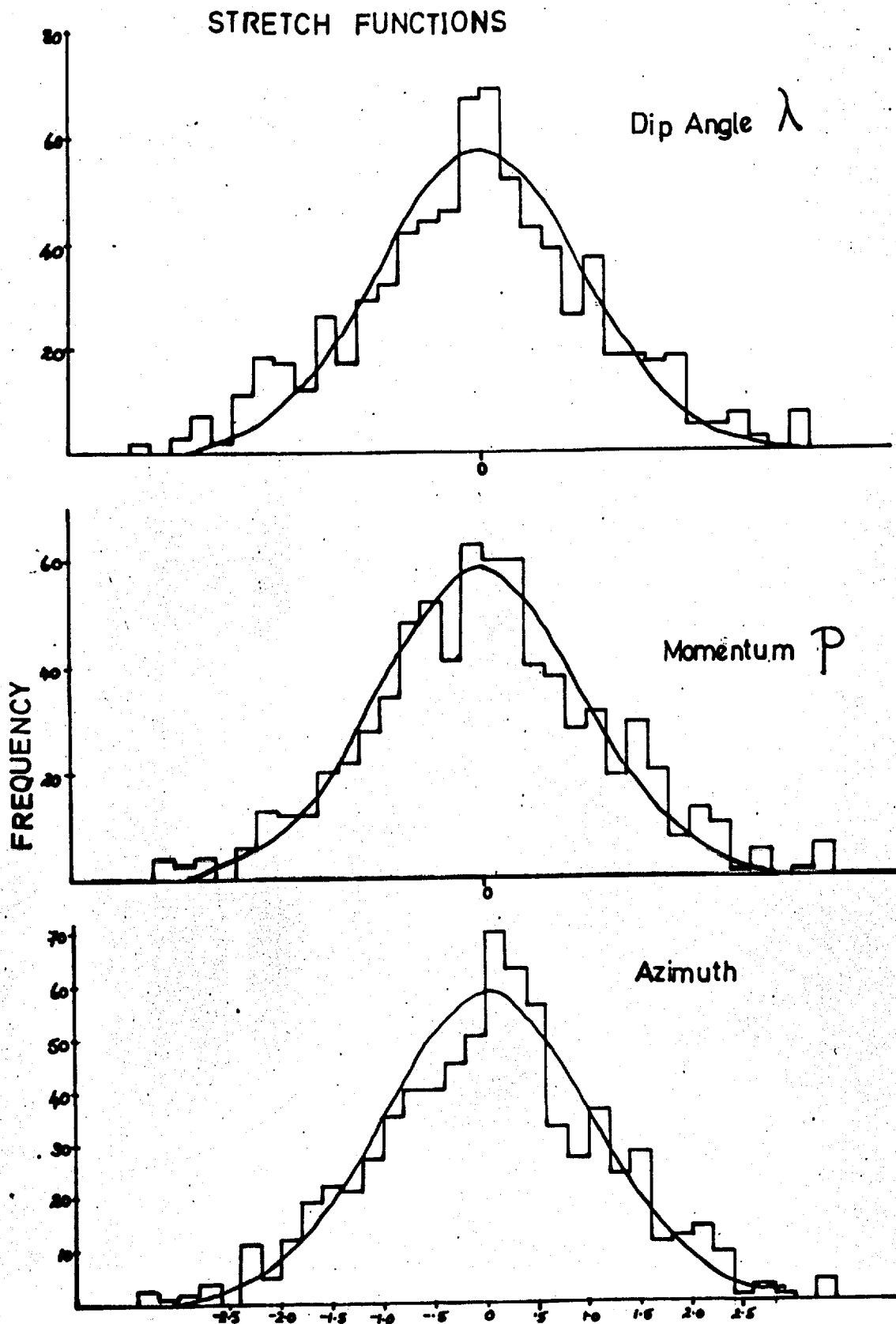


FIGURE 4.4

The missing quantities are calculated from the measured values of the variables.

In the post kinematics part of the program the quantities calculated are

(a) E ffective masses of different particle combinations with their errors. The effective mass of n particles is defined as

$$M_{\text{eff}}^2 = \left(\sum_{i=1}^n (E_i)^2 - \left(\sum_{i=1}^n \vec{P}_i \right)^2 \right)$$

where E_i is the energy and $\vec{P}_i$ is the 3-momentum vector of the i^{th} particle.

(b) The centre of mass quantities in the initial K^-P system.

(c) Various angles used to analyse the production mechanism of resonances.

Section 4.3: Statistics Program: (24)

The object of this program is to make histograms of the quantities such as momentum transfers, centre of mass momentum distributions, effective masses, etc. which a physicist requires to analyse his data. There is also provision in the program to do 2-dimensional plots like Dalitz plots, Triangular plots or plots of momentum transfer against effective mass. The program calculates, for each event, a weight W . This weight is used to correct each

observed event for the detection efficiency of that event. Usually the weight W is defined as the inverse of the probability P that the particle will decay beyond a minimum length cut-off and before escaping from the fiducial volume and is given by

$$\frac{1}{W} = P = e^{-T_o/\tau_o} - e^{-T_p/\tau_o}$$

where T_o is the proper time to the minimum length (L_o) cut-off, T_p is the proper time to escape the fiducial volume (equivalent to a potential length L), and τ_o is the life time of the particle. The times T_i are calculated from L_i and the momentum p of the particle. It is given by the expression

$$T_i = mL_i/pc$$

where m is the mass of the particle and c is the velocity of light.

In the statistics program the angular loss of events in the weight calculation is also accounted for. The program uses some empirical formulas to calculate the weights for different momentum range.

For Σ^+ events, the weight is given by

$$\begin{aligned}\frac{1}{W} &= 0.81e^{-0.094/p} \quad \text{for } 0 \leq p \leq 0.8 \text{ GeV/c} \\ &= 0.893 - 0.169p + \frac{0.15}{p} - \frac{0.145}{p^2} \\ &\quad \text{for } 0.8 \leq p \leq 3.4 \text{ GeV/c} \\ &= 0.52 - 0.05p \quad \text{for } 3.4 < p\end{aligned}$$

For Σ^- events, the weight is given by

$$\begin{aligned}\frac{1}{W} &= 0.94e^{-0.058/p} \quad \text{for } 0 \leq p \leq 0.8 \text{ GeV/c} \\ &= 0.976 - 0.110p + \frac{0.075}{p} - \frac{0.072}{p^2} \\ &\quad \text{for } 0.8 \leq p\end{aligned}$$

To get the total number of events, the number of events is multiplied by the weight.

For the determination of the mass, width and percentage contribution of one or more resonances in any effective mass distribution it becomes necessary to fit this distribution by a Breit-Wigner shape plus a non-resonant background. This is done as follows:

The relativistic Breit-Wigner resonance form for a two body resonance can be written as

$$R(W) = \frac{\Gamma}{\left[\left(\omega_o^2 - \omega^2 \right)^2 + \Gamma^2 \omega_o^2 \right]}$$

where

$$\Gamma = \Gamma_o (P/P_o)^{2l+1}$$

$$\omega_o = \text{resonant mass}$$

$$\Gamma_o = \text{width of the resonance}$$

$$\omega = \text{effective mass}$$

$$P_o = \text{momentum of the decay}$$

product in the rest frame of the two bodies when they have effective mass ω_o

P = momentum of the decay product in the rest frame of the two bodies when they have effective mass ω .

l = relative angular momentum of the particles involved in the decay.

The contribution of i resonances plus a background B in any distribution can be written as

$$\sum_i \left[n_i R_i B / \int BR_i \right]$$

+

$$\left(1 - \sum_i n_i \right) \left(B / \int B \right)$$

where n_i is the fractional contribution of the resonance i . A maximum-likelihood fit to this distribution gives the best values for the three parameters for a resonance namely its mass, width and percentage contribution.

CHAPTER 5

ΣH_3 AND EIGHTFOLD WAY

Section 5.1 Object of this experiment:

If we look back at the status of the elementary particles and resonances in the fall of 1962 we would find that the figure 1.1b of the $3/2^+$ baryons looked like a truncated triangle, the singlet member with $Y = -2$ (omega minus, denoted as Ω^-) was missing. The predicted mass was ~ 1685 Mev. To that date no experiment with incident K^- particles had been done in a hydrogen bubble chamber above the Ω^-

production threshold ($\sim 2,68$ Gev in the centre of mass). Consequently it was decided to build a beam of 3.5 Gev/c K^- at CERN, Geneva. This energy would correspond to a centre of mass energy of $2,77$ Gev which is just above the threshold for Ω^- production. This experiment would also enable physicists to look for resonances found in experiments at lower energies and search for more massive resonances.

Section 5.2: Eightfold way:

In the following few pages SU_3 and the 'Eightfold' way or the octet model (of which Ω^- prediction was one of the direct consequences) will be discussed.

SU_3 appears mathematically as the generalisation of the charge conservation or the Isotopic spin conservation concept. Charge conservation is a one parameter unitary group and corresponds to the gauge transformation $e^{i\alpha}$ whereas isotopic spin conservation is a three parameter unitary group and corresponds to rotations in a three dimensional space which can be written as

$$e^{i[\sigma_e \theta_{e/2}]} \begin{pmatrix} p \\ n \end{pmatrix}$$

where σ_e are the Pauli matrices, θ_e is the rotation and $\begin{pmatrix} p \\ n \end{pmatrix}$ is the iso-spin doublet.

The above equation in the matrix form turns out to be

$$\begin{pmatrix} \alpha & \beta \\ -\beta^* & \alpha^* \end{pmatrix}$$

with $|\alpha|^2 + |\beta|^2 = 1$

The group of unitary unimodular 2×2 matrices is denoted by SU_2 . Non-strange objects like pions can be built up very easily in SU_2 .

The difficulty arises when we try to construct strange particles from these two non-strange objects namely, the proton and the neutron. As a result we have to invoke another field with strangeness. Instead of having 2×2 matrices we have this time 3×3 traceless matrices.

The historical origin of this symmetry was in the Sakata model⁽⁹⁾ in which there existed three basic fields.

$$\psi_i \quad (i = 1, 2, 3)$$

with the same quantum numbers as P , n and Λ . From these three fields and their Hermitean conjugates, it is possible in principle, to build up states with any desired set of quantum numbers B , Q and Y . According to this model of SU_3 Σ and Ξ belong to different representations from P , n , Λ . But the fact that $\Sigma\Lambda$ parity is even goes against this model. This model also predicts spin $3/2$ for Ξ^- but experiments

done so far suggest strongly that the spin is $\frac{1}{2}$. Another argument against the Sakata model is the observation of the process⁽²⁵⁾

$$\vec{p} + p \rightarrow k_1^0 + k_2^0$$

which is forbidden according to this model. The Sakata model does not allow any baryon family to belong to the representation [8]. Hence, we turn to Gell-Mann and Ne'eman's octet model.⁽¹²⁻¹⁵⁾

Starting from two mathematical multiplets, one with $B = 0$ and the other with $B = 1$ one can construct a baryon octet containing Σ , Λ , P and Ξ . The observed mesons with spin parity 0^- and 1^- can also be put into two octets.

This model makes the following predictions:

- (1) All members of a unitary multiplet should have the same spin and parity.
- (2) They must have the same mass if SU_3 is exact.

Experimentally this is not the case.

Okubo⁽¹⁷⁾ has obtained the general expression for the multiplet masses $m(I, Y)$

$$m(I, Y) = m_0 \left\{ 1 + a Y + b \left[I(I+1) - \frac{1}{4} Y^2 \right] \right\}$$

For the meson families a value of $a = 0$ is required by charge conjugation invariance. For a meson octet replacing m by m^2 we get

$$m_{\frac{1}{2}}^2 = \frac{3 m_0^2 + m_1^2}{4}$$

since the two $I = \frac{1}{2}$ multiplets have the same mass $m_{\frac{1}{2}}$, being particle and anti-particle. Experimentally for the 0^- meson octet the left-hand side gives $(496 \text{ mev})^2$ while the right-hand side is equal to $(480 \text{ mev})^2$.

The mass relation is not so good for the 1^- octet mesons. The mass formula with the observed ρ and K^* mass predicts the $I = 0$ member of the octet at 920 Mev (rather than at 780 Mev for the mass of ω or at 1020 Mev for the mass of ϕ). Some mixing of the ω and ϕ might explain this discrepancy. (46-47)

For the baryon octet the Gell-Mann mass formula is given by

$$\frac{m_N + m_{\Xi}}{2} = \frac{3m_{\Lambda} + m_{\Sigma}}{4}$$

Experimentally for the left-hand side we have 1128 Mev and for the right-hand side 1134 Mev.

For the baryon decuplet the Okubo mass formula reduces to

$$m = m_0 (1 + a' Y).$$

This "equal spacing rule" was in excellent agreement with the experimental values of the masses of the different multiplets in the $3/2^+$ decuplet namely

$$N_{3/2}^* \quad 1238 \text{ Mev}$$

$$Y_1^* \quad 1385 \text{ Mev}$$

$$\Xi_{1/2}^* \quad 1530 \text{ Mev}$$

The only snag was that the singlet member Ω^- was missing till recently. The predicted Ω^- mass according to the "equal spacing rule" is ~ 1685 Mev. As this is lower than $K\Xi$ threshold it should be stable against decay via strong interactions. It can be produced in the following reactions:

$$K^- P \rightarrow \Omega^- + K^0 + K^+$$

$$P\bar{P} \rightarrow \Omega^- + \bar{\Omega}$$

and it should decay into

$$\Omega^- \rightarrow \Xi^- + \pi^0$$

$$\rightarrow \Xi^0 + \pi^-$$

$$\rightarrow K^- + \Lambda$$

via weak interactions.

Recently in the 5 Gev/c and 4.2 Gev/c K^-P experiments at Brookhaven (26,48,49) examples of the Ω^- production were seen. As a result our confidence in SU_3 has increased considerably.

CHAPTER 6

BIASES AND LOSSES: BEAM STATISTICS

Scanning bias can arise from the fact that charged decays, specially $\Sigma^\pm$'s might have been lost due to short decay lengths or small decay angles. A check for the possible bias in the detection of the charged decay of Σ^- and Ξ^- can be done as follows.

The probability of decay in a length L for a particle is given by

$$P = e^{-Lm/pc \tau}$$

where p is the fitted momentum of the parent particle, m is its mass, τ its life time and c is the velocity of light.

A histogram of L/p against $\log_e P$ should therefore give a distribution which can be fitted by a straight line of slope $m/c\tau$. Figure 6.1 gives these distributions for the Σ^- and the Ξ^- events. The theoretical distribution lines are also drawn for comparison. For Σ^- events the agreement is not as good as in the Ξ^- case. In the Σ^- case there is some loss expected in the scanning for low L/p values.

The three body decay mode of a neutral vee was also not tried in the kinematical fitting. For this reason

L/p vs. $\log_e P$ Plots

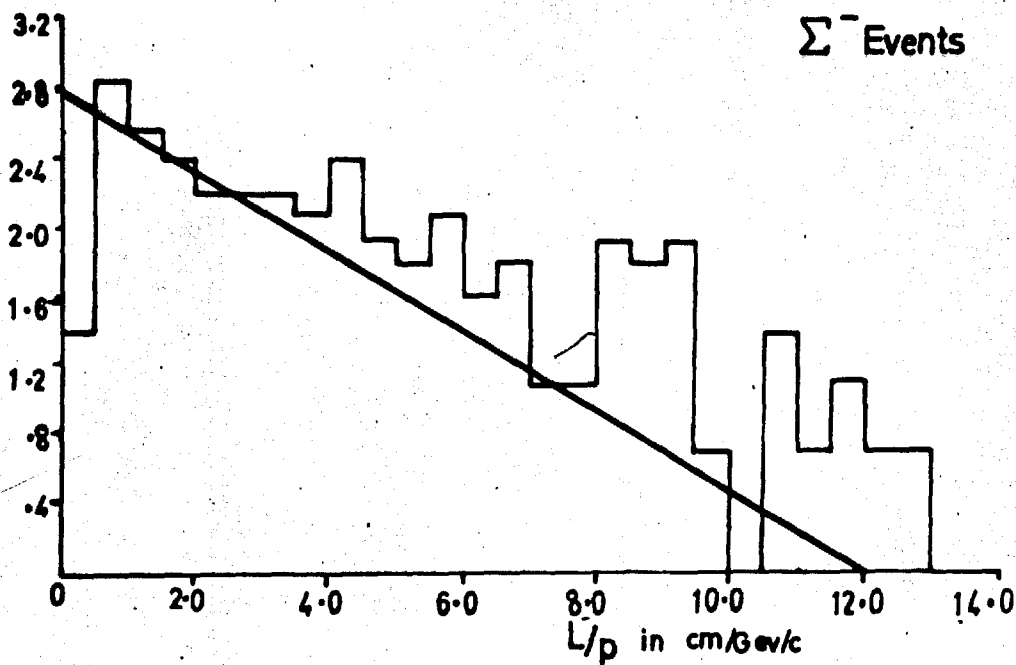
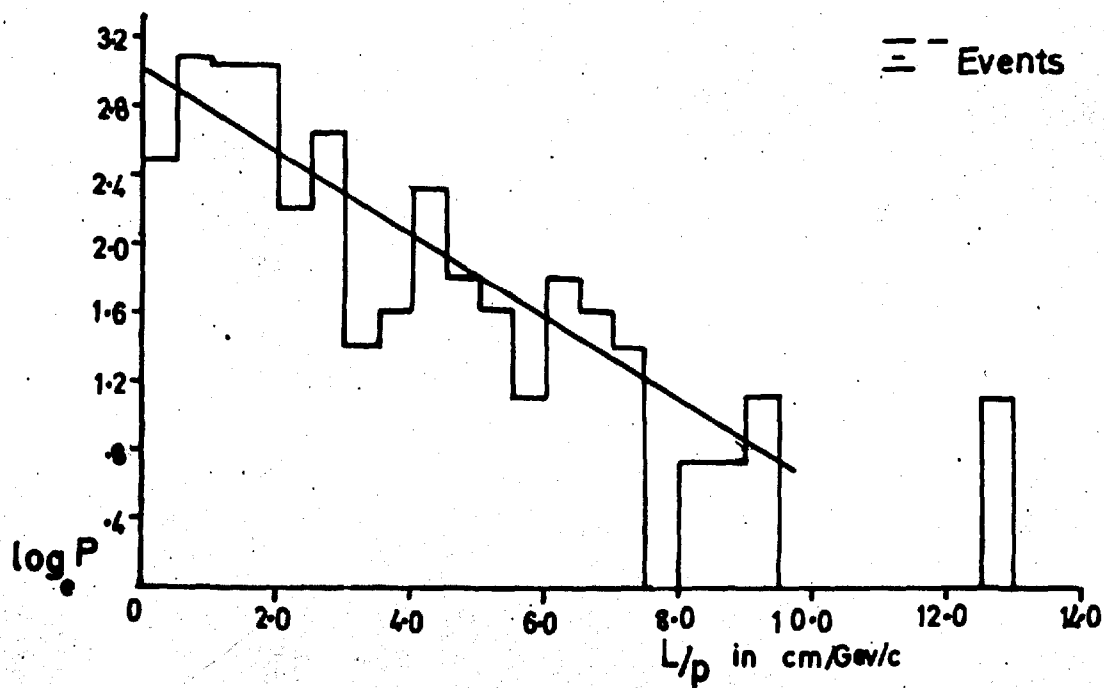


FIGURE 6.1

events with these V^0 's did not fit. The loss on this account is negligible. Corrections to the cross-section were also made for the neutral decay modes of the K^0 and the Λ^0 . A correction for the fact that some of the particles would not decay in the chamber due to its finite volume was also made. This is important in the case of $K^\pm$ decays which have rather a long life time ($\sim 10^{-8}$ sec).

Forward-Backward angle:

The angular distribution of the Λ^0 from the Ξ^- decay with respect to a direction contained in the production plane should exhibit no asymmetry. The distribution of the angle

$$\cos \theta_{\Lambda}^* = \frac{(\hat{\Lambda} \cdot \hat{\Xi})}{|\hat{\Lambda}| |\hat{\Xi}|}$$

should be flat.

Here, $\hat{\Lambda}$ is the direction of the Λ in the rest frame of the parent Ξ^-

and $\hat{\Xi}$ is the direction of the Ξ^- as seen in the overall centre of mass system.

Figure 6.2a shows the distribution of this angle. It looks quite flat as is expected. Figure 6.2b shows the equivalent distribution for the Σ^- events. This is also consistent with a flat distribution.

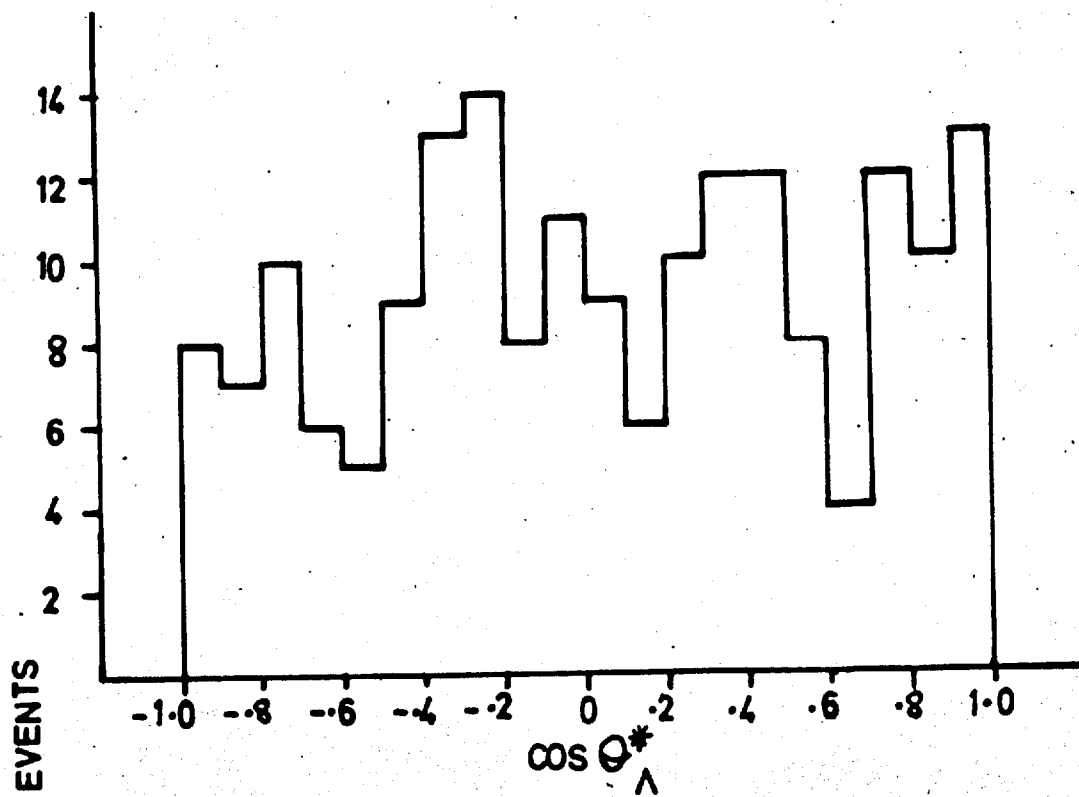


Fig 6.2 a

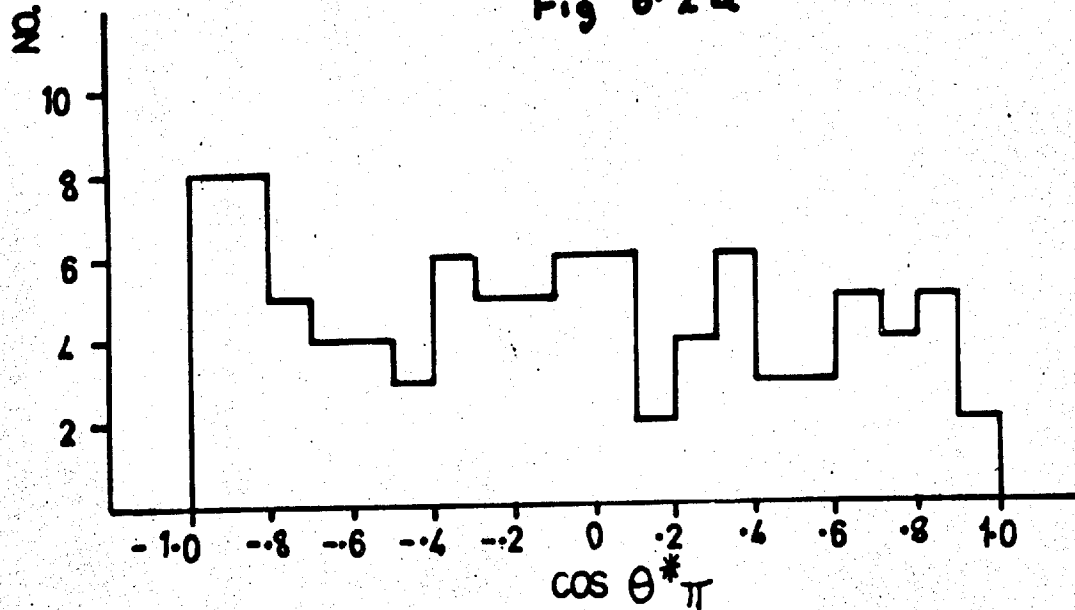


FIGURE 6.2 b

$\frac{\Delta P}{P}$ vs. L plots:

The accuracy with which a momentum can be determined by measuring track curvature in a magnetic field is limited by multiple Coulomb scattering of the charged particle. The relative error in the measurement of the momentum of a track due to Coulomb scattering can be expressed as follows (27)

$$\frac{\Delta P}{P} = \frac{E_s}{e\beta H} \sqrt{\frac{2\rho}{3L X_0}}$$

where

$$E_s = \left(\frac{4\pi}{\alpha} \right)^{\frac{1}{2}} m_e c^2$$

X_0 = Radiation length

ρ = density

L = Length of the track

β = $\frac{\text{velocity of the particle}}{\text{velocity of light}}$

and H = magnetic field.

One notices that this relative error decreases with increasing momentum and becomes independent of P when β is close to 1. Figure 6.3 shows the plots of $\frac{\Delta P}{P}$ against the length L of the tracks for different ranges of momentum. As is expected $\frac{\Delta P}{P}$ clusters around smaller values for higher momentum.

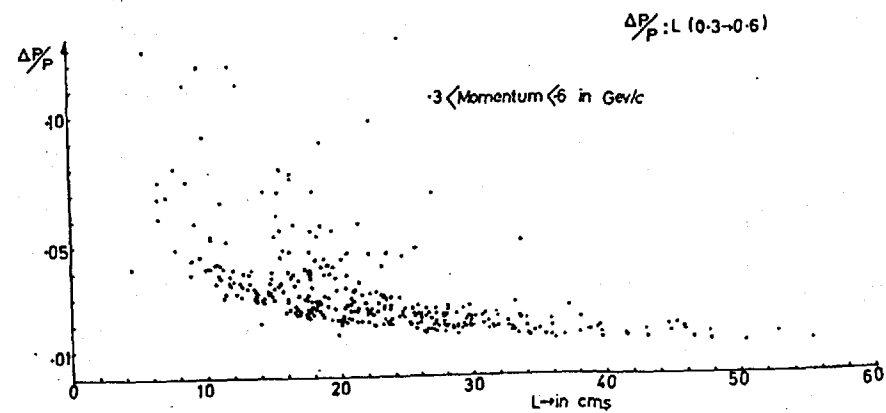
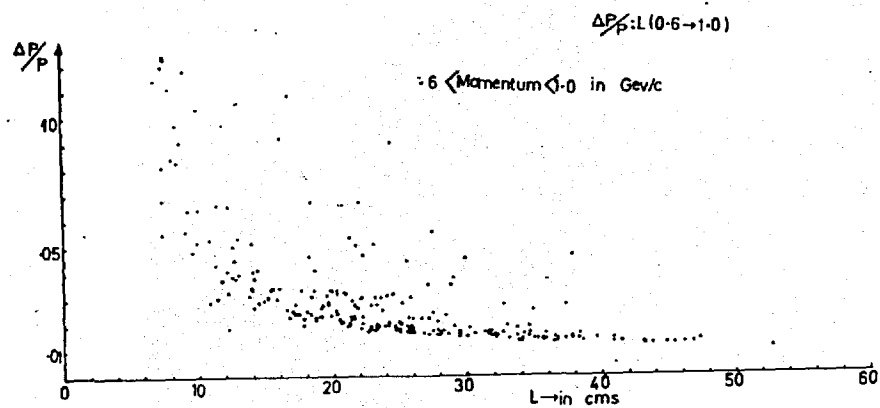
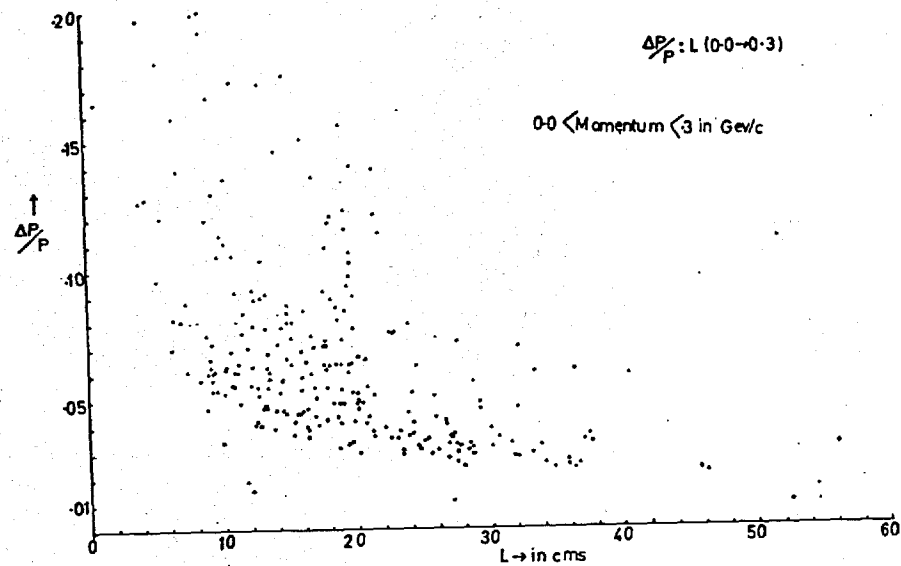


FIGURE 6-3

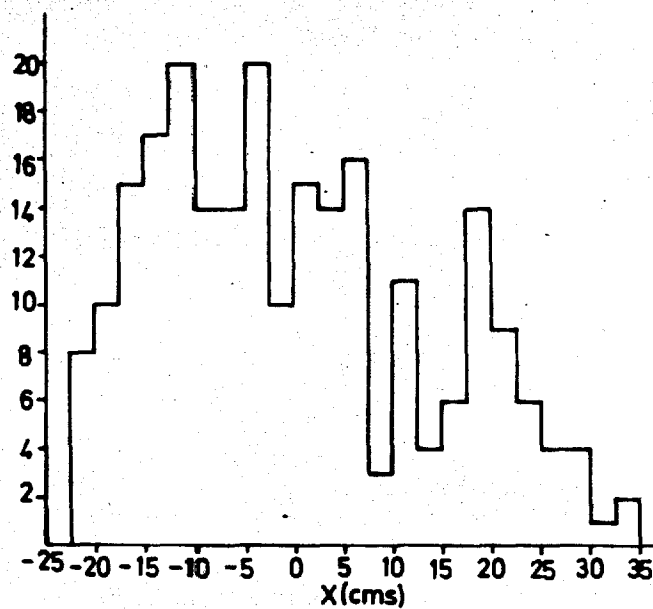
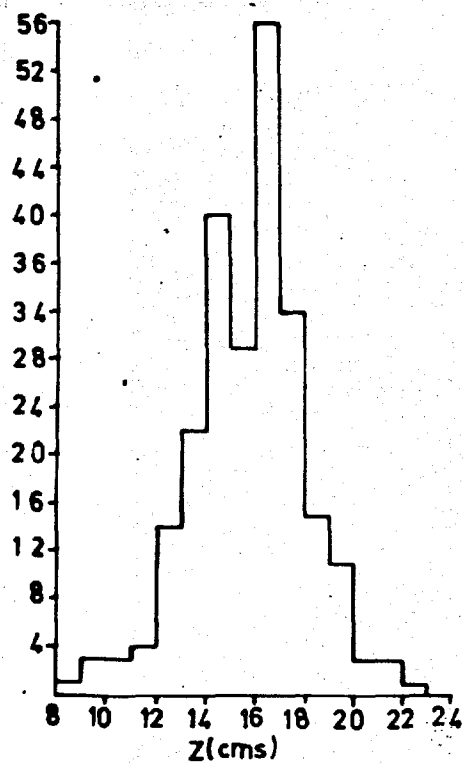
Apex positions:-

Figure 6.4 shows the distributions of the x, y and z coordinates of the production apices of all the Ξ^- events. For the x coordinate we notice a flat distribution which gradually decreases towards the increasing x direction. This is exactly what is expected because cascade produced in this region would escape the illuminated volume of the chamber before decaying. Moreover, the interesting point here is that the events at the down stream end of the chamber are mostly the ones in which the Λ was not seen. This is again explained by the fact that at this region the Λ 's coming from the Ξ^- 's decay outside the chamber.

The y and z coordinates have also got the expected distributions i.e. peaking at the middle of the chamber and then falling off at both sides, this being the known distribution of the beam.

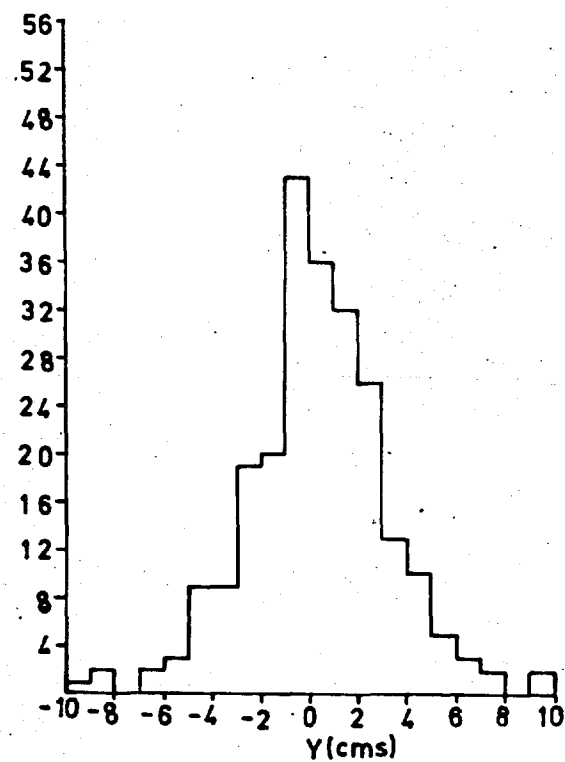
Apex errors:

Figure 6.5 shows the plots of apex reconstruction errors of some 110 arbitrary Ξ^- events. The distribution of Δx peaks at about 100 microns in space. The peaking of the Δy distribution occurs at a slightly lower value, at 85 microns. The Δz distribution gives a peak at 575 microns, about six times the value of the average peaking in either the Δx or Δy distribution. These errors are

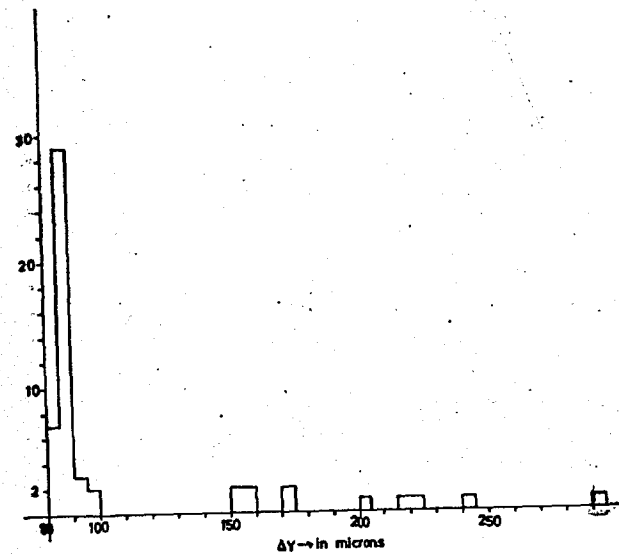
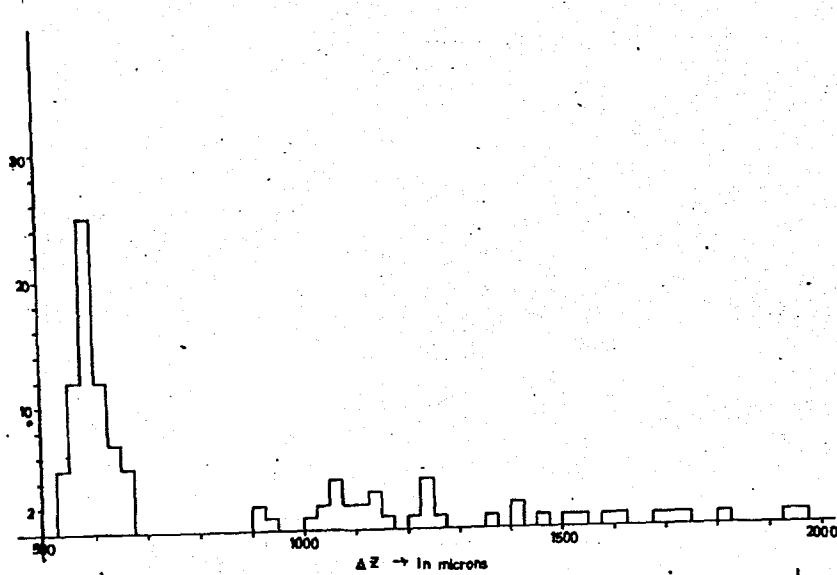


APEX POSITIONS
237 EVENTS

FIGURE 6.4



APEX ERRORS



PROJECTED APEX ERROR ON THE FILM

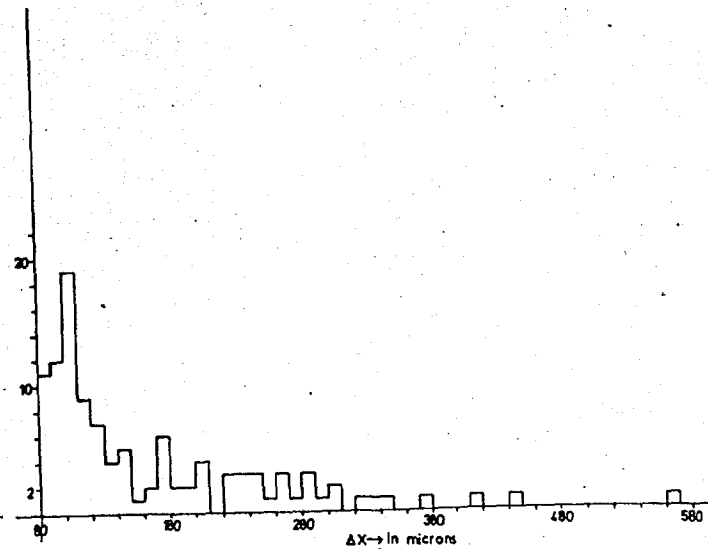
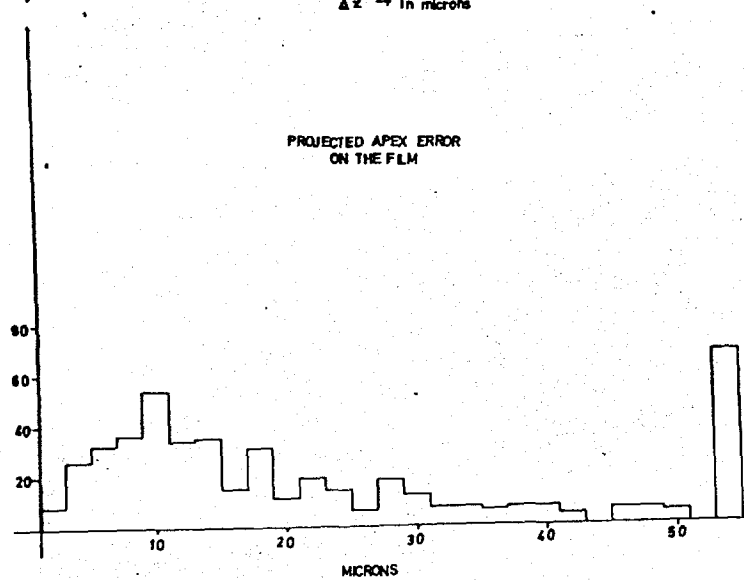


FIGURE 6-5

slightly higher than the errors due to the measuring machines. So, these errors are due to the distortion in the bubble chamber optics and also due to the uncertainties in the actual operating condition of the bubble chamber. Figure 6.5 also shows the distribution of the error of the projected vertices on the film. This peaks at about 20 microns on the film.

Beam statistics:

Figure 6.6 shows the distributions for the momentum, azimuth and dip of the beam for some 350 fitted events. The lower half of the figure also shows the corresponding error distributions. The mean value for the beam momentum is 3.456 Gev/c. The corresponding error distribution of the beam momentum peaks at about 0.015 Gev/c. The mean value of the azimuthal distribution ϕ is 358.69° . This is the corrected value of ϕ at $x = 0$ of the chamber. The dip angle distribution of the beam has a mean of 0.368° . The distribution of the error in the dip angle is much wider than the error distribution of ϕ . This is not very surprising because the dip angle involves measurement in the z direction whereas for the azimuthal angle case it is done on the x - y plane. The statistics on the beam parameters have been obtained from the events of the first run. The beam parameter values for the second run are also compatible with the above mentioned quantities.

EVENTS 305
BEAM TRACKS T13/1

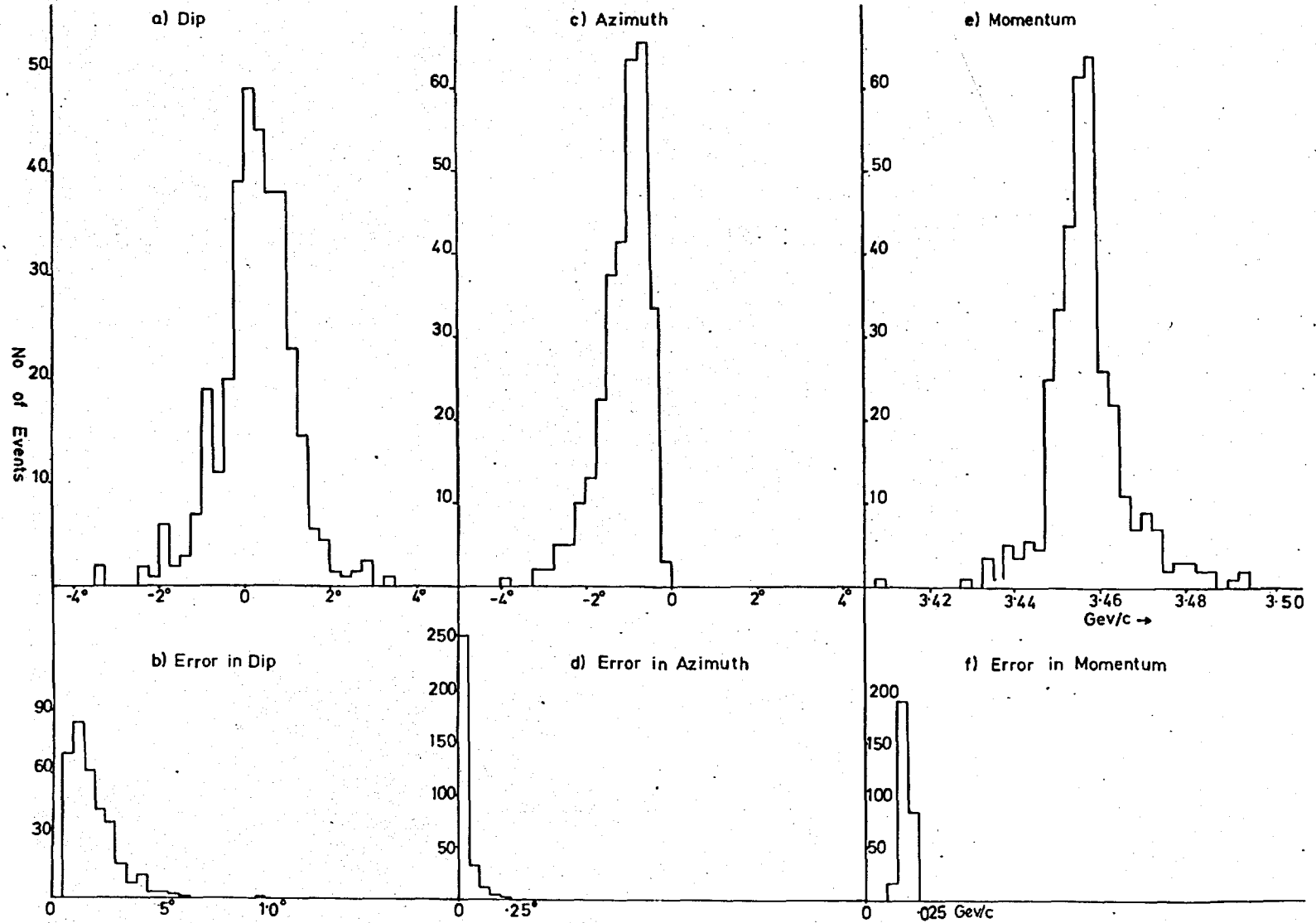


FIG 6.6

CHAPTER 7

RESULTS ON Σ^- CHANNELS, Y_1^* (1385) AND $N_{3/2}^*$ (1238).

Section 7.1: Introduction:

Various aspects of the Σ^- production and the resonance production in the Σ^- channels have been studied at different energies in bubble chamber experiments. (28-35) Σ^- forms the $U = \frac{1}{2}$ doublet with Ξ^- . In this chapter the Σ^- production in K^-P interactions at 3.5 GeV/c will be discussed. Different angular distributions will also be shown. In section 7.4 the production of Y_1^{*-} (1385 MeV) in various Λ channels and also the angular distribution of its production and decay will be discussed. In section 7.5 the production and decay of $N_{3/2}^*$ will be described. In section 8.8 in chapter 8 various checks of the Ne'eman-Gell-Mann octet model regarding cross-sections and comparisons of the angular distributions of the different multiplets in the $U = \frac{1}{2}$ doublet and $U = 3/2$ quartet will be made.

Section 7.2: Analysis of the Σ^- events:

The analysis of the Σ^- events was done together with the events of the other "common" categories. Events were noted down during the scanning only if they occurred inside the fiducial region (the region has already been

defined in section 3.1). The general procedure of scanning, measuring and computing was followed in the analysis of these events. The probability cut-off for rejecting a fit was 5% . In the case of events with more than one fit, if one of the fits is five times more probable than the others, then the higher probability fit is accepted as unique. Each event was checked on the scanning table for consistency of the predicted and observed ionisations.

To find the cross-section we used the following expression,

$$\sigma = \frac{\Lambda n \times 10^{27}}{\rho N L}$$

where σ = cross-section in millibarns

Λ = Atomic number = 1 for hydrogen

n = number of events observed

ρ = density of liquid hydrogen

at the operating temperature and pressure of the bubble chamber. We used a value of 0.0625 gm/cm^3 for ρ .

N = Avogadro's number = 6.0249×10^{23} atoms/gm.atom

L is equal to length of the observed K^- beam track in centimetres. This is calculated from the τ counts in the fiducial region. The length thus calculated also includes a correction factor for the tracks which give interactions in the chamber. The cross-sections for different Σ^- channels are given in Table II. The Σ^+ channel

cross-sections are also given in the same table for the purpose of comparison. These cross-sections are corrected for scanning loss and life time bias (see section 4.3).

Section 7.3: Discussion of the Σ channels:

$\Sigma^\mp \pi^\pm$:

The ratio of the cross-section for Σ production is

$$\frac{\sigma(\Sigma^+)}{\sigma(\Sigma^-)} = 12.7 \pm 3.5$$

At lower energies this dominance of the production of Σ^+ over Σ^- was also noticed. From the angular distribution of $\Sigma^- \pi^+$, see figure 7.1, it is obvious that the production process is non-peripheral in contrast to $\Sigma^+ \pi^-$ which is strongly peaked backwards indicating a possible K^* exchange. The Σ^- production cannot benefit from the K^* exchange and this explains the low value of the Σ^- production cross-section. The somewhat forward peaking of the Σ^- angular distribution suggests nucleon exchange. The forward-backward ratio for $\Sigma^- \pi^+$ states is

$$\frac{f - b}{f + b} = 0.62$$

whereas in the case of the $\Sigma^+ \pi^-$ events

$$\frac{f - b}{f + b} = -0.74$$

TABLE II

Final State	Cross-section(mb)
$\Sigma^- \pi^+$	0.011 ± 0.003
$\Sigma^+ \pi^-$	0.14 ± 0.01
$\Sigma^- \pi^+ \pi^0$	0.183 ± 0.013
$\Sigma^+ \pi^- \pi^0$	0.347 ± 0.02
$\Sigma^- \pi^+ \pi^+ \pi^-$	0.14 ± 0.006
$\Sigma^+ \pi^- \pi^+ \pi^-$	0.162 ± 0.012
$\Sigma^- \pi^+ \pi^+ \pi^- \pi^0$	0.186 ± 0.005
$\Sigma^+ \pi^- \pi^+ \pi^- \pi^0$	0.25 ± 0.012

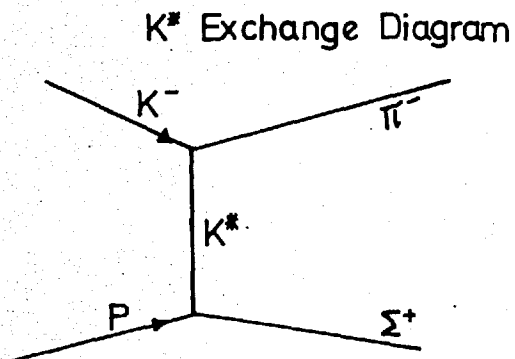
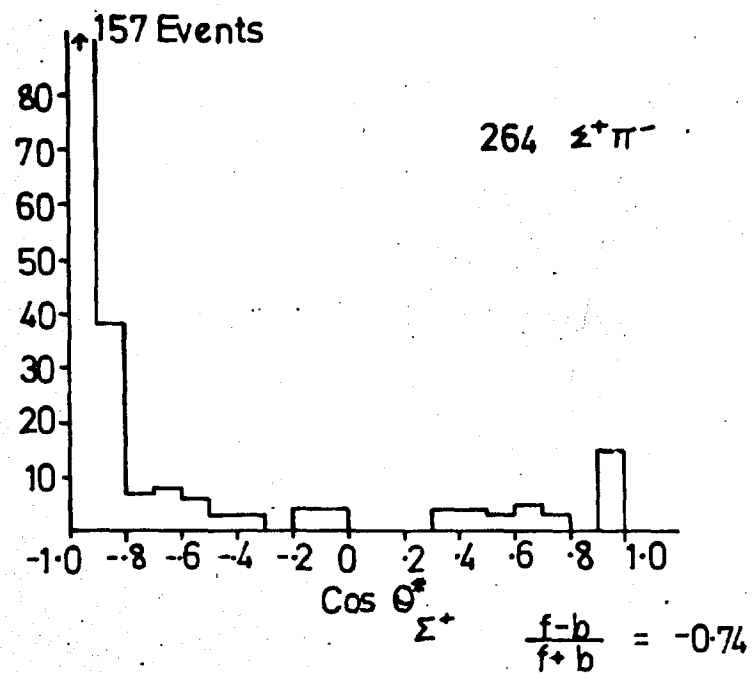
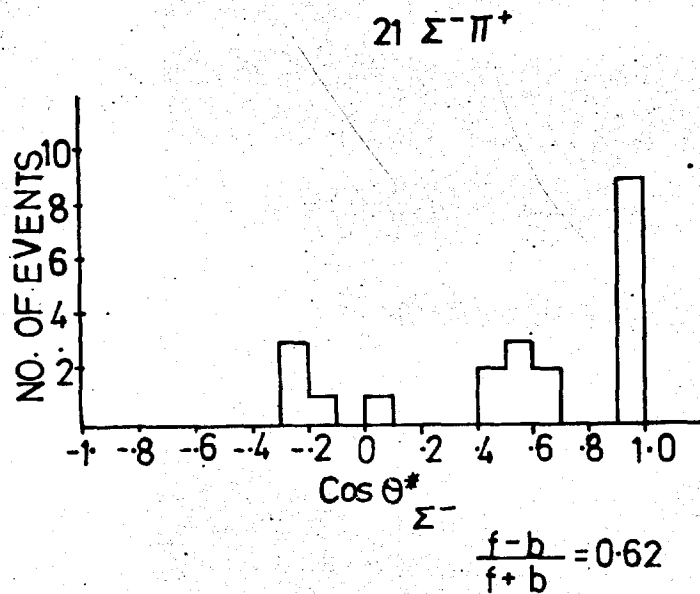


FIG. 7.1

$\Sigma^\mp \pi^\pm \pi^0$:

This channel is somewhat difficult to analyse because of possible contamination from the multi-neutral events. A plot for the missing mass of all the $21^\mp 0$ type Σ events is given in figure 7.2. Here we notice that there is no sharp separation between the events with no particle missing, events with one π^0 missing or events with more than one π^0 missing.

The $\Sigma^\mp \pi^\pm \pi^0$ channel mainly goes via the production of $\Sigma^\mp \rho^\pm$, $Y_0^*(1405)$, $Y_0^*(1520)$, $Y_1^{*0}(1660)$ and $Y_0^*(1815)$. Table III shows the branching ratios of the different resonance production in this channel and also their cross-sections. Figure 7.3 gives the $\Sigma^\mp \pi^\pm$ effective mass distribution. The cross-hatched area corresponds to events containing no $\rho^\pm$. A Breit-Wigner resonance fitting procedure was carried out for this distribution. The results obtained for the four resonances, namely, $Y_0^*(1405)$, $Y_0^*(1520)$, $Y_1^{*0}(1660)$ and $Y_0^*(1815)$ are displayed in Table IV. The masses and widths of these resonances are consistent with the accepted values. In the $\Sigma^\mp \pi^0$ effective mass distribution there is no evidence of any resonance production. This is somewhat surprising because we would expect to see the production of the $Y_1^{*0}(1660)$ in these charged states. This marked absence of both the charged states casts a shadow of doubt over the identification of the

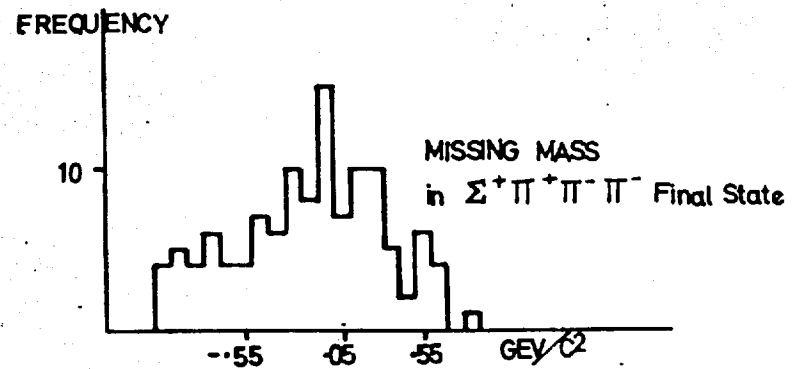
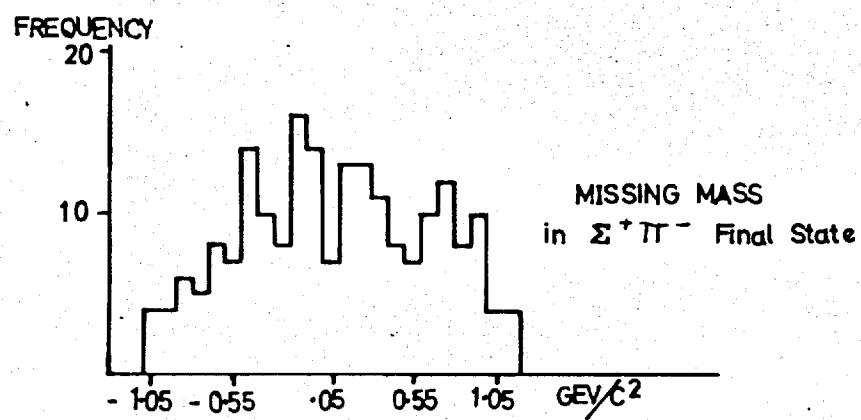
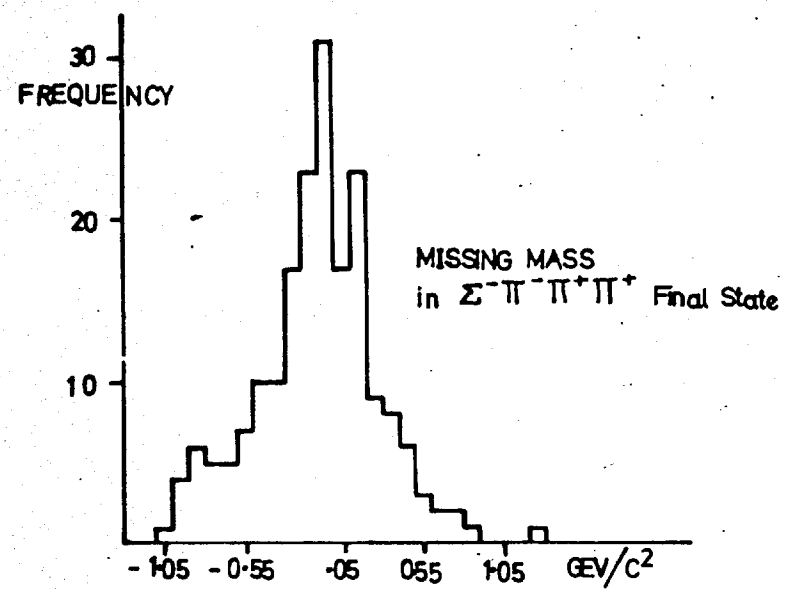
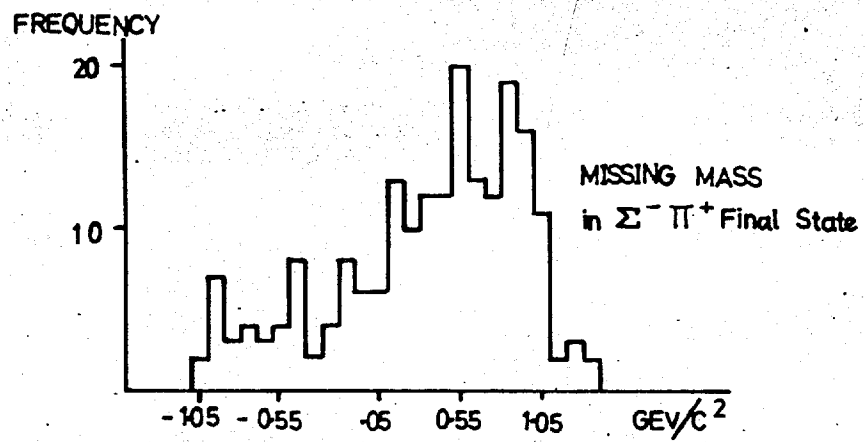


FIGURE 7-2

TABLE III

Final State	Cross-section in m b	Branching ratio %
$\Sigma^- \rho^+$	0.04 ± 0.01	23 ± 6
$\Sigma^+ \rho^-$	0.15 ± 0.02	44 ± 5
$Y_0^* (1405) + \pi^0$	0.06 ± 0.01	11.0 ± 2
$Y_0^* (1520) + \pi^0$	0.03 ± 0.01	5.0 ± 1
$Y_1^{*0} (1660) + \pi^0$	0.04 ± 0.01	8 ± 2
$Y_0^* (1815) + \pi^0$	0.04 ± 0.01	8 ± 2

EFFECTIVE MASS OF $\Sigma^\mp \pi^\pm$ IN $\Sigma^\mp \pi^\pm \pi^0$

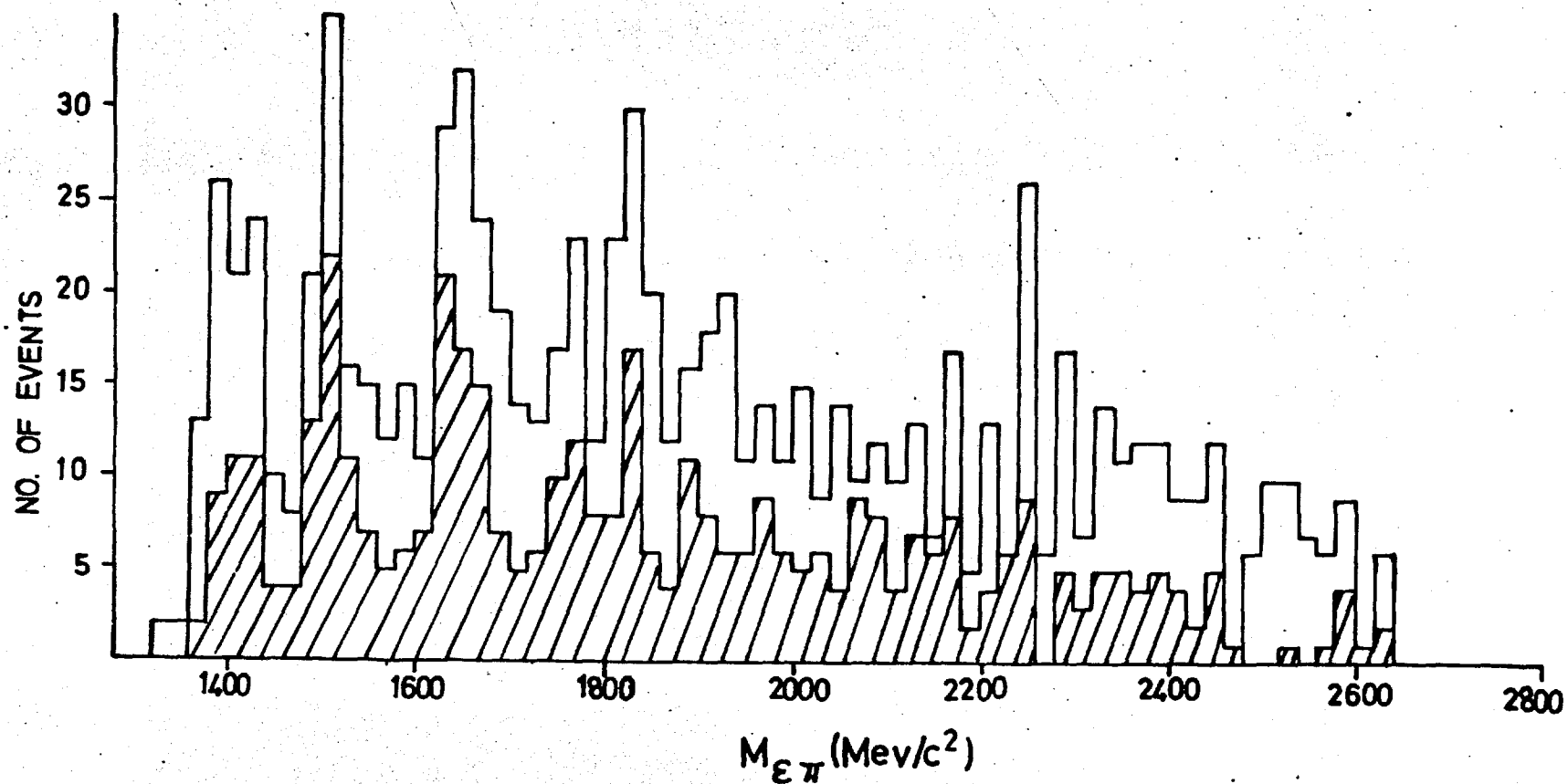


FIGURE 7-3

TABLE IV

Resonance	Mass in Mev	Width in Mev
$Y_0^* (1405)$	1408 ± 6	34 ± 10
$Y_0^* (1520)$	1510 ± 3	21 ± 8
$Y_1^{*0} (1660)$	1640 ± 7	37 ± 10
$Y_0^* (1815)$	1810 ± 20	110 ± 50

TABLE V

Channels	Resonant State	Cross-section in m b	Branching ratio %
$\Sigma^\pm \pi^\mp \pi^+ \pi^-$	$Y_0^* (1520) + \rho^0$	0.05 ± 0.01	9 ± 1
$\Sigma^\pm \pi^\mp \pi^+ \pi^-$	$Y_0^* (1405) + \pi^+ \pi^-$	0.05 ± 0.01	10 ± 2
$\Sigma^- \pi^+ \pi^+ \pi^-$	$Y_1^{*+} (1660) \pi^-$	0.006	4.4. $\rightarrow$
This state is discussed in the thesis in detail			

$Y_1^*(1660)$ in the $\Sigma^\pm \pi^\mp$ mass distribution. This enhancement in the $Y_1^*(1660)$ mass region may be due to an altogether different resonance.

Figure 7.4a and 7.4b show the distributions of the centre of mass production angle of $\Sigma^\mp$ in $\Sigma^\mp \pi^\pm \pi^0$ channels. The cross-hatched area corresponds to events where $\rho^\pm$ is produced. The striking feature of the Σ^- distribution is the backward peaking in contrast to the forward peaking of Σ^- in the $\Sigma^- \pi^+$ channel (see figure 7.1). This can be explained by the fact that the main contribution to the backward peaking of the Σ^- comes from the $Y_0^*(1405)$ which is strongly peripheral in production. In the $\Sigma^+ \rho^-$ distribution there is some evidence of backward production of Σ^+ indicating a K^* exchange. But the $\Sigma^- \rho^+$ events show no such peripheral behaviour. This might be due to the limited production of ρ^+ .

$\Sigma^\mp \pi^\pm \pi^+ \pi^-$:

Figure 7.2 shows the missing mass distribution of all the $41^\mp 0$ type Σ events. Again, as in the 210 events, there is not a very sharp separation between no missing neutral, a π^0 and $n\pi^0$ peaks. Table V gives the branching ratios and cross-sections for different resonance production in this channel. There is some indication of associated production of $Y_0^*(1520)$ and ρ^0 . The production

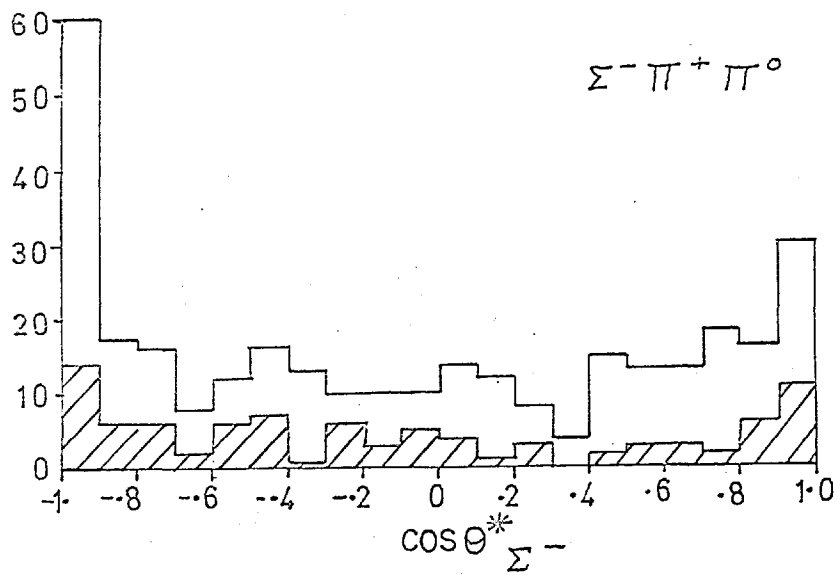


FIG 7.4a

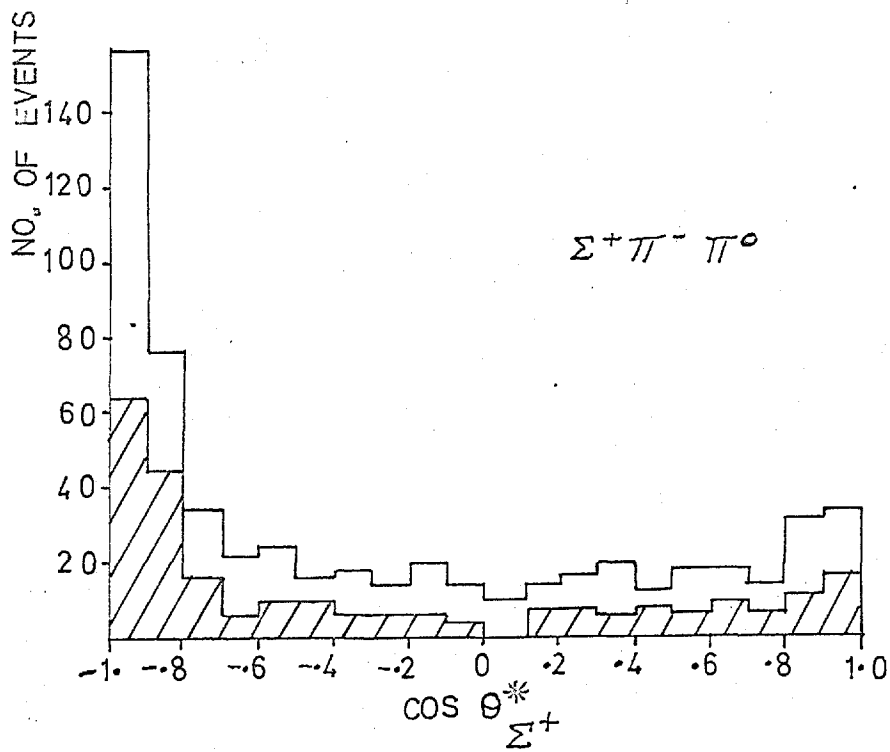


FIG 7.4b

of $Y_1^{*+}(1660)$ is the important aspect of $\Sigma^- \pi^+ \pi^+ \pi^-$ channel. Figure 7.5 shows the effective mass distribution for the $\Sigma^- \pi^+ \pi^+$ system. The shaded area of the figure corresponds to the events when the cosine of the angle of the π^- in the total centre of mass is more than 0.7. A peak is evident in the region of the $Y_1^{*+}(1660)$ which is well separated from the background when events of low momentum transfer are selected. From the maximum likelihood analysis of the decay distribution of the $Y_1^{*+}(1660)$ an attempt was made to find its parity.⁽⁷⁹⁾ For this analysis 29 events with $\cos \theta_{\pi^-}^{c.M.} \geq 0.5$ and $1.610 \leq M(\Sigma^- \pi^+ \pi^+) \leq 1.690$ Gev have been selected.

We define the maximum likelihood function for the i^{th} event with mass E_i for the $\Sigma^- \pi^+ \pi^+$ system assuming spin parity J^P as follows

$$F_i = \alpha f_i + (1 - \alpha) g_i$$

where α is the percentage of $Y_1^{*+}(1660)$ events in the sample

$$\text{and } f_i(J^P) = \left[\frac{B(E_i)}{\int_{E_1}^{E_2} B(E_i) dE} \right]$$

$$\times \left[\frac{\left| M_{JP}(p_i, q_i) \right|^2}{\int_S \left| M_{JP} \right|^2 dS_i} \right]_{E_i}$$

is the density of $Y_1^{*+}(1660)$ events, $B(E_i)$ is a simple Breit-Wigner function fitted to the experimental distribution of $\Sigma^- \pi^+ \pi^+$ mass of 1645 ± 7 Mev and $\Gamma = 55 \pm 10$ Mev ;

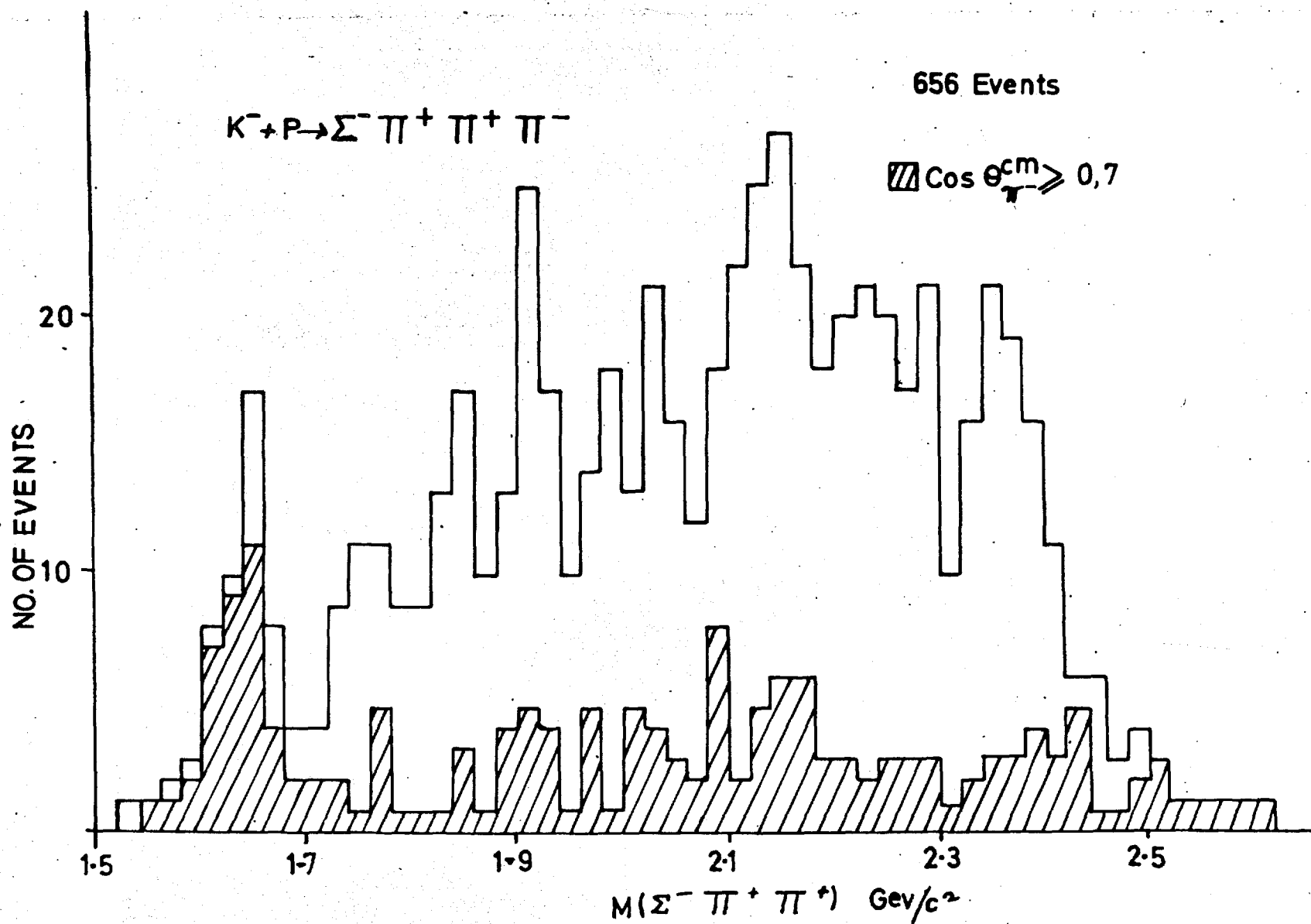


FIGURE 7.5

$|M_{JP}(p_i, q_i)|^2$ is the squared matrix element, taken from Table VI, and evaluated for the i^{th} event; p is the momentum of the Σ^- in the Y_1^* rest frame and q is the pion momentum in the dipion rest frame. S is the area of the Dalitz plot at energy E_i ; g_i represents the background contribution. This analysis favours a positive parity for $Y_1^{*+}(1660)$. A study of the alternative decay mode of $Y_1^*(1660)$ namely

$$Y_1^*(1660) \rightarrow Y_0^*(1405) + \pi^+$$

also favours positive parity. The maximum likelihood function in this case uses the matrix element also given in Table VI. In the expressions for the matrix elements, the G 's are defined as

$$G_j = e^{i\delta_j} \sin \delta_j / K_j$$

where
$$K_j \cot \delta_j = 2K_R \left[M\left(\sum \pi_j\right) - M_R \right] / \Gamma$$

$M\left(\sum \pi_j\right)$ is the invariant mass of the $\left(\sum \pi_j\right)$

combination, M_R and Γ the mass and width of the $Y_0^*(1405)$; K_j the momentum of the Σ^- in the $\left(\sum \pi_j\right)$ rest frame and

K_R its value for $M\left(\sum \pi_j\right) = M_R$. This analysis assumes

spin parity $\frac{1}{2}^-$ for $Y_0^*(1405)$. But in our analysis it was

J^P

TABLE VI

		M^2
	(a) $Y_1^{*+}(1660) \rightarrow \Sigma^- \pi^+ \pi^+$	(b) $Y_1^{*+}(1660) \rightarrow Y_0^*(1405) + \pi^+$
$\frac{1}{2}^+$	1	$ G_1 ^2 + G_2 ^2 + 2\text{Re}(G_1^* G_2)$
$\left. \begin{array}{l} 3/2^+ \\ 5/2^+ \end{array} \right\}$	$p^4 + Aq^4$	$K_2^4 G_1 ^2 + K_1^4 G_2 ^2 + \text{Re}(G_1^* G_2) \times \left[3(\bar{K}_1 \cdot K_2)^2 - K_1^2 K_2^2 \right]$
$\left. \begin{array}{l} \frac{1}{2}^- \\ 3/2^- \end{array} \right\}$	$p^2 + Bp^2 q^4$	$K_2^2 G_1 ^2 + K_1^2 G_2 ^2 + 2\text{Re}(G_1^* G_2) \times \bar{K}_1 \cdot \bar{K}_2$
$5/2^-$	$p^6 + Cp^2 q^4$	$K_2^6 G_1 ^2 + K_1^6 G_2 ^2 + \text{Re}(G_1^* G_2) + \times \left[5(\bar{K}_1 \cdot \bar{K}_2)^3 - 3(\bar{K}_1 \cdot \bar{K}_2) K_1^2 K_2^2 \right]$

A,B,C are unknown parameters depending upon the relative amounts of the relevant amplitudes.

impossible to distinguish between spin $3/2$ and $5/2$ for $Y_1^*(1660)$. A spin of $\frac{1}{2}$ has been ruled out by Bastein and Berge⁽⁵⁰⁾ who also suggest $3/2$ as the most likely value.

This result is in agreement with that of Taher-Zadeh et al⁽⁵¹⁾ but not with the recent work of Berley et al⁽⁵²⁾ who obtain negative parity. Positive parity does not allow assignment of $Y_1^*(1660)$ to the $3/2^-$ octet suggested by Glashow and Rosenfeld⁽⁵³⁾. If the $Y_0^*(1405)$ is a unitary singlet and if $Y_1^*(1660)$ does decay into the $Y_0^*(1405)$ this means that the $Y_1^*(1660)$ must be assigned to an octet.

The production angular distribution for both Σ^- and Σ^+ in the four body channels have flat distributions.

$\Sigma^\mp \pi^\pm \pi^+ \pi^- \pi^0$:

This channel mainly goes through the following intermediate production of

$$\Sigma^\pm \pi^\mp \omega^0$$

$$Y_0^*(1405) \pi^+ \pi^- \pi^0$$

There is little evidence of the associated production of $Y_0^* \omega^0$. Table VII gives the branching ratios and cross-sections for this channel.

The production angular distribution of the Σ^- and Σ^+ in these channels show a slight backward peaking.

To summarize the results obtained in the different $\Sigma^\pm$ channels we can draw the following conclusions.

In the two body channels Σ^+ production dominates over that of Σ^- . The production mechanism in the former case involves, quite possibly, a K^* exchange whereas in the latter case a possible neutron exchange. The angular distribution of the Σ^- in the three body channel is different from that in the two body channel because of the intermediate peripheral production of $Y_0^*(1405)$. There is little $\Sigma^- \rho^+$ production in contrast with the strong $\Sigma^+ \rho^-$ production. But both the Σ^+ and Σ^- channels give $Y_0^*(1405)$, $Y_0^*(1520)$, $Y_1^{*0}(1660)$ and $Y_0^*(1815)$ to an almost equal extent. The difference in the production cross-section of Σ^+ and Σ^- in the three body channels is not very large. In the four body channels, only the $\Sigma^- \pi^+ \pi^+ \pi^-$ state gives $Y_1^*(1660)$. We do not get any $Y_1^{*-}(1660)$ from the corresponding Σ^+ channel. The production cross-section of Σ^- and Σ^+ are almost equal. Their angular distribution also look flat. In the five body channels Σ^- and Σ^+ behave almost in the same way as far as the production of different resonances is concerned. Σ^- and Σ^+ production cross-sections are also equal and they have similar angular distribution.

Section 7.4: $Y_1^*(1385)$ Production:

$\Lambda \pi^+ \pi^-$:

The interesting point about this channel is that it is dominated mainly by the production of $Y_1^{*+} \pi^-$, $\Lambda \rho^0$ and Λf^0 , see Table VIII, but there is no evidence for the production of $Y_1^{*-}(1385)$. This can be accounted for by the fact that only Y_1^{*+} production can occur through a K^* exchange.

$\Lambda \pi^+ \pi^- \pi^0$:

About 4% of this channel goes via the production of $Y_1^{*-}(1385)$.

$$K^- P \rightarrow Y_1^{*-} + \pi^+ + \pi^0$$

The mass distribution of the $\Lambda \pi^-$ system is shown in figure 7.6. The fractional contribution of $Y_1^{*+} \pi^- \pi^0$ to the final state is about 3%. An interesting point is the occurrence of the associated production of Y_1^{*+} and ρ^- in contrast with no evidence of the associated production of Y_1^{*-} and ρ^+ . This again suggests a K or a K^* exchange in the production process. The branching ratios and cross-sections for different resonance states in this channel are given in Table VIII.

Figure 7.7 shows the centre of mass production angular distribution of the $Y_1^{*-}(1385)$. The production is not

TABLE VII

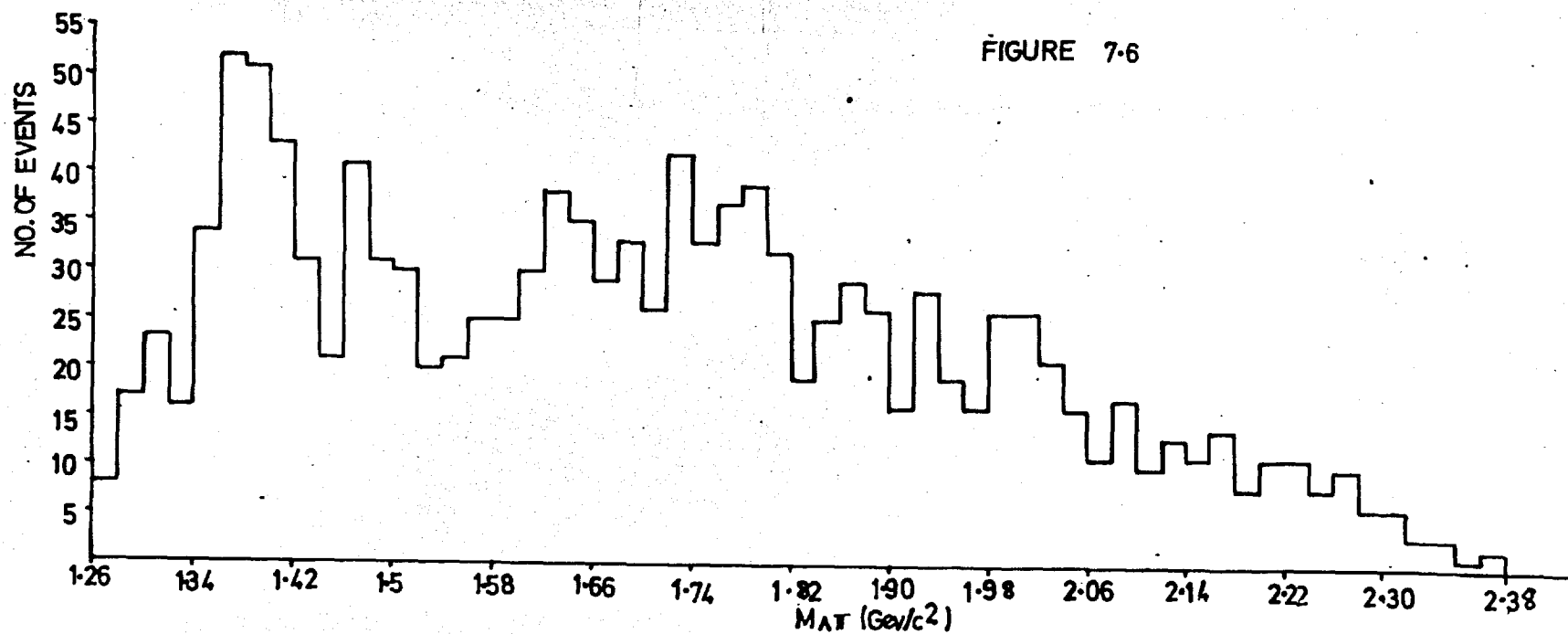
Final State	Cross-section in mb	Branching ratio $\frac{b}{b}$
$\Sigma^+ \pi^- \omega^0$	0.03 ± 0.005	12 ± 2
$\Sigma^- \pi^+ \omega^0$	0.03 ± 0.006	10 ± 3
$Y_0^* (1405) \pi^+ \pi^- \pi^0$	0.04 ± 0.01	11 ± 2

TABLE VIII

Channels	Resonant state	Cross-section in mb	Branching ratio %
$\Lambda \pi^+ \pi^-$	$Y_1^{*+} (1385) \pi^-$	0.09 ± 0.01	27 ± 4
	$\Lambda \rho^0$	0.09 ± 0.02	27 ± 5
	Λf^0	0.06 ± 0.02	19 ± 5
$\Lambda \pi^+ \pi^- \pi^0$	$\Lambda \omega_0$	0.09 ± 0.01	6 ± 1
	$Y_1^{*-} \pi^+ \pi^0$	0.06 ± 0.02	4 ± 1
	$Y_1^{*+} \rho^-$	0.04 ± 0.01	3 ± 1
$\Lambda \pi^+ \pi^+ \pi^- \pi^-$	$Y_1^{*+} \rho^0 \pi^-$	0.02 ± 0.004	12 ± 3
	$Y_1^{*-} \rho^0 \pi^+$	0.04 ± 0.007	22 ± 4

EFFECTIVE MASS OF ΛT^- SYSTEM IN
 $\Lambda \pi^+ \pi^- \pi^0$

FIGURE 7-6



limited to events with low momentum transfer only. The production angular distribution of the Y_1^{*-} looks quite different from that of the Y_1^{*+} which is strongly peripheral in character. The distribution of the decay angle of the Y_1^{*-} with respect to its line of flight in the overall K^-P centre of mass system looks flat (also shown in figure 7.7).

To analyse the decay distributions of resonances and to find out its properties, mainly its J^P and also the J^P of the exchanged particle we define four angles. Smith 1 (S_1), Smith 2 (S_2), Smith 3 (S_3)⁽⁵⁴⁾ and Treiman-Yang angle (T.Y)⁽⁵⁵⁾, in the following manner.

The direction of the normal to the production plane of the resonance, the direction of the incident beam in the rest system of the resonance and the other orthogonal direction define a rectangular Cartesian coordinate system, see figure 7.8a. Now, the angles made by the direction of the decay product in the resonance rest frame with these three axes are called S_1 , S_2 and S_3 respectively. As is shown in the article by Smith et al⁽⁵⁴⁾ the form of the three angular distributions will be $1 + a \cos^2 \theta$ with the value of a depending on the angle plotted and the particle exchanged in the production of the resonance.

Treiman and Yang⁽⁵⁵⁾ proposed a test for single pion exchange in a production process. According to them the angle between two planes namely, one that is made by the two

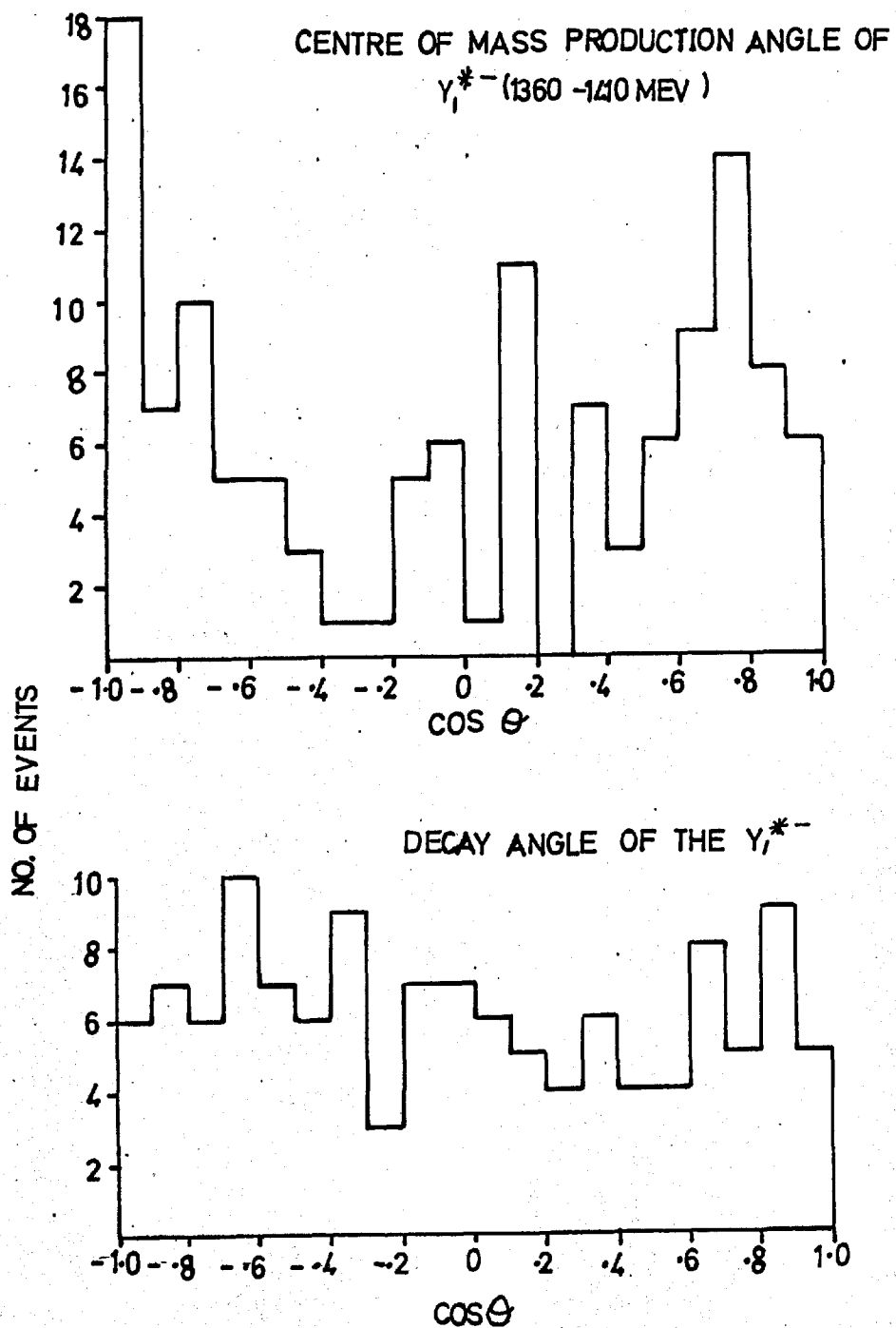


FIGURE 7.7

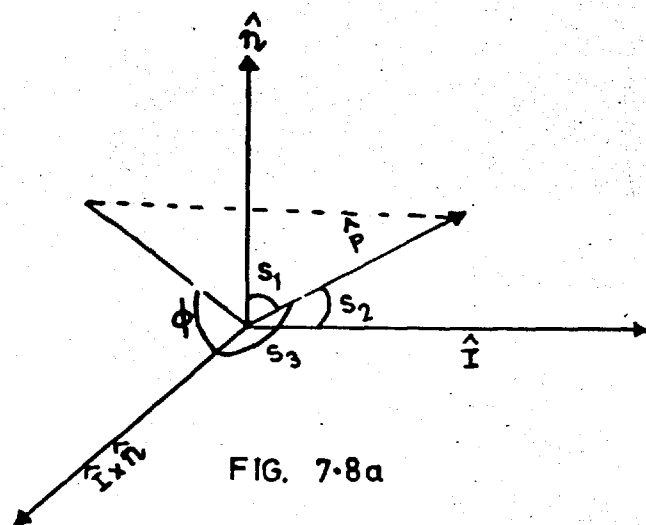


FIG. 7-8a

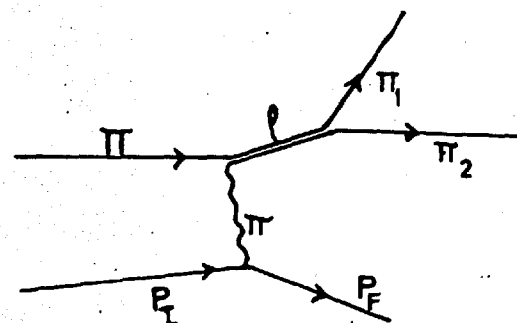
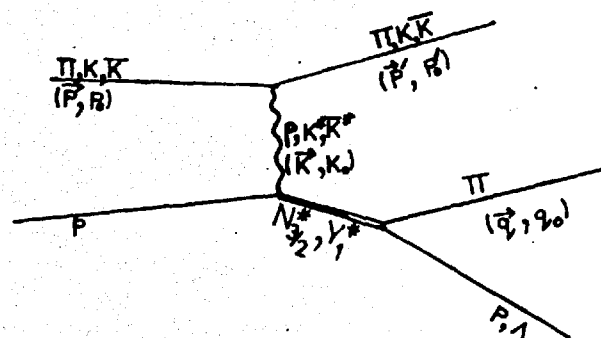


FIG. 7-8 b

$$\cos(T.Y) = \frac{(\hat{\pi}_1 \times \hat{\pi}_2)}{|\hat{\pi}_1 \times \hat{\pi}_2|} \cdot \frac{(\hat{p}_1 \times \hat{p}_2)}{|\hat{p}_1 \times \hat{p}_2|}$$



$$\cos \phi = \frac{(\vec{p} \times \vec{p}')}{|\vec{p} \times \vec{p}'|} \cdot \frac{(\vec{R} \times \vec{q})}{|\vec{R} \times \vec{q}|}$$

FIGURE 7-8c

outgoing π 's (see figure 7.8b) in the rest system of the incoming π and the plane made by the initial and final nucleon at the bottom vertex, also in the rest system of the incoming π should have a uniform distribution for a π exchange as it is a zero spin particle. Stodolsky and Sakurai⁽⁵⁶⁾ extended this idea to a vector meson exchange case. They show that the angle ϕ defined as

$$\cos \phi = \frac{(\vec{p} \times \vec{p}') \cdot (\vec{k} \times \vec{q})}{|\vec{p} \times \vec{p}'| |\vec{k} \times \vec{q}|}$$

should have a distribution of the form $A + B \cos \phi + C \cos^2 \phi$ where $\vec{p}$, $\vec{p}'$ are the 3-momentum vectors for the incident and final 'peripheral' π or K meson, see figure 7.8c.. $\vec{k}$ and $\vec{q}$ are the 3-momentum vectors of the exchanged vector meson and the decay meson from the resonance. All these quantities are evaluated in the rest system of the resonance. This test is applicable regardless of the quantum numbers of the resonance produced. J.D. Jackson⁽⁷³⁾ has showed that the azimuthal angle ϕ , see figure 7.8a, will have the same distribution as the T.Y. angle. The plots shown in this thesis as T.Y. angular distributions are actually the distributions for the angle ϕ .

Figure 7.9 shows the distributions of S_1 , S_2 , S_3 and T.Y. Angle for the Y_1^{*-} from the channel $\Lambda\pi^+ \pi^- \pi^0$ selecting the Y_1^{*-} from the band of $\Lambda\pi^-$ mass between 1360

$\Upsilon_1^*(360-140 \text{ Mev})$ in $\Lambda \pi^+ \pi^- \pi^0$

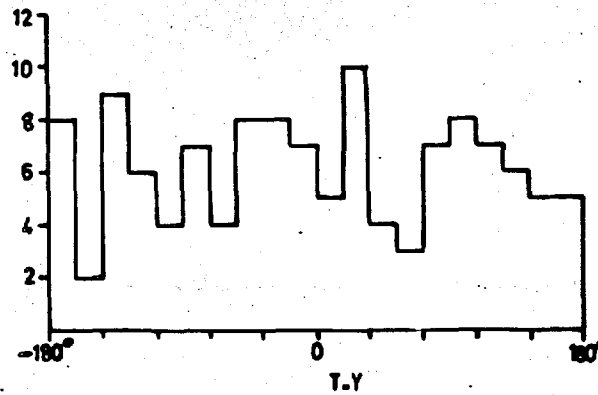
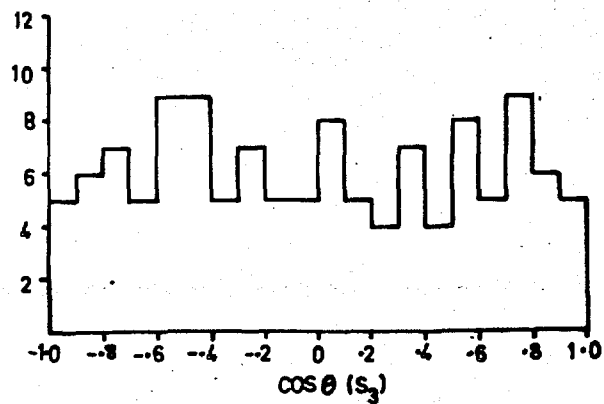
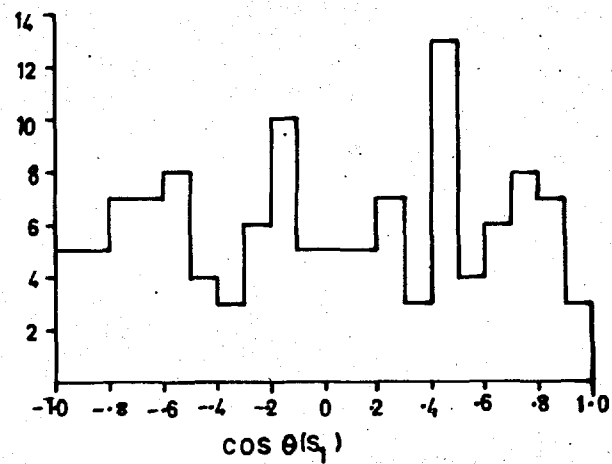
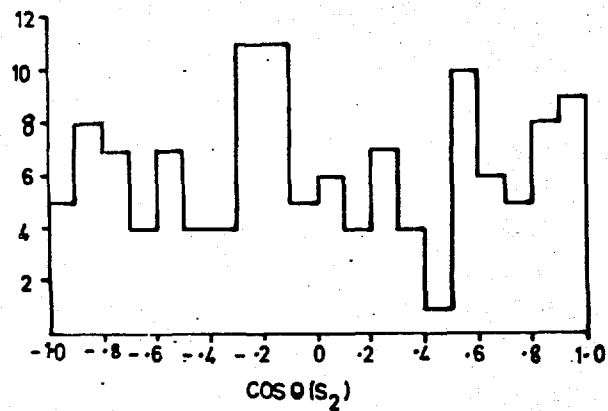


FIGURE 7-9

and 1410 Mev . All these distributions look flat within statistics. This is what is expected because $\Lambda K^- P \rightarrow Y_1^{*-} + \pi^+$, K^* exchange is forbidden. Y_1^{*-} production can occur through an exchange of baryon. The analysis of the decay of the Y_1^{*+} in the $\Lambda \pi^+ \pi^- \pi^0$ channel shows that the production mechanism involves a mixture of K and K^* exchange.

$\Lambda \pi^+ \pi^+ \pi^- \pi^-$:

This channel is dominated by the production of $Y_1^{*+}(1385)$ in association with ρ and π . Their branching ratios are given in Table VIII. The associated production of Y_1^{*-} with ρ^0 and π^+ is somewhat weaker than that of Y_1^{*+} with ρ^0 and a π^- .

There is very little evidence of the associated production of Y_1^* and Λ meson.

The production angular distributions for the Y_1^{*-} and Y_1^{*+} in the centre of mass system look similar. There is no evidence of a peripheral mechanism in the Y_1^{*+} production in contrast to the 3 and 4 body Λ channels.

$\Lambda \pi^+ \pi^- \pi^+ \pi^- \pi^0$:

There is some evidence for the production of $Y_1^{*\pm} \omega \pi^\mp$ in this channel. There is no real difference in the centre of mass production angular distributions of Y_1^{*-} and Y_1^{*+} . Both of them look flat. But this is based

on a very limited statistics after the contributions from other resonances are taken out.

Concluding, it is quite safe to say that all the low multiplicity Λ^0 channels are dominated by the production of Y_1^{*+} (1385 Mev) indicating a K or a K^* exchange whereas in the higher multiplicity channels there are almost equal amounts of Y_1^{*-} and Y_1^{*+} production.

Section 7.5

$N_{3/2}^*(1238)$ Production:

We shall discuss the production of the $N_{3/2}^{*-}$ in the reaction

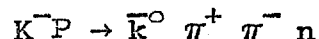
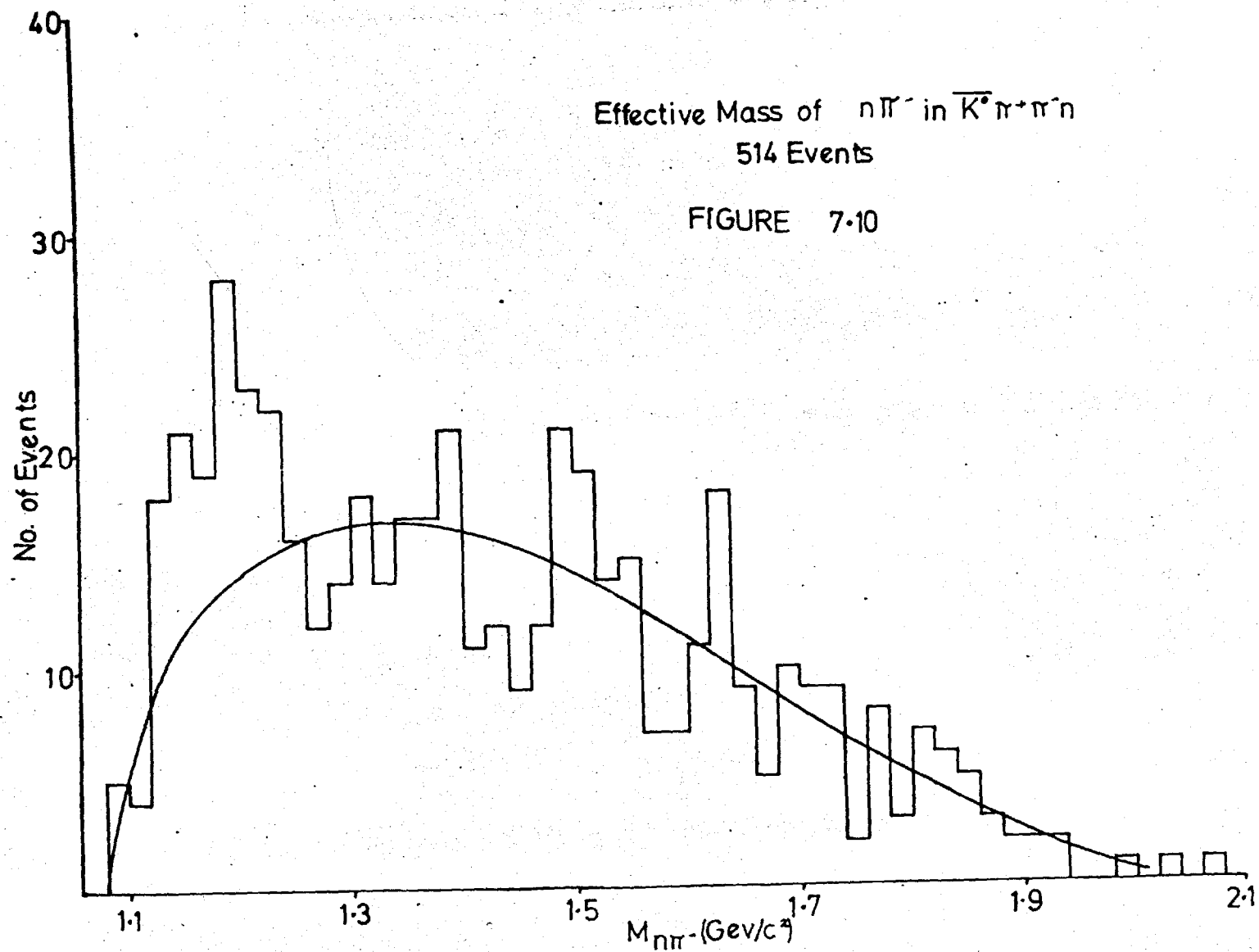


Figure 7.10 shows the effective mass distribution of the $n\pi^-$ system in this channel. The phase space curve is normalised to the total number of events inside the plot. The $N_{3/2}^{*-}$ peak shows up quite well in this distribution. The best mass value obtained for $N_{3/2}^{*-}$ from this distribution is 1183 Mev. The dominant feature of this channel is the production of $K^*(888)$ with a branching ratio of about $40\frac{0}{b}$. The production and decay angular distributions of the $N_{3/2}^{*-}$ in the overall $K^- P$ centre of mass system are shown in figure 7.11. The production angular distribution shows a slight backward peak. The decay distribution is almost flat. Figure 7.12 shows the plots of S_1 , S_2 and S_3 and T.Y. angle. All of them have a flat distribution within statistics.



CENTRE OF MASS

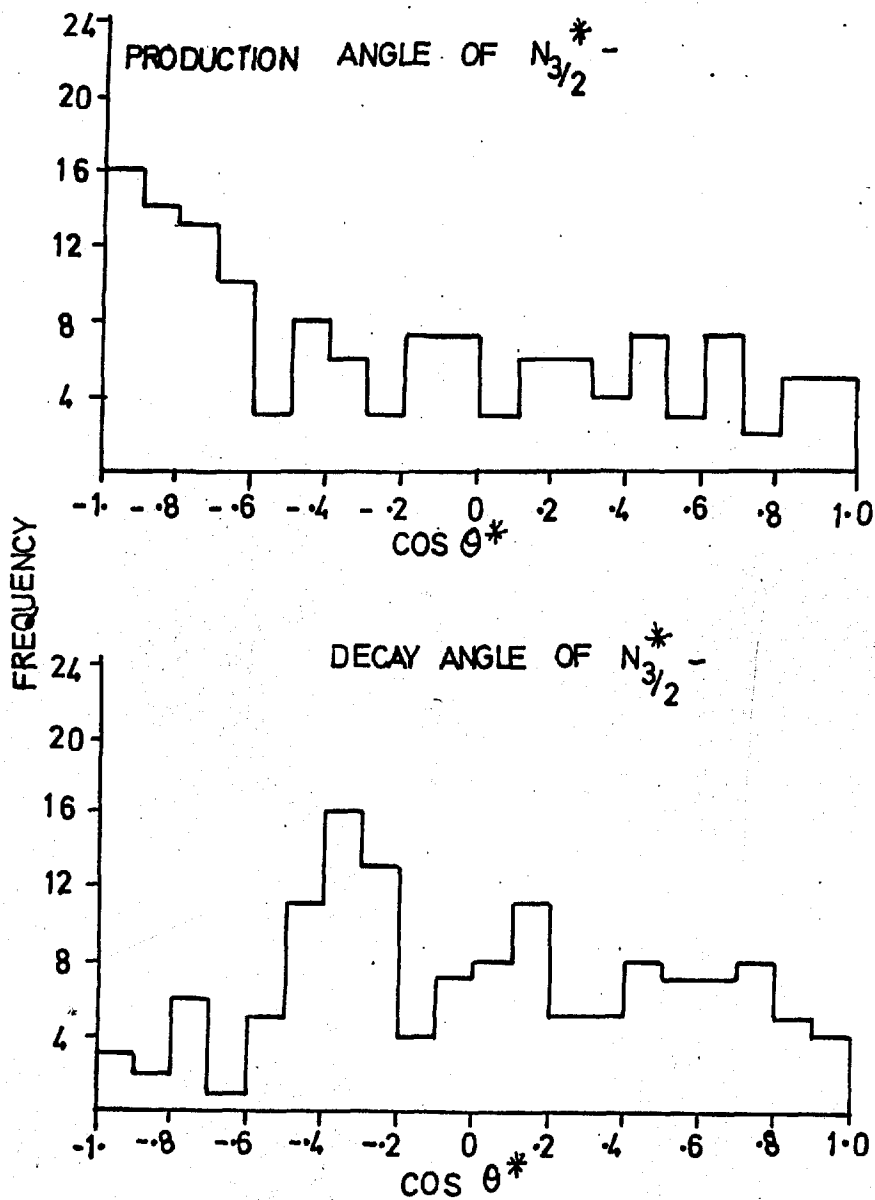


FIGURE 7.11

$N_{3/2}^{*-}$ in $\bar{K}^0 \pi^+ \pi^- n$

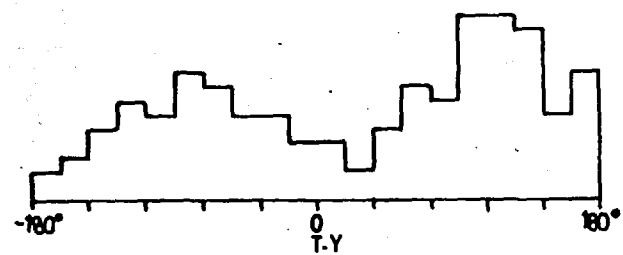
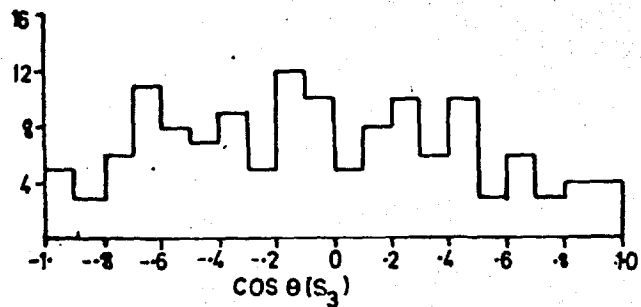
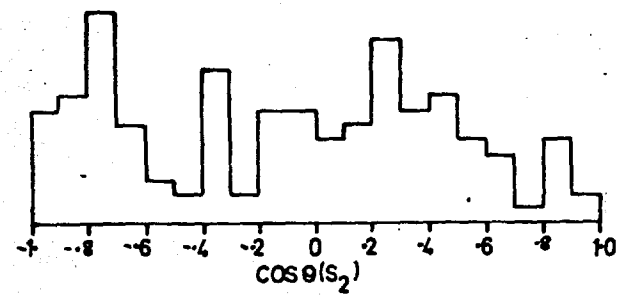
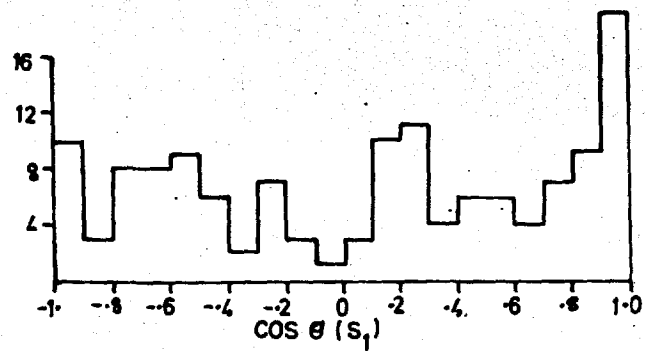


FIGURE 7-12

CHAPTER 8

RESULTS ON Ξ^- CHANNELS

Section 8.1: Introduction

Cascade minus hyperons were first observed in the cosmic ray work of Armenteros, Barker, Butler.⁽⁵⁷⁾ Later on they were observed in several other cosmic ray and bubble chamber experiments.⁽⁵⁸⁻⁶²⁾ The observation of the Ξ^0 hyperon production by Alvarez et al in 1959⁽⁶³⁾ in the reaction

$$K^- P \rightarrow \Xi^0 + K^0$$

establishes the existence of an isospin doublet,

$$\begin{pmatrix} \Xi^- \\ \Xi^0 \end{pmatrix}$$

and it also confirms the assignment of strangeness - 2 to this doublet.

The observed decays are

$$\Xi^- \rightarrow \Lambda^0 + \pi^-$$

$$\Xi^0 \rightarrow \Lambda^0 + \pi^0$$

The Ξ^- life time of 1.74×10^{-10} sec. is characteristic of the weak decays. The decay of the Ξ^- is uniquely determined by the subsequent charged decay of the Λ^0 .

$$\text{The branching ratio } R = \frac{\Lambda \rightarrow p + \pi^-}{\Lambda \rightarrow n + \pi^0} = 2$$

We looked for the production of the Ξ^- in the 3.5 GeV/c K^-P interactions via the following channels:

$$K^-P \rightarrow \Xi^- k^+ \quad (a)$$

$$\rightarrow \Xi^- k^+ \pi^0 \quad (b)$$

$$\rightarrow \Xi^- \pi^+ k^0 \quad (c)$$

$$\rightarrow \Xi^- k^+ \pi^+ \pi^- \quad (d)$$

$$\rightarrow \Xi^- k^0 \pi^0 \pi^+ \quad (e)$$

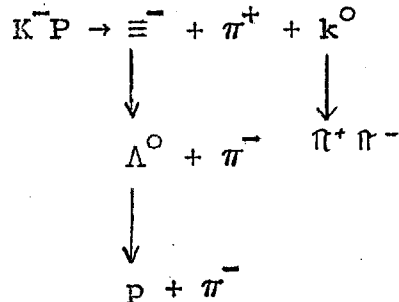
$$\rightarrow \Xi^- k^+ \pi^+ \pi^- \pi^0 \quad (f)$$

$$\rightarrow \Xi^- k^0 \pi^+ \pi^- \pi^+ \quad (g)$$

$$\rightarrow \Xi^- k^0 \pi^+ \pi^- \pi^+ \pi^0 \quad (h)$$

In this thesis mainly the results from two-body, three-body and four-body Ξ^- production channels will be discussed, namely the reactions from (a) to (e). The small number of events in the five and six-body final states makes a detailed analysis impossible.

A picture of a typical Ξ^- production and decay is shown in figure 8.1. The figure also shows the decay of the K^0 from the production apex. The reaction is



The cross-sections for the different channels of the Ξ^-

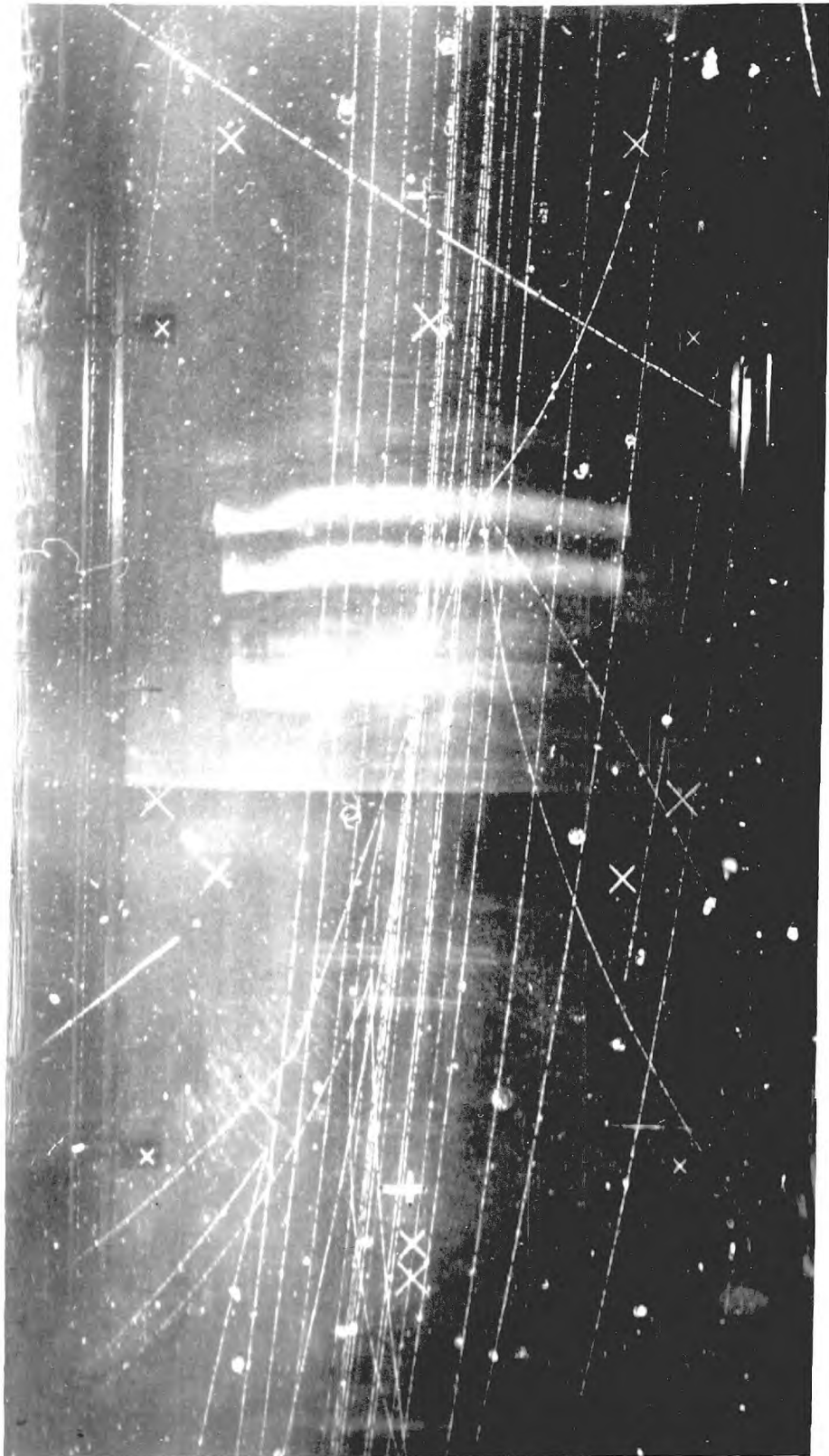


FIG 8.1

production at 3.5 GeV/c are given in Table IX. These cross-section estimates are based on the number of τ 's found in the film. They are corrected for the neutral decay modes of Λ^0 and K^0 and also for the scanning efficiency.

Section 8.2: Analysis of the Ξ^- events:

The procedure of scanning and measuring and the general ideas of geometrical reconstruction and kinematical fitting have already been discussed in detail in Chapter 3 and Chapter 4 respectively. In this section the analysis of the Ξ^- events after the geometrical reconstruction stage including some pertinent points about the special features of the kinematical fitting will be discussed. The results presented in this thesis on the Ξ^- hyperons are based on the eventsⁱⁿ which at least two strange particle decays are seen, one of them being always the negatively charged Ξ^- decay. Ξ^- type events were found in the categories 21^-1 , 21^-2 , 41^-1 , $42^\pm 1$, $22^\pm 1$ (see section 3.1 for the meaning of this terminology).

The kinematical fitting of a Ξ^- type event is done as follows:

Let us take a simple 21^-1 type event. We assume that all the tracks are well measured and have got all their three parameters (p , Λ and ϕ) determined at the geometry stage except for the decay track which is short and has its

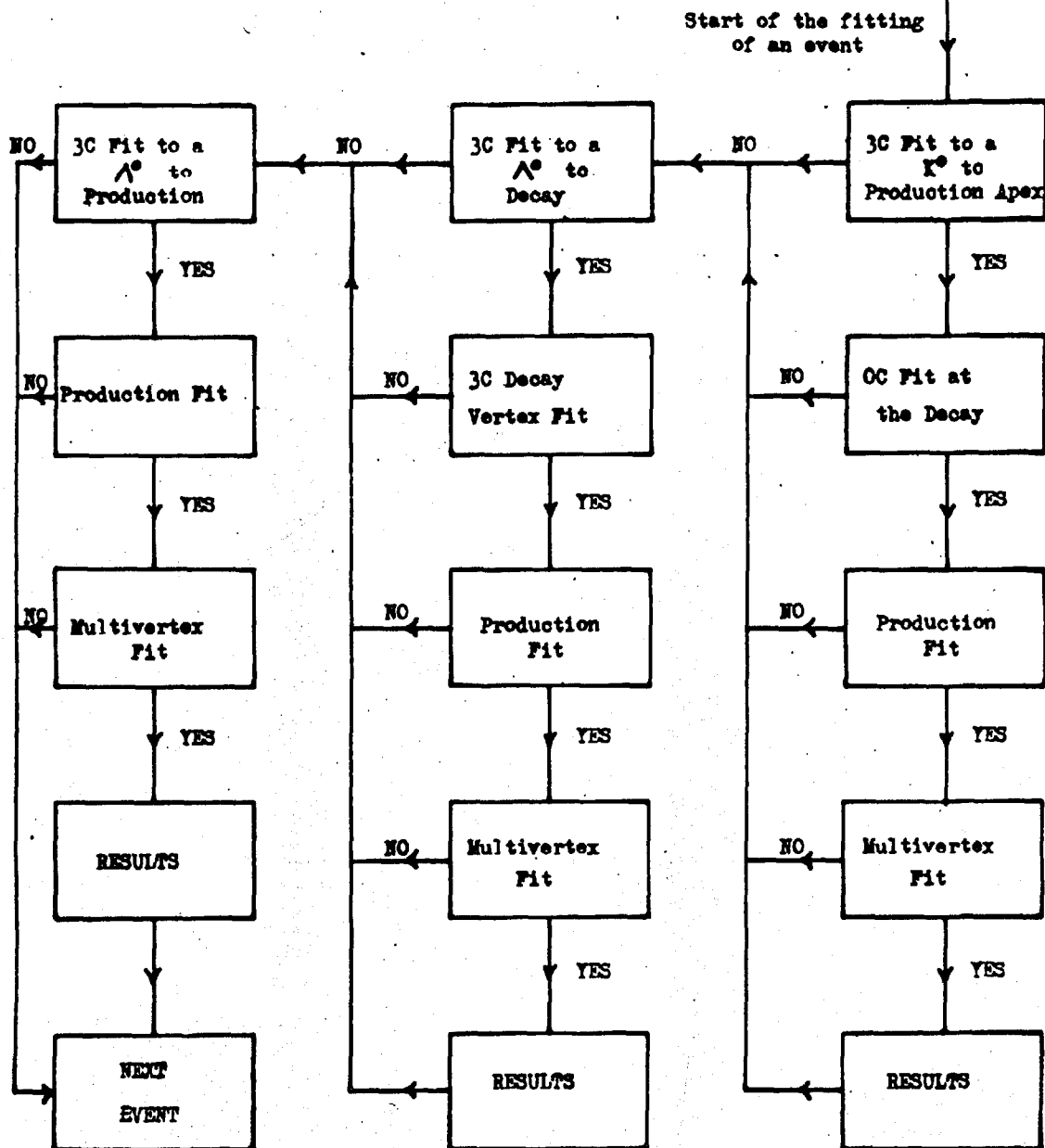
TABLE IX

Channel	Cross-section in μb
$\Xi^- K^+$	9.4 ± 3.2
$\Xi^- K^+ \pi^0$	21.6 ± 5.5
$\Xi^- \pi^+ K^0$	31.3 ± 5.7
$\Xi^- \pi^+ K^+ \pi^-$	19.9 ± 4.1
$\Xi^- \pi^+ K^0 \pi^0$	36.9 ± 10.2
$\Xi^- K \pi \pi \pi$	5.13 ± 1.8
$\Xi^- + ??$	21.5 ± 7.1
total = 145.7 ± 15.6	

These cross-section are based on the events of the Imperial College, Oxford and NIRS.

momentum undetermined. A 3-constraint fit is done at the V^0 vertex treating it as a K^0 coming from the production apex. If this fit is successful a 0-c fit is done at the charged decay apex. Then a production fit is tried with both the solutions of the 0-c fit, followed by a 3 vertex fit, which includes the K^0 , the charged decay vertex and the production vertex. A 3-c fit is also done at the V^0 apex treating it as a Λ^0 coming from the decay vertex. When this fit is successful a 3c - fit is tried at the charged decay vertex. Then a production fit is carried out followed by multivertex fit. The V^0 is also tried as a Λ^0 coming from the production apex and if successful subsequent non Ξ^- fits are done. The flow diagram of the fitting procedure of a 21^{-1} events is shown in figure 8.2.

The results of all the events have been checked by the author. Every event in the Imperial College data was checked on the scanning table for consistency between the predicted and observed ionisations. A fit is accepted if it is unique, the multivertex probability is above $1/b$, and the missing mass and the ionisations of the tracks are consistent with that particular hypothesis. In the case of ambiguous fits an effort is made to make them unique from the knowledge of the relative ionisations of the tracks. Also, if a fit is five times more probable than the other then the higher probability fit is accepted as unique. Events are sent for remeasurements only if the quality of



the measurement is below the goodness of measurement criterion which is about 20 microns on film for a track (this is the measure of the scatter of the measured points about the fitted curve, discussed in section 4.2) and 50 microns on film for a vertex (see apex errors in section 6.1). This step is taken because poor measurements can lead to kinematic ambiguities. In the case of Ξ^- events the ambiguities arise mainly between channel (b) and the sub-group of channel (c) in which the K^0 is not seen. By visual ionisation estimation a π^+ can be distinguished from a k^+ to a momentum up to 750 Mev/c. From 750 Mev/c to ~ 1000 Mev/c bubble counting can be used for this purpose.

The histograms of the missing mass squared for the fitted Ξ^- events are shown in figure 8.3. The top half of the picture contains all the events without any missing neutral and the bottom half displays the distribution of the missing mass squared for all the events with one missing π^0 . It is noticeable from the top distribution that it is not centred around the value 0, but shifted to a negative value of $(M.M)^2$.

When there is no missing neutral, the missing mass squared is given by the expression, (64)

$$(M.M)^2 = \sum_i (\beta_i^2 - 1) \Delta P_i^2$$

where ΔP is the error in the momentum measurement and β_i

MISSING MASS SQUARED DISTRIBUTION

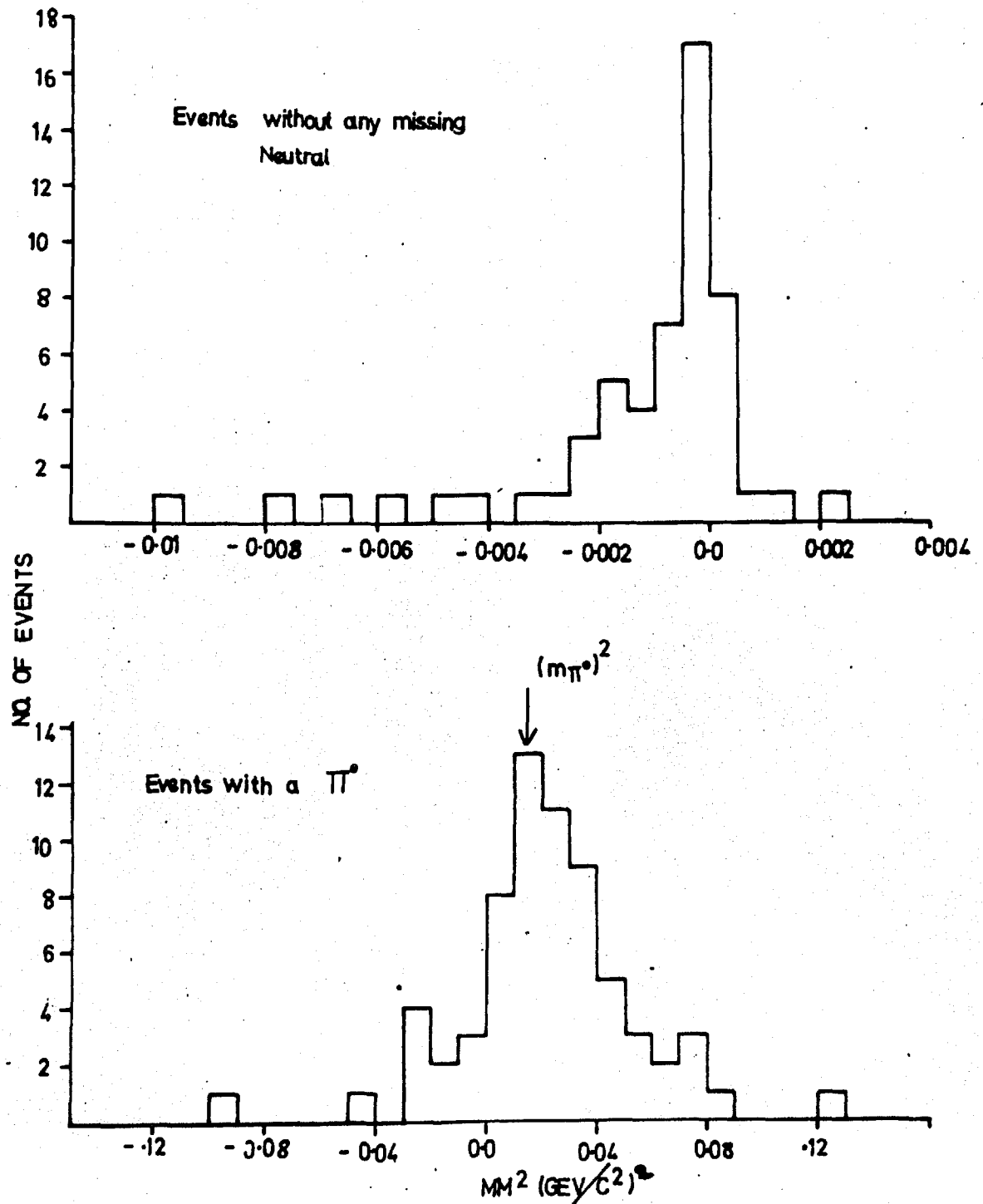


FIGURE 8.3

is v/c : the velocity of particle/velocity of light.

Thus in the case when all particles produced are observed, and true missing mass is zero, the calculated value for the square of the missing mass is always negative, since $\beta_i \leq 1$.

Section 8.3: Ξ^- Mass:

The Ξ^- mass was determined using the direction cosines and momenta of the fitted Λ and the unfitted π^- from the Ξ^- decay. The invariant mass of this $\pi\Lambda$ system is given by the following expression

$$M_{\Xi^-}^2 = (E_{\Lambda} + E_{\pi^-})^2 - (\vec{P}_{\Lambda} + \vec{P}_{\pi^-})^2$$

with

M_{Ξ^-} = Mass of the Ξ^-

E_{Λ} = Energy of the Λ

E_{π^-} = Energy of the π^-

$\vec{P}_{\Lambda}$ = 3-momentum vector of the Λ

$\vec{P}_{\pi^-}$ = 3-momentum vector of the π^-

The mass distribution for 147 events is shown in figure 8.4. Ideograms of Ξ^- mass and mass squared are also shown in the figure 8.5. The Ξ^- mass value thus obtained is

$$M_{\Xi^-} = 1321.0 \pm 0.2 \text{ Mev.}$$

The full width at half maximum is 7 Mev, which agrees well with the experimental resolution. This value was obtained using the Λ mass value as

$$M_{\Lambda} = 1115.4 \pm 0.11 \text{ Mev.}$$

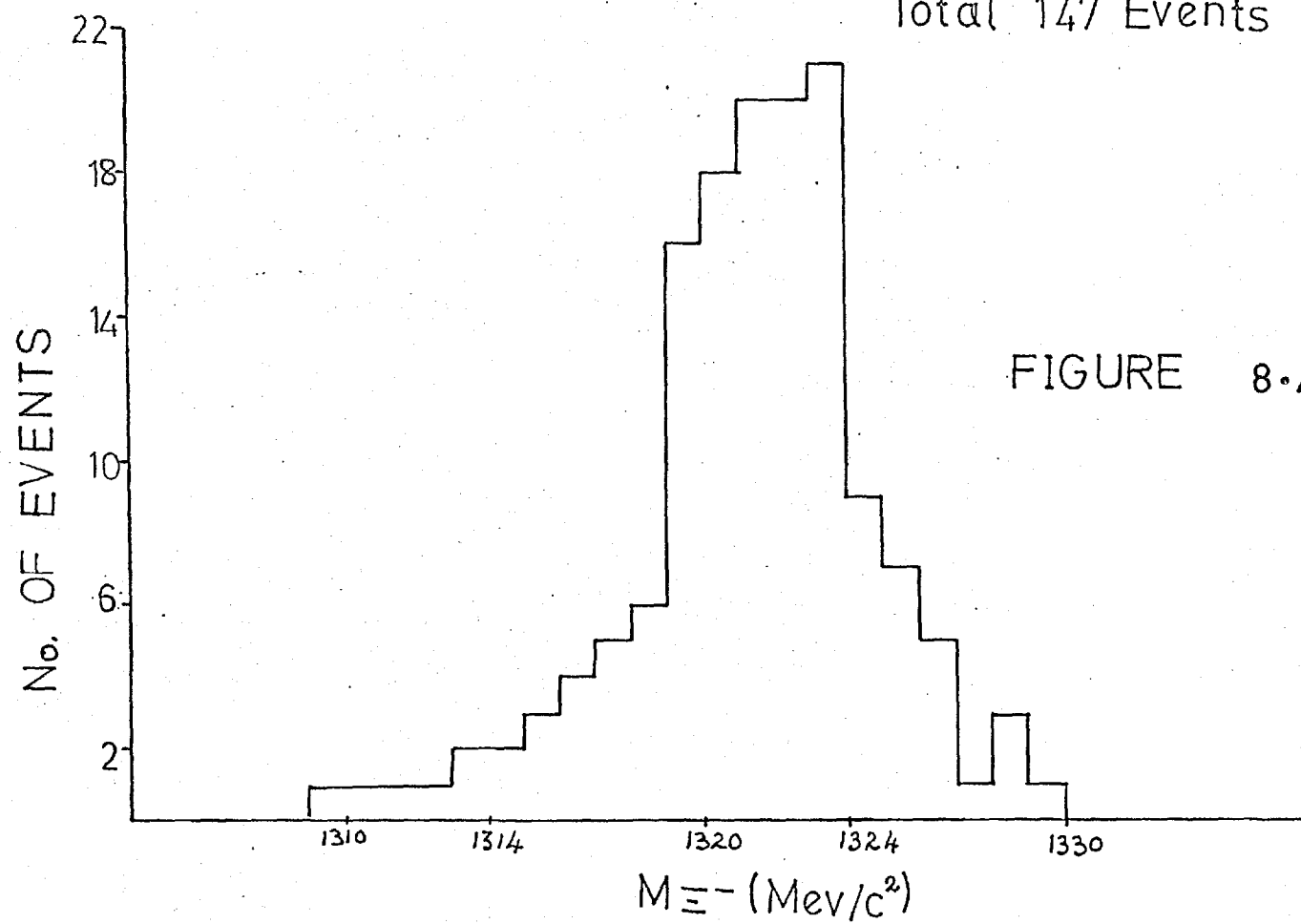
In order to investigate for any systematic errors the Λ^0 mass was calculated in a way analogous to that used for the Ξ^- mass, in this case using the unfitted momenta and direction cosines of the decay proton and π^- . Only the Λ^0 's associated with the Ξ^- decays are included for this determination. The resultant mass distribution for 131 events is shown in figure 8.6. Gaussian ideograms of the Λ mass and mass squared are also shown in figure 8.7. The width of the distribution at half maximum is 5 Mev. The Λ mass thus obtained is

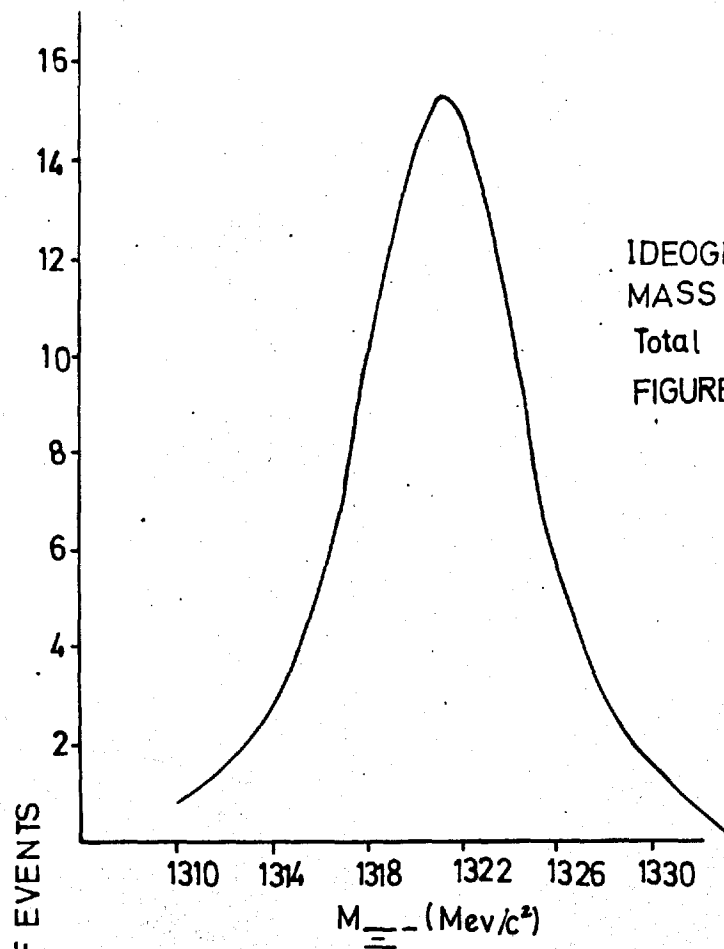
$$M_{\Lambda} = 1115.4 \pm 0.3 \text{ Mev}$$

which is in very good agreement with the accepted value of M_{Λ} . The quoted errors in the Ξ^- mass and Λ mass values are only statistical.

MASS OF Ξ^-

Total 147 Events

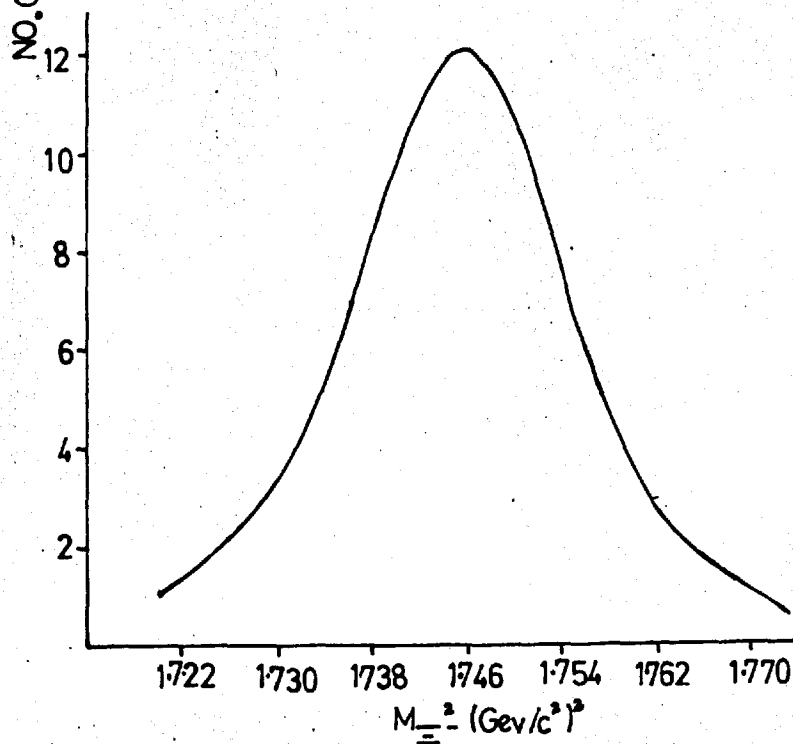


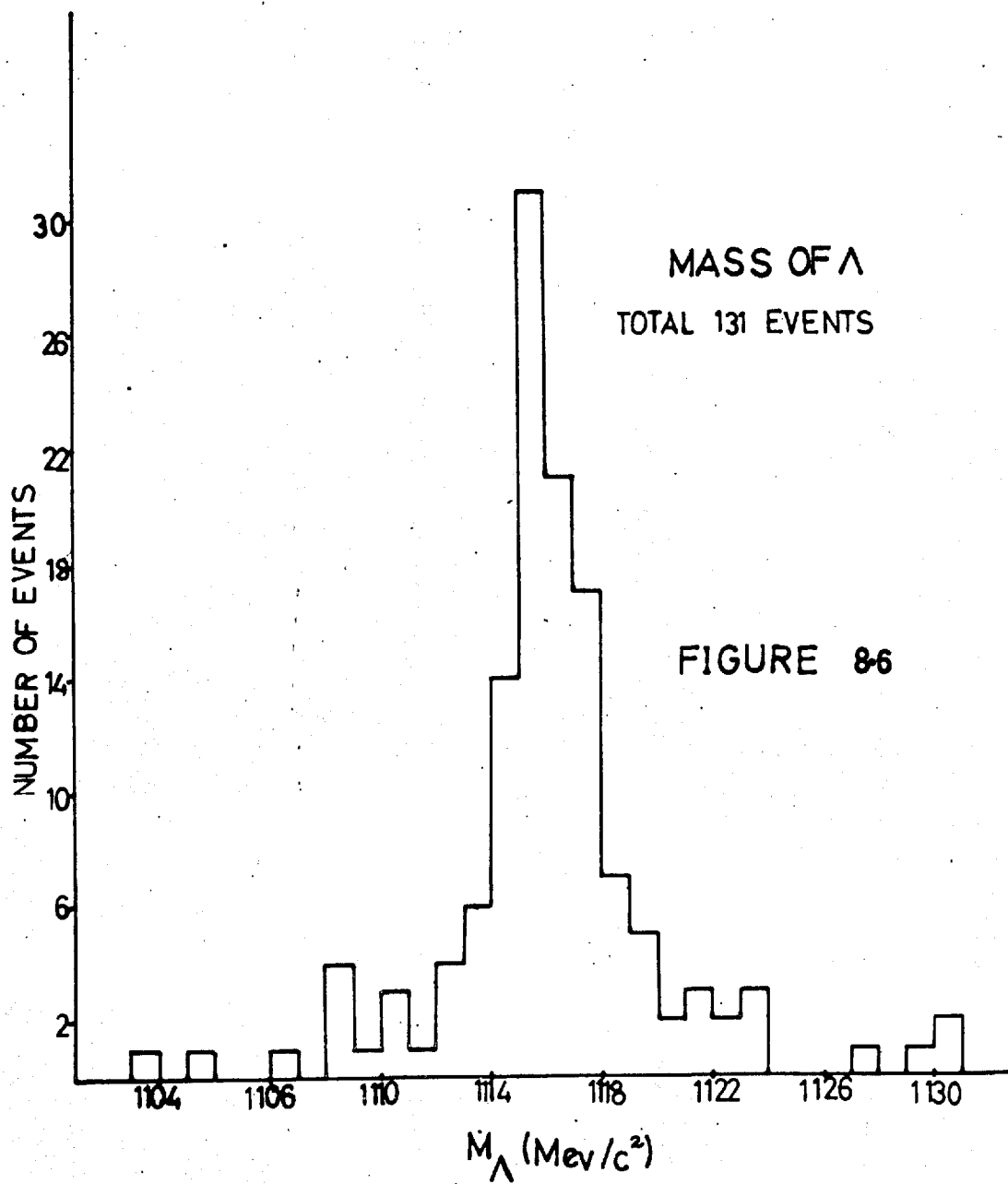


IDEOGRAMS OF MASS AND
MASS SQUARED OF Ξ^-

Total 139 Events

FIGURE 8.5





IDEOGRAMS OF Λ^0 MASS AND MASS SQUARED

TOTAL 126 EVENTS

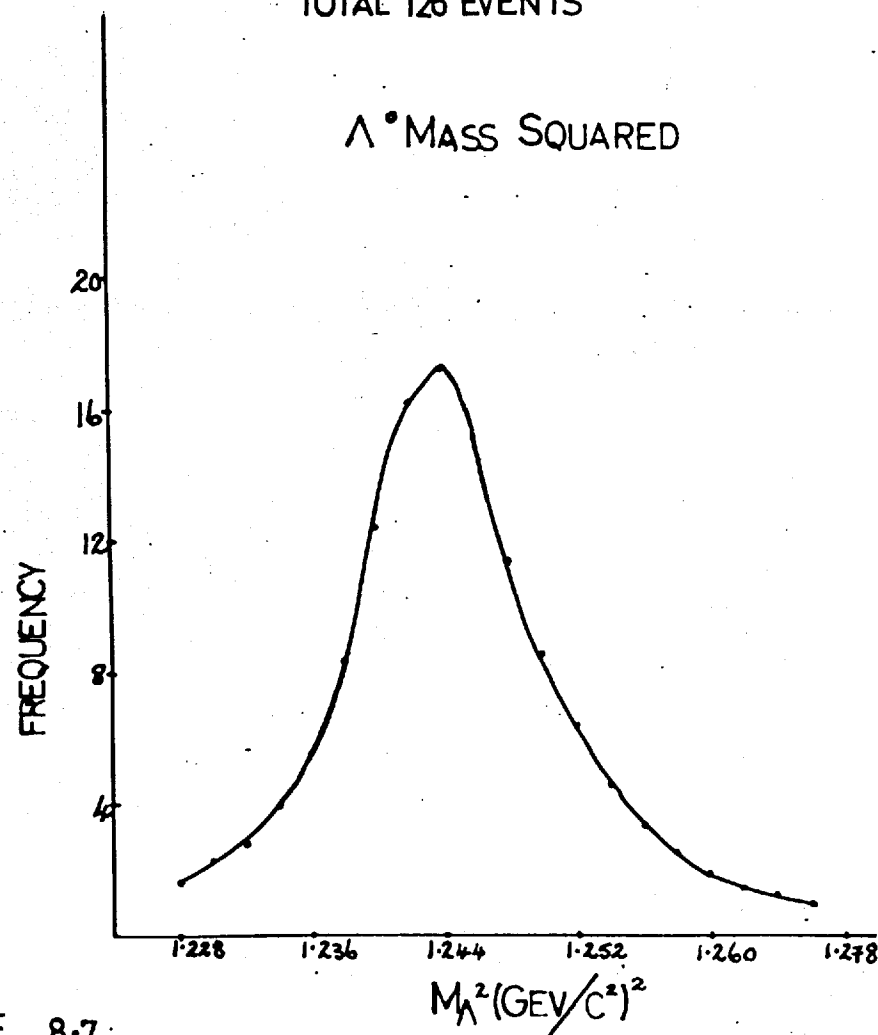
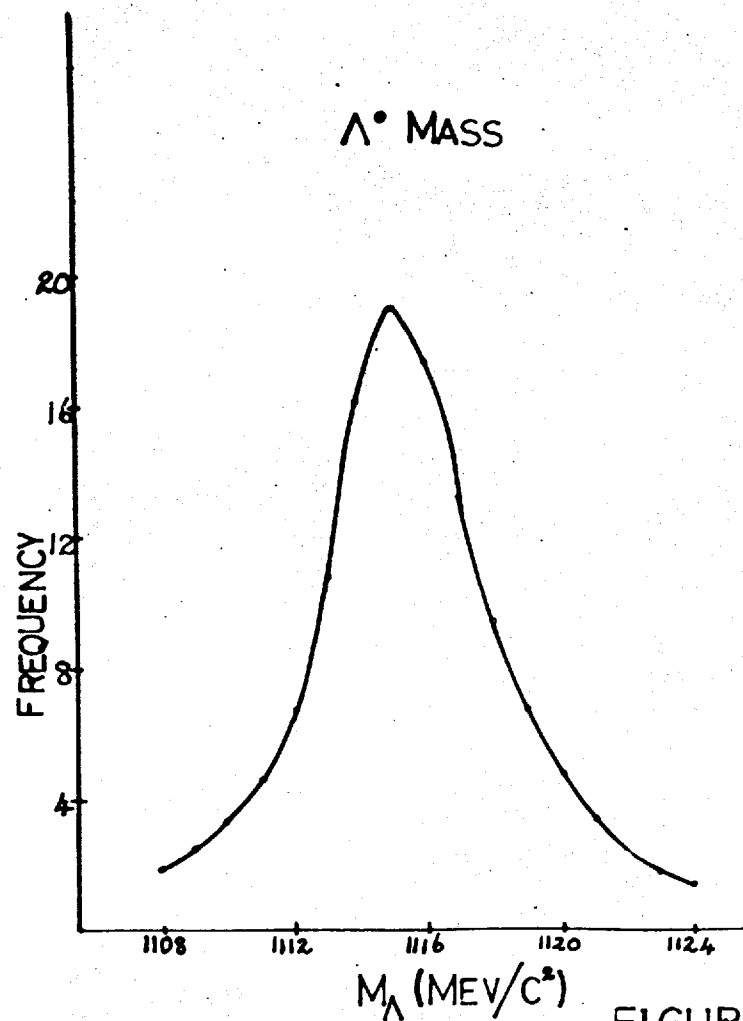


FIGURE 8.7

Section 8.4: The decay parameters of the Ξ^- :

We consider the non-leptonic decay mode of the Ξ^-

$$\Xi^- \rightarrow \Lambda^0 + \pi^-$$

We shall assume both Λ^0 and Ξ^- have spin $\frac{1}{2}$.⁽⁷⁵⁾ The decay angular distribution of the Ξ^- with its spin pointing towards the positive z-direction in its own centre of mass system is given by

$$\frac{dN}{d \cos \theta} = 1 + 2 \operatorname{Re} (A_s^* A_p) \cos \theta$$

where A_s and A_p are the amplitudes of the S and P angular momentum state respectively. The so-called decay parameters α , β and γ are defined as

$$\begin{aligned} \alpha &= 2 \operatorname{Re} (A_s^* A_p) \\ \beta &= 2 \operatorname{Im} (A_s^* A_p) \\ \gamma &= |A_s|^2 - |A_p|^2 \end{aligned}$$

with the constraint equation

$$\alpha^2 + \beta^2 + \gamma^2 = 1$$

and the wavefunction normalised so that

$$|A_s|^2 + |A_p|^2 = 1$$

If $\alpha \neq 0$ an updown asymmetry is observed in the decay which directly indicates parity violation. If there are no final state interactions it can be shown that time reversal invariance requires β to be zero.⁽⁶⁹⁾ The expressions for α , β and γ are modified when the effect of the final state interactions⁽⁷⁰⁾ is taken into account. Such interactions have the effect of multiplying the s and p amplitudes by a phase factor which depends upon the $\Lambda\pi$ phase shifts and the invariance properties of the interaction.

If time reversal invariance holds, then

$$\alpha_{\equiv} = \frac{2|s| \cdot |p|}{|s|^2 + |p|^2} \cos(\delta_p - \delta_s);$$

if charge conjugation invariance holds then

$$\beta_{\equiv} = \frac{2|s| \cdot |p|}{|s|^2 + |p|^2} \sin(\delta_p - \delta_s)$$

where δ_s and δ_p are, respectively, the $s_{\frac{1}{2}}$ and $p_{\frac{1}{2}}$ $\Lambda\pi$ scattering phase shifts.

α , β and γ and $p_{\equiv}$, the polarization of the Ξ^- can be found from the following distribution functions:

$$\frac{dN}{d \cos \theta} = 1 + \alpha_{\equiv} \alpha_{\Lambda} \cos \theta_1; \quad \cos \theta_1 = \hat{e}_p \cdot \hat{e}_1$$

$$\frac{dN}{d \cos \theta_2} = 1 + \frac{\pi}{4} P_{\equiv} \beta_{\equiv} \alpha_{\Lambda} \cos \theta_2; \quad \cos \theta_2 = \hat{e}_p \cdot \hat{e}_2$$

$$\frac{dN}{d \cos \theta_3} = 1 + \frac{\pi}{4} P_{\Xi} \gamma_{\Xi} \alpha_{\Lambda} \cos \theta_3; \cos \theta_3 = \hat{e}_P \cdot \hat{e}_3$$

$$\frac{dN}{d \cos \theta} = 1 + P_{\Xi} \alpha_{\Xi} \cos \theta; \cos \theta = \hat{e}_1 \cdot \hat{n}$$

where, $\hat{e}_P$ is the emission direction of the proton in the Λ rest frame and $\hat{n}$ is the direction of the Ξ^- polarisation i.e. the direction perpendicular to the production plane of the Ξ^- and

$$\hat{e}_1 = \hat{e}_{\Lambda}$$

$$\hat{e}_2 = \frac{(\hat{n} \times \hat{e}_1)}{|\hat{n} \times \hat{e}_1|}$$

$$\hat{e}_3 = \frac{(\hat{e}_1 \times \hat{e}_2)}{|\hat{e}_1 \times \hat{e}_2|}$$

$\hat{e}_{\Lambda}$ being the direction of the Λ in the Ξ^- rest frame.

From the above expressions it is obvious that to find β_{Ξ} and γ_{Ξ} we require polarised Ξ^- 's. This means only $\Xi^- k^+$ events are useful because there is no complication arising from the intermediate resonance production. But with only 25 events in this channel a meaningful determination of the values of β_{Ξ} and γ_{Ξ} cannot be made and hence nothing can be said about the final state interactions. But for the determination of the α_{Ξ} all the Ξ^- production events can be used as the theoretical correlation function is independent of Ξ^- polarisation.

Figure 8.19 shows a distribution of $\cos \theta_1$. The least square fitting to a straight line to the data gives

$$\alpha_{\Lambda} \alpha_{\Xi} = -0.36 \pm 0.08$$

Using the value of $\alpha_{\Lambda} = 0.62 \pm 0.07^{(74)}$ we obtain

$$\alpha_{\Xi} = -0.58 \pm 0.15.$$

Section 8.5: Production of Ξ^* (1530 Mev) in 3-body channels.

The 1530 Mev resonance in the $\Xi\pi$ system was first observed and reported by Bertanza et al ⁽⁴²⁾ at Brookhaven in the K^-P interactions at 2.24 and 2.5 Gev/c from the study of the following reactions.

$$K^-P \rightarrow k^0 \Xi^- \pi^+ \quad \dots\dots (1)$$

$$\rightarrow k^+ \Xi^- \pi^0 \quad \dots\dots (2)$$

$$\rightarrow k^0 \Xi^0 \pi^0 \quad \dots\dots (3)$$

$$\rightarrow k^+ \Xi^0 \pi^- \quad \dots\dots (4)$$

Subsequently its existence was confirmed by the work of Pjerrou et al ⁽⁴³⁾ in the K^-P interactions at 1.8 Gev/c and by Schlein ⁽⁴⁴⁾ et al at 1.95 Gev/c. References 35, 44, 45 also give an account of the work done on this resonance by other groups.

We shall discuss in this section the production of this resonance via the channels (1) and (2). The other two channels containing the Ξ^0 were not analysed due to the inherent difficulty in fitting a Ξ^0 decay. As is known Ξ^0 decays into $\Lambda^0 + \pi^0$, the Λ^0 again decaying two-thirds of the time through the charged mode, P and π^- . The possibility of the materialisation of the two γ rays from the decay of the π^0 into two electron pairs is quite small in the liquid hydrogen of the bubble chamber. The heavy liquid bubble chamber is more suitable for an analysis of the

Ξ^0 channels. As a result of this difficulty of the kinematical fitting of the Ξ^0 most of the fitted events of the $\Xi^0 k^0$ type are ambiguous with $\pi^- p \rightarrow \Lambda^0 k^0$.

Also in the 201 events the ambiguity between $\Xi^0 k^+ \pi^-$ and $\pi^- p \rightarrow \Sigma^0 k^+ \pi^-$ or $\pi^- p \rightarrow \Lambda^0 k^+ \pi^-$ could not be resolved. $\Xi^0 k^+ \pi^-$ events are sometimes also ambiguous with $\Sigma^0 \pi^+ \pi^-$ or $\Lambda^0 \pi^+ \pi^-$ types when the positive track cannot be identified as π^+ or k^+ by bubble counting. Channel (1) can give rise to the following three topologically different types of events:

(1a): where only the Λ^0 from the Ξ^- decay is seen

(1b): where only the k^0 is seen

(1c): where both Λ^0 and k^0 are seen

It can be shown that the expected ratio of (1a): (1b): (1c): is 4:1:2 because,

1) the probability of a Λ decaying in its charged mode i.e. $\Lambda^0 \rightarrow p + \pi^-$ is $2/3$

and the probability of not observing a k^0 is $2/3$

∴ Probability of observing a Λ^0 decay only is $2/3 \times 2/3 = 4/9$.

The probability of observing a k^0 is $1/3 \times 1/3 = 1/9$ and the probability of observing both a Λ^0 and k^0 is $2/3 \times 1/3 = 2/9$.

∴ (1a):(1b):(1c) ∴ 4: 1: 2

The ratio obtained from our data is

$$46: 12: 18$$

which is in good agreement with the expected ratios. The contamination from other topologically similar events is negligible (see section 8.2). For each of the above reaction types the distribution of the square of the effective mass was obtained. Figure 8.8 shows the Dalitz plot of $M_{\text{eff}}^2(\Xi\pi)$ vs. $M_{\text{eff}}^2(k\pi)$ and their projections on the axes. The Dalitz boundary is also shown. The solid curves in the projected distributions represent the phase space normalised to the total number of events. Cross-hatched events are the $\Xi^- k^+ \pi^0$ type and the unshaded ones are $\Xi^- \pi^+ k^0$ type. The Ξ^* (1530) shows up quite convincingly but mainly in the neutral mode. Figures 8.9a and 8.9b show the effective mass distributions of the $\Xi^- \pi^+$ and $\Xi^- \pi^0$ systems respectively. The phase space curves are also drawn. In these distributions there is some accumulation of events at the higher mass values of the $\Xi\pi$ combination. However the statistics are too small to permit a detailed analysis of these events. The cross-hatched areas correspond to events which have the mass of the $k\pi$ system between 840 and 940 Mev. This accumulation of events does not seem to be due to a kinematical reflection of the k^* formation. Table X shows the branching ratios and cross-sections of different resonance production in

these two channels.

I-spin of Ξ^* (1530):

Some information concerning the isotopic spin of the Ξ^* can be obtained by examining the decay ratios,

$$R_1 = \frac{\Xi^* \rightarrow \Xi^- \pi^+}{\Xi^* \rightarrow \Xi^0 \pi^0}$$

and

$$R_2 = \frac{\Xi^* \rightarrow \Xi^0 \pi^-}{\Xi^* \rightarrow \Xi^- \pi^0}$$

The expected values are $R_1 = R_2 = 2$ for $I_{\Xi^*} = \frac{1}{2}$ and $R_1 = R_2 = \frac{1}{2}$ for $I_{\Xi^*} = \frac{3}{2}$. These ratios are not useful in our case because the data on Ξ^0 events is not available. But a similar indication is obtained from the observed production ratios. The production amplitudes for the $\Xi\pi k$ reaction, starting with K^- on protons, can be written as follows:

$$\Xi^- \pi^0 k^+ \rightarrow \left[-\sqrt{2} a_{3/2, 1} + a_{1/2, 1} - a_{1/2, 0} \right] \quad (a)$$

$$\Xi^- \pi^+ k^0 \rightarrow \left[a_{3/2, 1} + \sqrt{2} a_{1/2, 1} + \sqrt{2} a_{1/2, 0} \right] \quad (b)$$

$$\Xi^0 \pi^0 k^0 \rightarrow \left[\sqrt{2} a_{3/2, 1} - a_{1/2, 1} - a_{1/2, 0} \right] \quad (c)$$

$$\Xi^0 \pi^- k^+ \rightarrow \left[-a_{3/2, 1} - \sqrt{2} a_{1/2, 1} + \sqrt{2} a_{1/2, 0} \right], \quad (d)$$

where $a_{I,I'}$ is the amplitude for the production of the $\Xi\pi$ system in isospin state I from an overall isospin state I' . If we assume that the production of the resonance occurs in a pure isospin state and if we neglect the interference effects with non resonant backgrounds, (a) and (b) predict a production ratio

$$\frac{(\Xi^- \pi^+ k^0)}{(\Xi^- k^+ \pi^0)} = \frac{1}{2} \text{ for } I_{\Xi}^* = 3/2$$

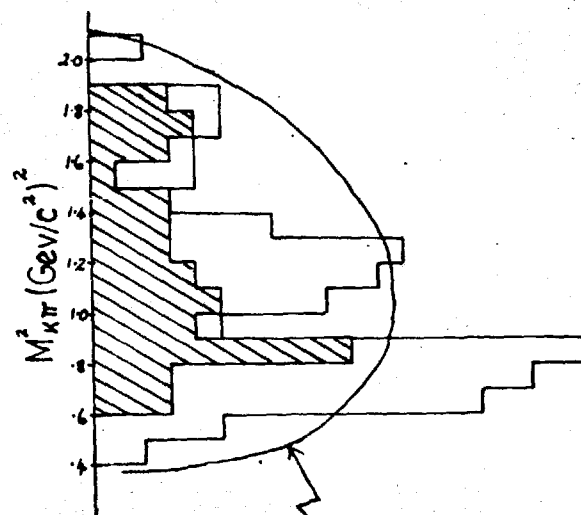
The observed ratio in the $M_{\Xi\pi}$ region between 1500 Mev and 1550 Mev is, in fact, $\sim 1.4 \pm 0.63$. This suggests (always bearing in mind the poor statistics) that the $I_{\Xi}^* = \frac{1}{2}$. If it is $\frac{1}{2}$ then the $a_{\frac{1}{2},1}$ and $a_{\frac{1}{2},0}$ amplitudes may interfere such as to give any production ratio for these two channels. Again, if the $a_{3/2,1}$ amplitude is negligible, then the production ratio of

$$\frac{\Xi^0 \pi^- k^+}{\Xi^- k^+ \pi^0} = 2$$

Spin of the $\Xi^*(1530)$

According to a method suggested by Byers and Fenster⁽⁶⁵⁾ the spin of the Ξ^* can be determined from a density matrix analysis of its decay. This method is only applicable when there is no interference with the background events and the Ξ^* decays as a free particle. In view of our small statistics this analysis was not attempted.

DALITZ PLOT and PROJECTIONS



PHASE
SPACE

1 Event $\square$

49 $\Xi^- K^+ \pi^0$
76 $\Xi^- \pi^+ K^0$
Total 125 Events

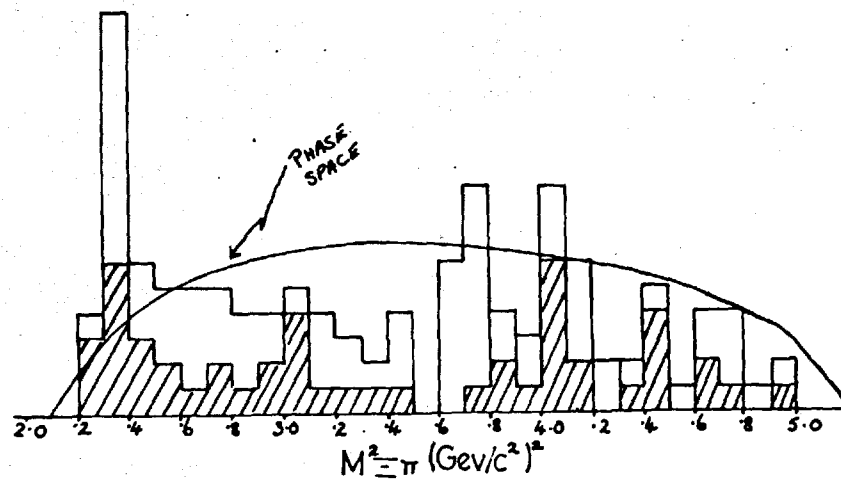
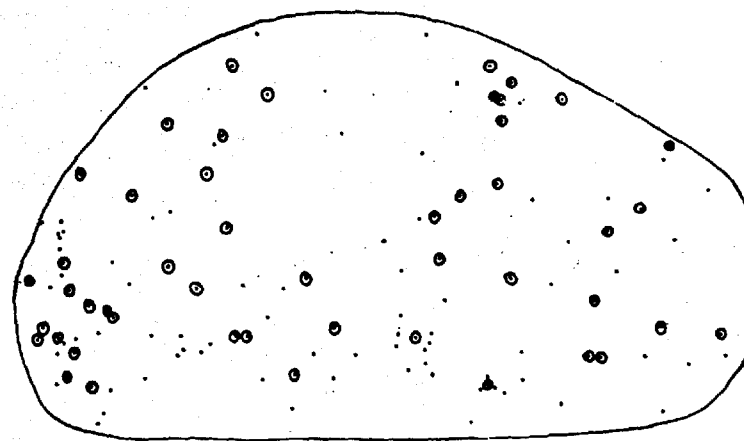


FIGURE 8-8

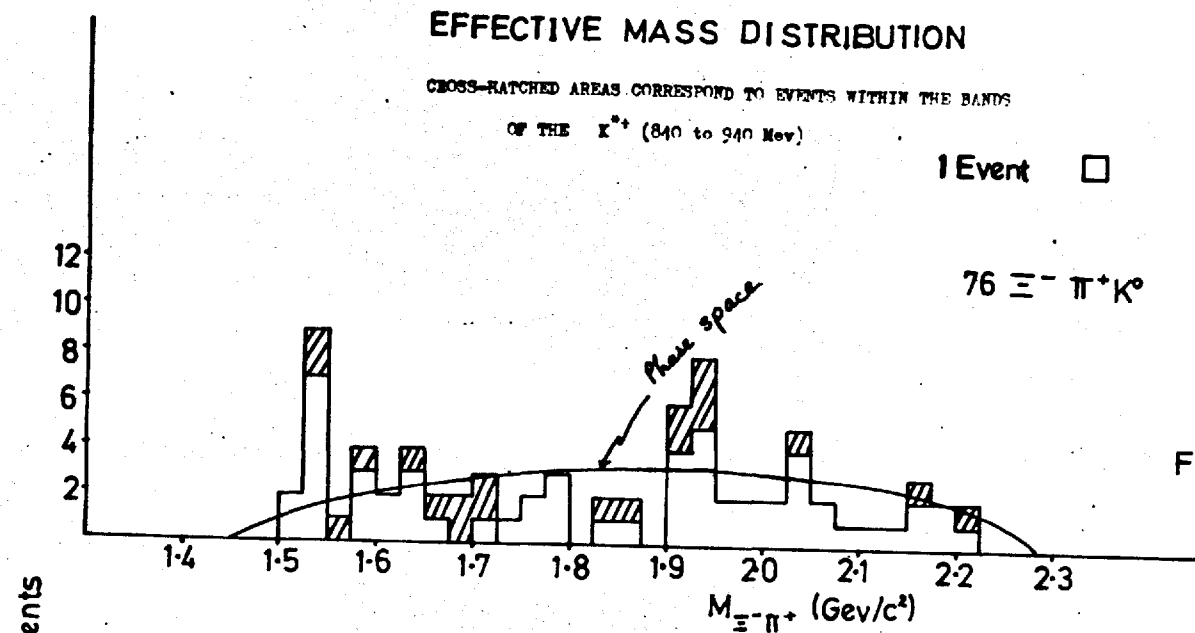


FIGURE 8-9a

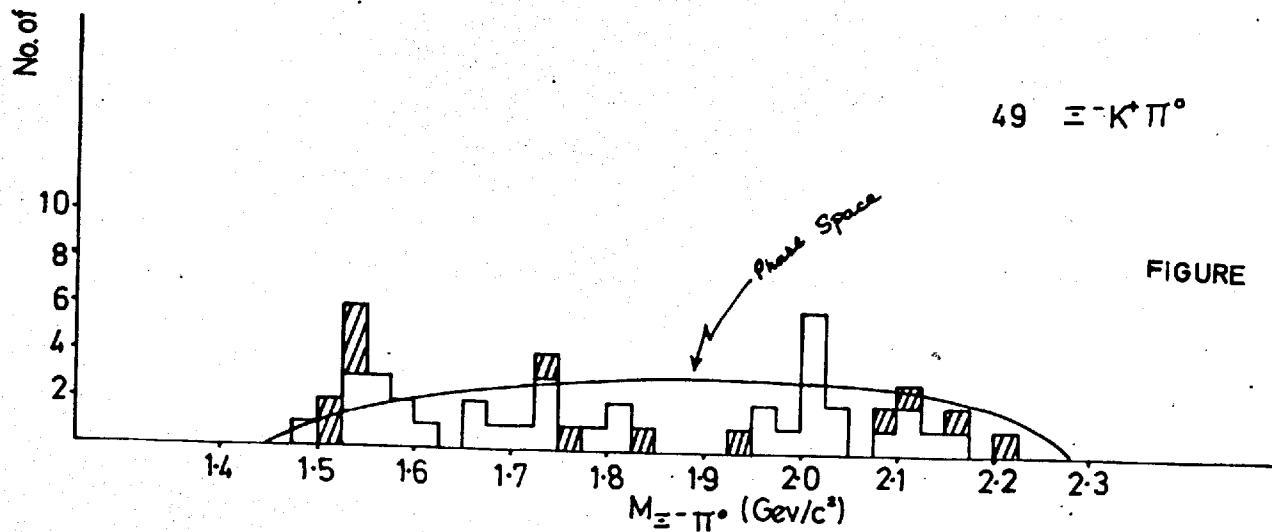


FIGURE 8-9b

TABLE X

Channel	Resonant State	Cross-section in μb	Branching ratio %
	$\Xi^{*-} K^+$	< 2	< 4
$\Xi^- K^+ \pi^0$	$\Xi^- K^{*+}$	2.7 ± 0.7	13 ± 3
	$\Xi^{*0} K^0$	3.4 ± 0.6	10.6 ± 1.8
$\Xi^- \pi^+ K^0$	$\Xi^- K^{*+}$	4.8 ± 0.9	15.2 ± 3
$\Xi^- K^+ \pi^+ \pi^-$	$\Xi^{*0} K^+ \pi^-$	17.15 ± 2.98	30 ± 6
	$\Xi^- \pi^+ K^{*0}$	11.63 ± 1.92	20 ± 4
$\Xi^- K^+ \pi^+ \pi^-$	$\Xi^{*0} K^{*0}$	5.56 ± 1.14	29 ± 7

TABLE XI

Resonance	Mass	Width	Branching ratio %
$\Xi^* (1530)$	1533 Mev	9 Mev	36
$K^* (888)$	877 ± 5 Mev	30 ± 11 Mev	36 ± 8

Section 8.6: Angular Distributions in 2 and 3
body channels:-

$\Xi^- K^+$

Figure 8.10 shows the angular distribution of the Ξ^- in the overall centre of mass system. It shows a slight forward peaking. The forward backward ratio in our 23 events is

$$\frac{f - b}{f + b} = 0.39$$

The forward peaking of the Ξ^- in $\Xi^- K^+$ channel has also been noticed in other experiments. From our results it is clear that the mechanism dominating the production of Ξ^- particles is antiperipheral in the sense that the exchange process involves hyperons. According to a model suggested by R.C. King⁽⁶⁶⁾ the exchange of a hyperon in the u channel gives rise to a forward peak in the angular distribution of the Ξ^- from $\Xi^- K^+$. Before explaining the exchange mechanism we must define the s, t and u channels. The energies in these three channels are given by

$$s = (p_1 + q_1)^2 = (p_2 + q_2)^2$$

$$t = (p_1 - p_2)^2 = (q_2 - q_1)^2$$

$$u = (p_1 - q_2)^2 = (p_2 - q_1)^2$$

where q_1 and p_1 are the 4-momenta of the two initial state particles and q_2 and p_2 are those of the two final state

CENTRE OF MASS ANGULAR DISTRIBUTION

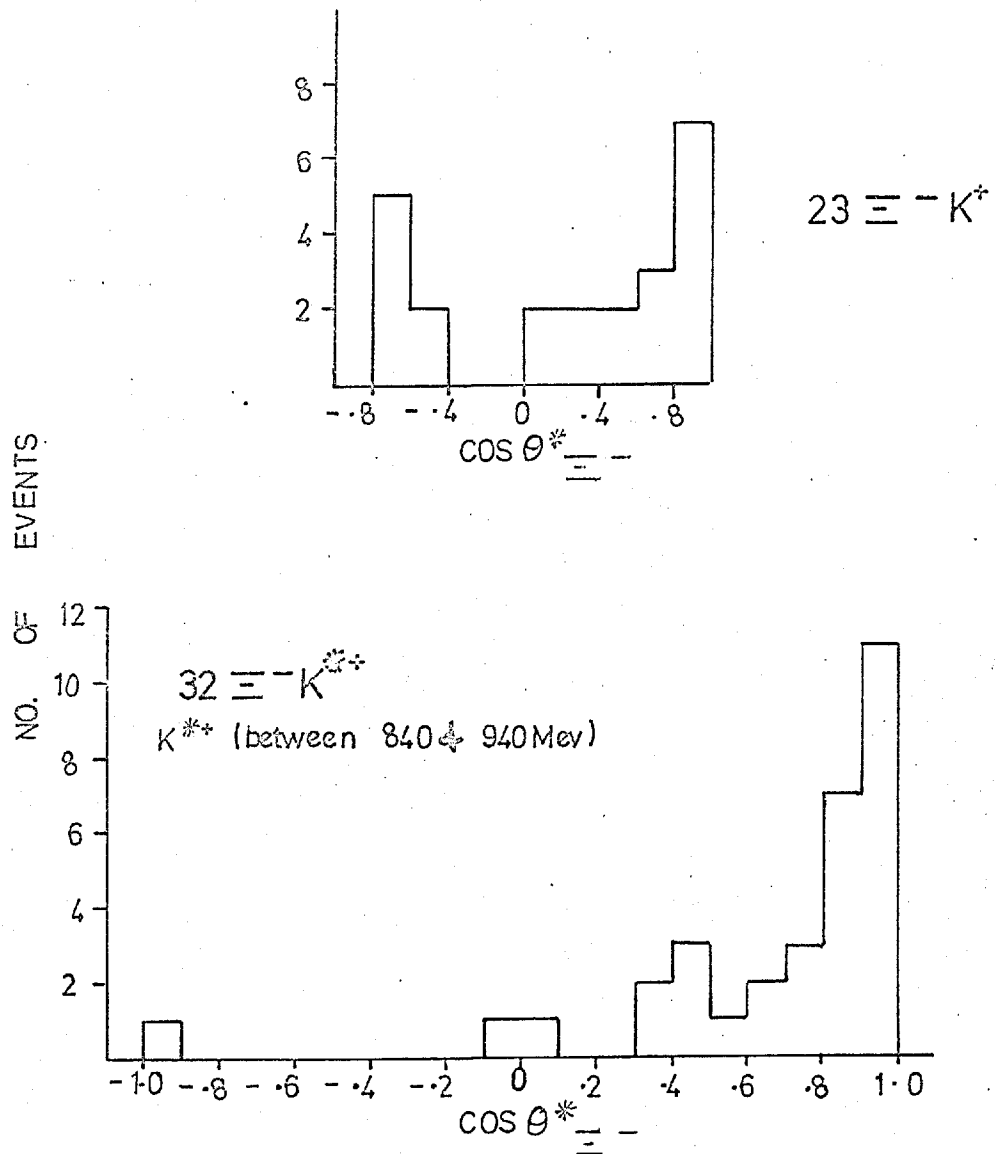


FIGURE 8.10

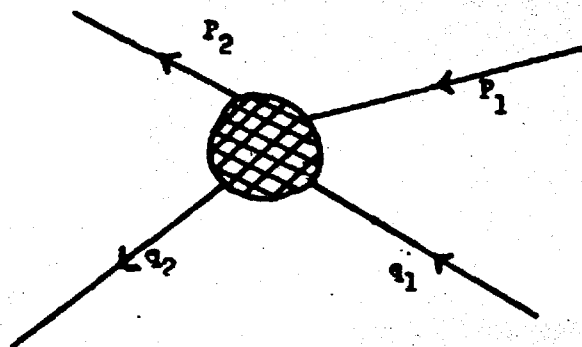
particles, figure 8.11. Figure 8.11 also shows diagrammatically what we understand by particle exchange in s, t or u channel. The size and shape of the peak depends on the spin of the exchanged particle and on the relative parity of the particle involved. This model gives a good fit to the experimental data at 1.8 Gev/c and 2.2 Gev/c $\bar{K}^0 p$ interactions for Ξ^- spin $\frac{1}{2}$. The number of events of $\Xi^- K^+$ class at our energy is not sufficient to do this analysis.

$\Xi^- K^{*+}$

This channel shows a very pronounced forward peaking of the Ξ^- in the distribution of the centre of mass production angle, see figure 8.10. The forward backward ratio is

$$\frac{f - b}{f + b} = 0.88$$

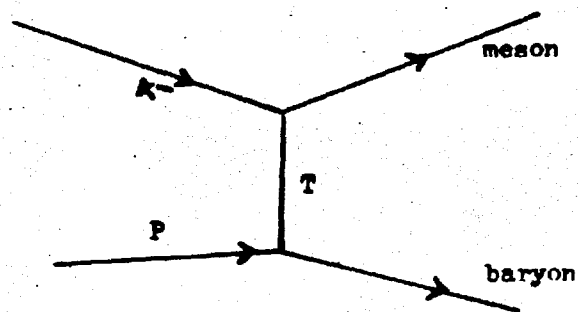
The events with K^{*} mass between 840 and 940 Mev have been selected for this plot. This effect was also noticed in low energy experiments. As was stated in the $\Xi^- K^+$ case, this forward peaking can only be explained by a process involving a hyperon exchange.



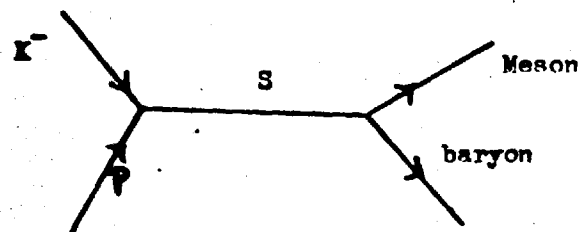
$$S = (P_1 + q_1 = P_2 + q_2)^2$$

$$t = (P_1 - P_2 = q_2 - q_1)^2$$

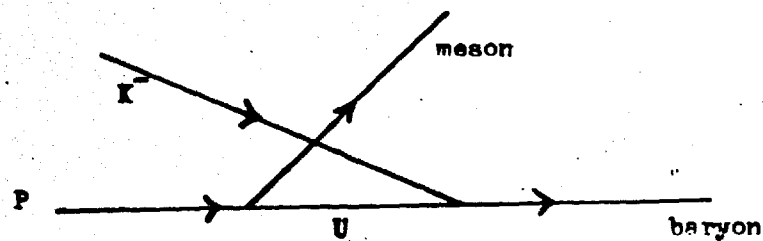
$$u = (P_1 - q_2 = P_2 - q_1)^2$$



Exchange of particle T in t Channel



Exchange of particle S in s Channel



Exchange of particle U in u Channel

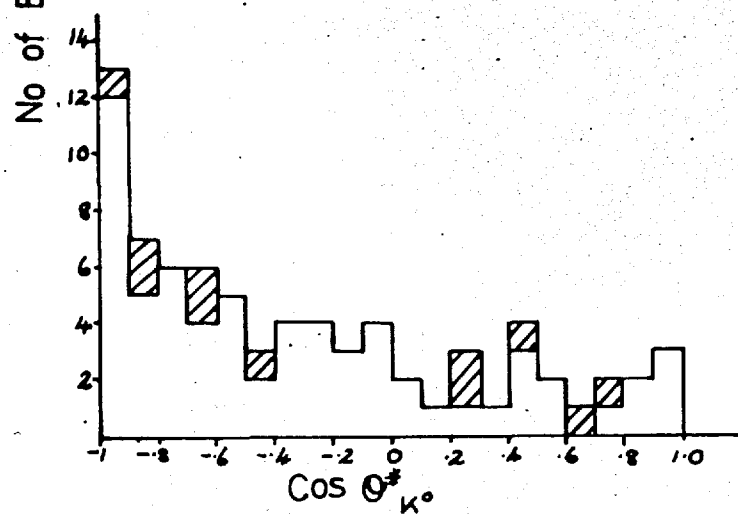
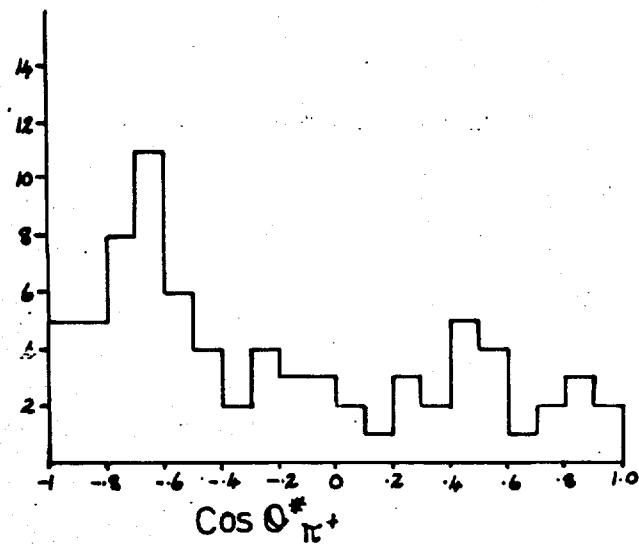
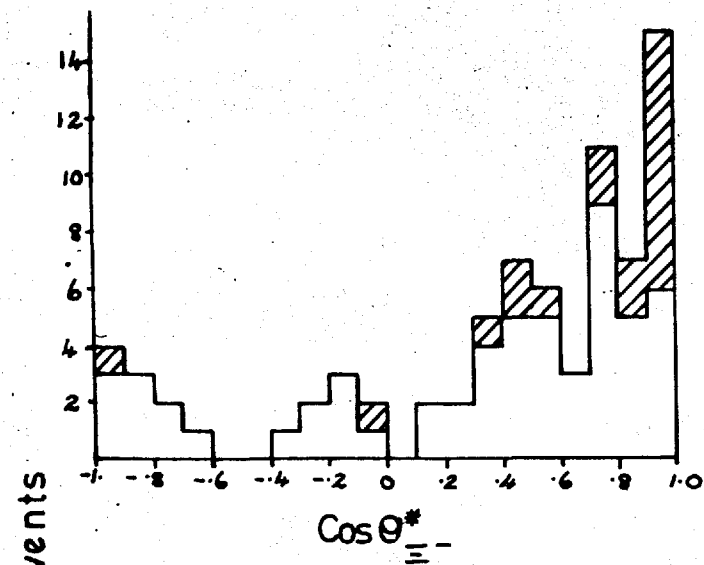
FIGURE 8-11

$\Xi^- \pi^+ K^0$:

Figure 8.12 shows the centre of mass angular distributions of the Ξ^- , K^0 and π^+ . The cross-hatched events in the Ξ^- distribution correspond to those which have a $K\pi$ mass between 840 and 940 Mev. Ξ^- shows some forward peaking. The cross-hatched events in the K^0 distribution are those containing the Ξ^* between 1500 and 1550 Mev. The K^0 shows a backward peaking.

$\Xi^- K^+ \pi^0$:

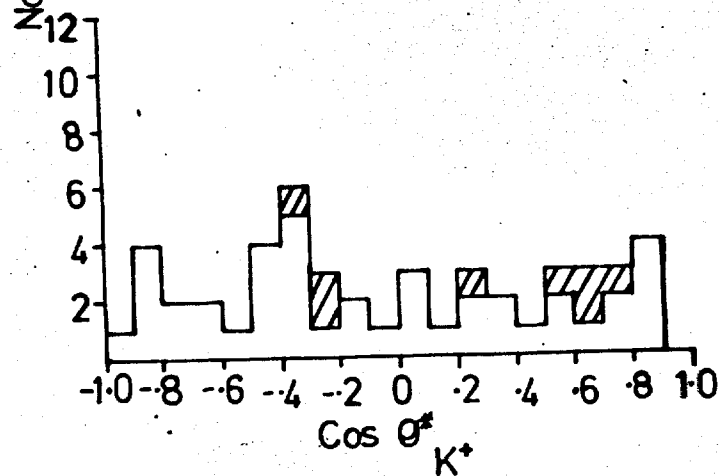
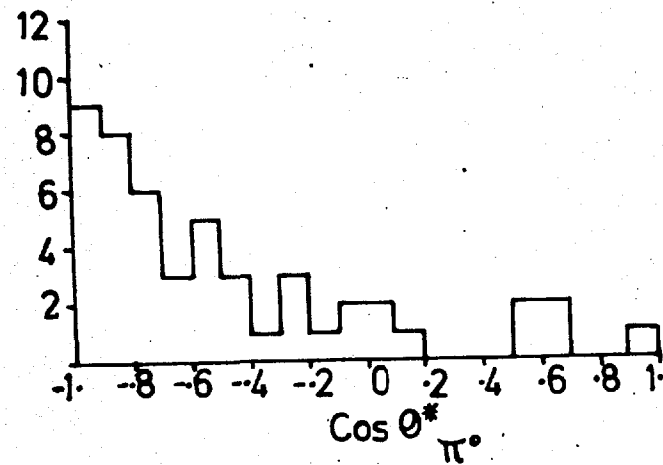
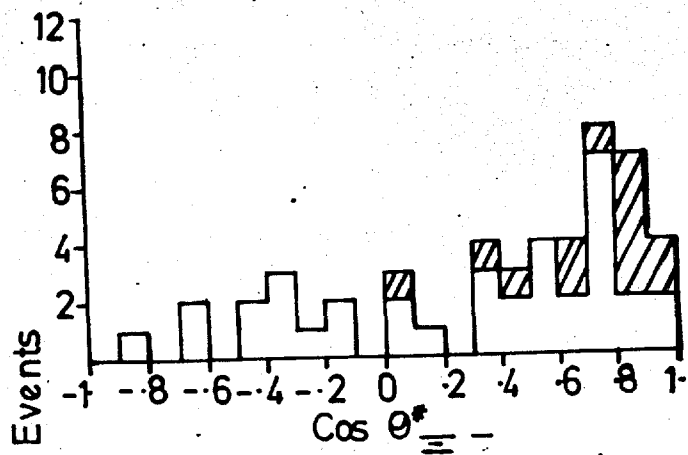
The distribution of the centre of mass production angles of Ξ^- , K^+ and π^0 are shown in figure 8.13. The cross-hatched events in the Ξ^- distribution correspond to those which have a K^{*+} in the range of 840 to 940 Mev. Similarly the cross-hatched events in the K^+ distribution are those which have a $\Xi\pi$ mass between 1500 and 1550 Mev. The distributions look similar to those of $\Xi^- \pi^+ K^0$ case except the distribution of K^+ . In $\Xi^- K^+ \pi^0$ case the K^+ distribution is almost flat.



Centre of Mass Angular Distributions

$76 \pi^- K^0$ 1 Event $\square$

FIGURE 8.12



Centre of Mass Angular Distributions
1Event $\square$

$\Lambda^0 \rightarrow -K^+ \pi^0$

FIGURE 8.13

Section 8.7: Analysis of the 4-body Ξ^- channels:-

There are three kinematically fittable four body channels; namely,

$$\Xi^- K^+ \pi^+ \pi^- \quad (a')$$

$$\Xi^- K^0 \pi^+ \pi^0 \quad (b')$$

$$\Xi^0 K^0 \pi^+ \pi^- \quad (c')$$

Analysis of the channel (a') is quite straightforward.

It usually has a 4c fit solution. Most of the time one of the two positive tracks is identified as a K^+ by ionisation estimate or bubble counting. The difficulty arises in the analysis of the channel (b') when the Λ^0 from the Ξ^- decay is not observed. These events are sometimes ambiguous with the $\Sigma^- K^+ \bar{K}^0 \pi^0$ type. Here the distinction of the positive track by ionisation becomes absolutely vital. We shall not present any result from the last channel as it is not completely analysed. The difficulty in analysing the Ξ^0 channels has been discussed before in section 8.5.

Reaction (a') has only one $\Xi\pi$ pair in the $I = \frac{1}{2}$ state whereas (b') has two $\Xi\pi$ pairs which are both in $I = \frac{1}{2}$ state. Figure 8.14 shows a triangular plot of $M_{\text{eff}}(\Xi\pi)$ vs. $M_{\text{eff}}(K\pi)$ in $I = \frac{1}{2}$ state. For reaction (b') there are two points per event. The dominant features of this plot are the production of Ξ^* (1530) and K^* (888) which are quite evident in the projections on the $\Xi\pi$ and $K\pi$ mass

axes, also shown in the figure. In the triangular plot the solid dots represent $\Xi^- \pi^+$ combinations in $\Xi^- K^+ \pi^+ \pi^-$ and $\Xi^- K^0 \pi^+ \pi^0$ channels and circles with dots inside correspond to the $\Xi^- \pi^0$ combinations in $\Xi^- \pi^+ K^0 \pi^0$ events. The cross-hatched events in $\Xi \pi$ mass projection correspond to $\Xi^- \pi^0$ events. Table X gives the branching ratios and cross-sections for different resonance productions in these two 4-body channels. A point worth noting about these figures is the dominant production of Ξ^* (1530) in the neutral state only. Table XI gives the values of the mass, width and fractional contribution of the Ξ^* (1530) after a Breit-Wigner resonance fitting process has been carried out with the 81 $\Xi^- \pi^+$ combinations from these channels. The corresponding values for K^* (888) are also given in this table.

The pure $I = 3/2$ system ($\Xi^- \pi^-$) in $\Xi^- K^+ \pi^+ \pi^-$ shows no particular mass enhancement.

Search for Ξ^* (1810):

Figure 8.15 is a Dalitz plot of $M_{\Xi \pi}^2$ vs. $M_{K\pi}^2$ selecting only the events in which the Ξ^* has a mass between 1500 Mev and 1550 Mev. The pion common to both axes is that one not included in the Ξ^* . There is no enhancement in the $3.1 - 3.4 \text{ (Gev)}^2$ region corresponding to the recently reported $\Xi^* \pi$ (1810 Mev).⁽⁶⁷⁻⁶⁸⁾ In the 3-body channels,

namely the $\Xi^- \pi^+ K^0$ and $\Xi^- K^+ \pi^0$ there is also no evidence of 1810 Mev in its $\Xi\pi$ decay mode, (figures 8.9a and 8.9b). To check for its $\Xi\pi\pi$ decay mode, the effective mass of $\Xi\pi\pi$ combinations from channels (a') and (b') are plotted in figure 8.15. Again there is no enhancement in the region of 1810 Mev. The shaded area corresponds to events containing K^* between 840 and 940 Mev.

A search for this resonance was also made in the $\Lambda K^0 \bar{K}^0$ and $\Lambda K^+ K^-$ channels. Figure 8.17 is the Dalitz plot for these reactions. Two points are plotted for each $\Lambda K^0 \bar{K}^0$ event both in the Dalitz plot and its projection. In the projection the shaded area corresponds to events where ϕ is produced with a mass of 1010 to 1030 Mev. There is no indication of the decay of 1810 via the $\Lambda \bar{K}$ mode.

We conclude therefore that $\Xi^* (1810)$ is not produced at our energy. The upper limit on the production of 1810 can be put as $1\mu\text{b}$. The production of yet another $\Xi^* (1705)^{(68)}$ is also not observed in our data. The upper limit on the production cross-section of this resonance in our data can be put as $1\mu\text{b}$.

Angular Distributions in 4 body channels:-

Figure 8.18 shows the centre of mass production angular distribution for the $\Xi^{*0,-}$ in the band 1500 $< M(\Xi\pi) < 1550$ Mev. The cross-hatched events correspond to the events containing K^* in the band between 840 Mev and 940 Mev. There is a slight indication of forward peaking when the Ξ^* is produced in association with a K^* . The bottom half of the picture shows the production angular distribution of the K^* in the region of 840 to 940 Mev. The shaded area correspond to the events containing a Ξ^* between 1500 and 1550 Mev. Again there is nothing striking about this distribution apart from the backward peaking of the K^* produced in association with the Ξ^* which has been described above.

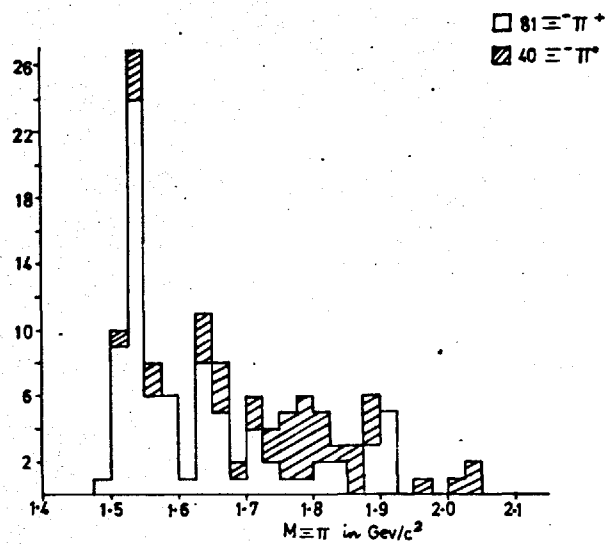
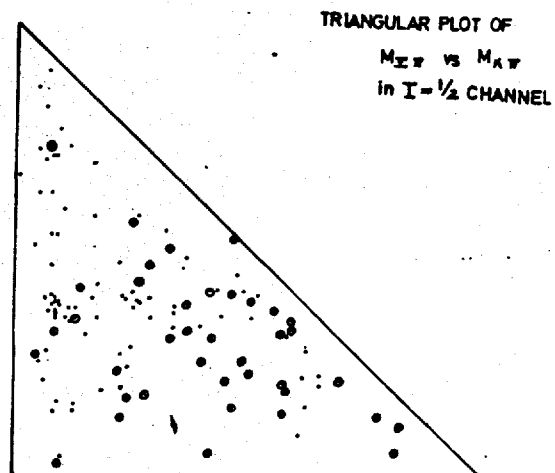
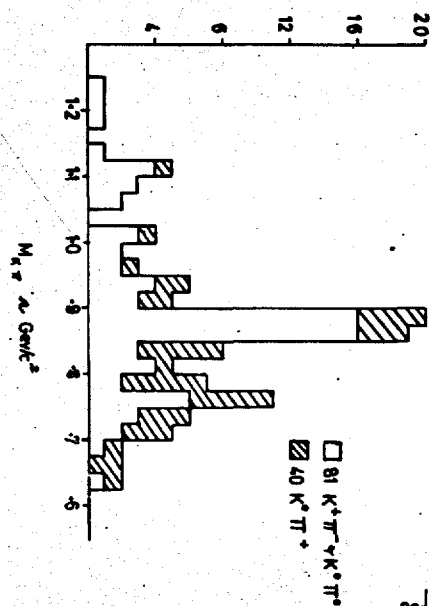
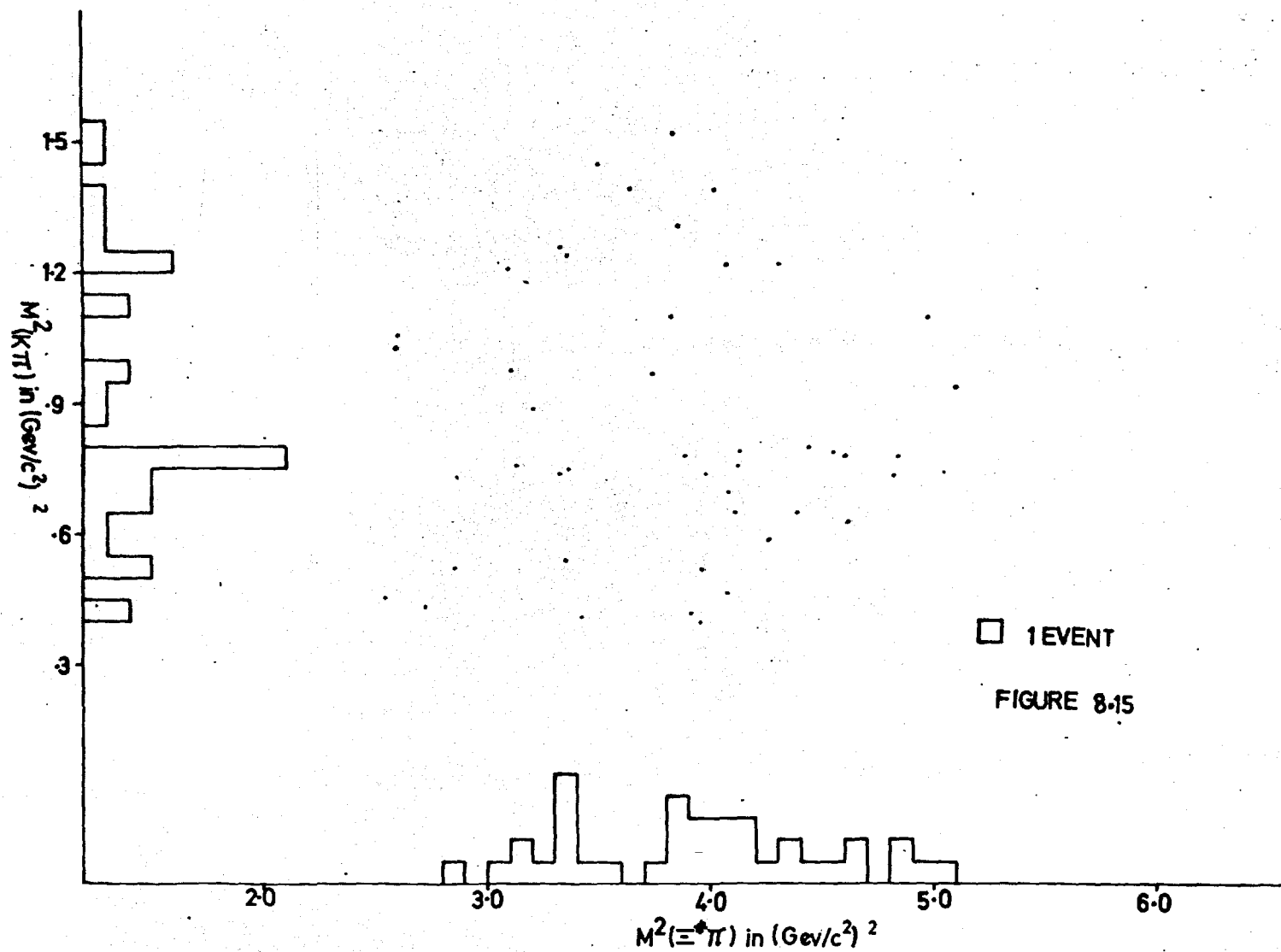


FIG 8-14



Effective Mass of $\Xi \pi \pi$ in 4 body channels

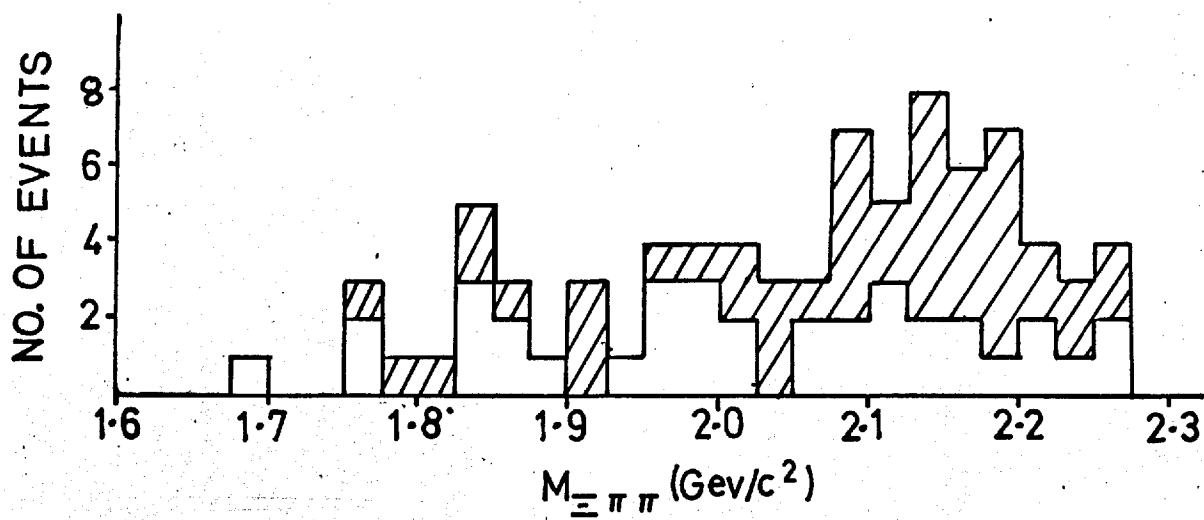
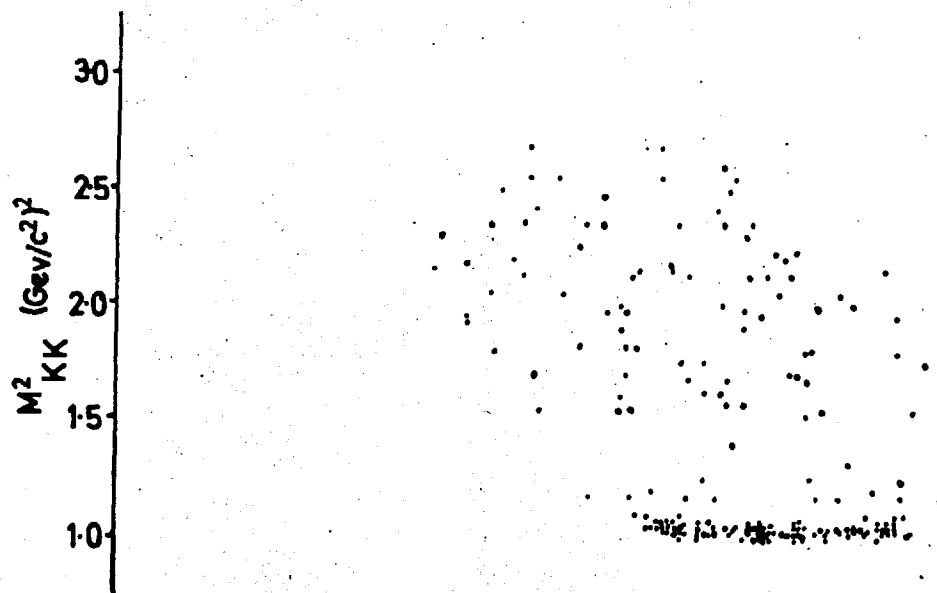


FIGURE 8.16



192EVENTS

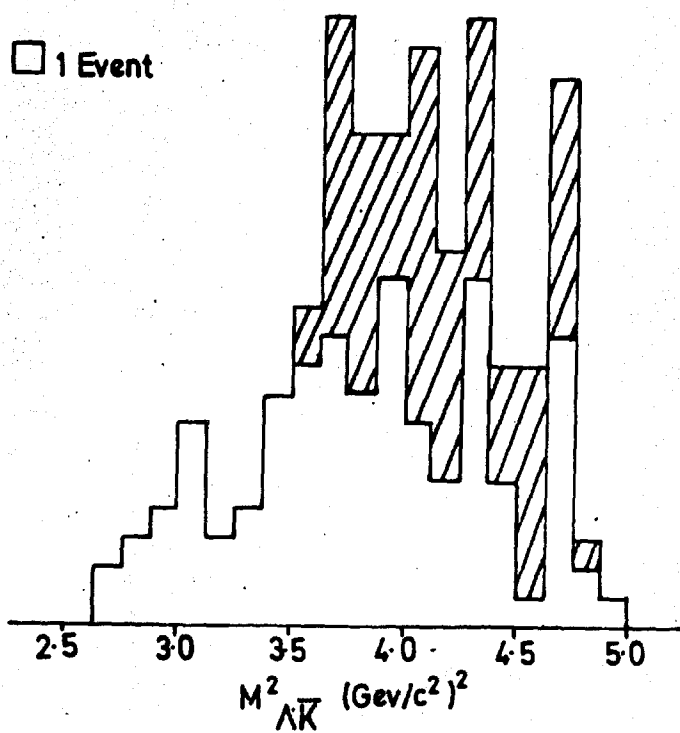


FIGURE 8-17

4-Body Centre of Mass Angular Distribution

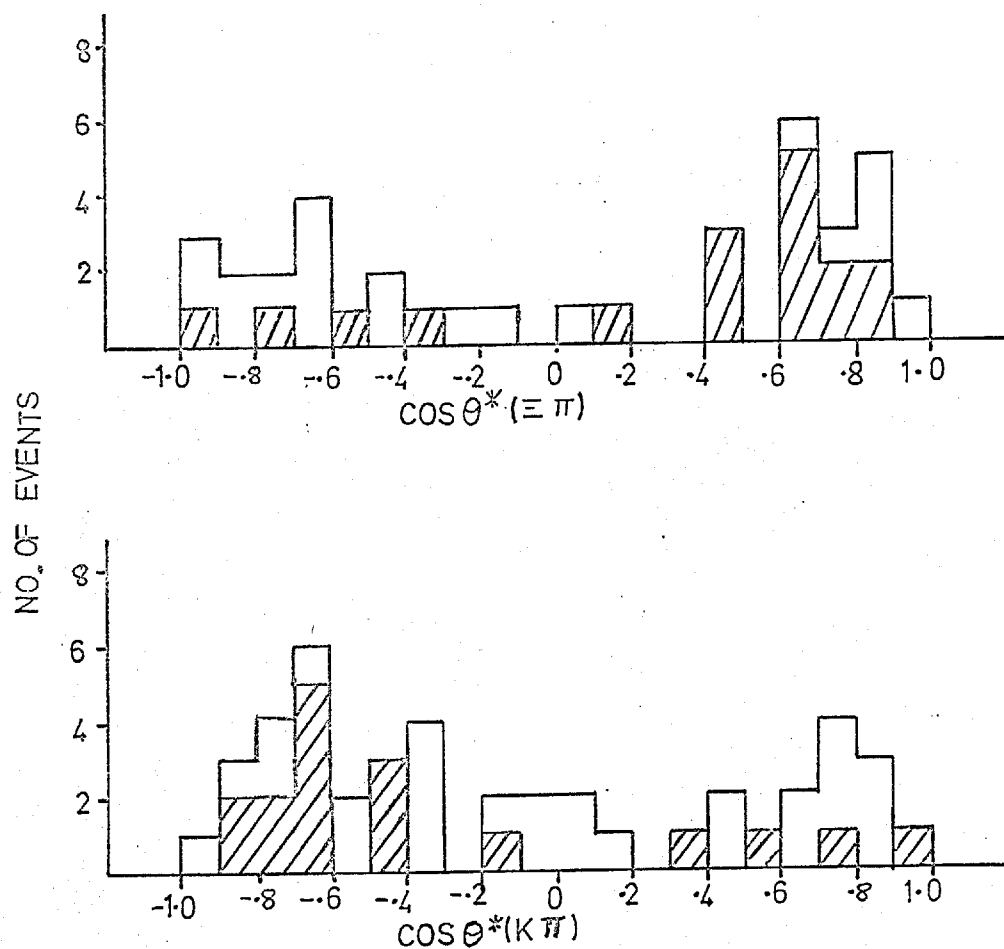
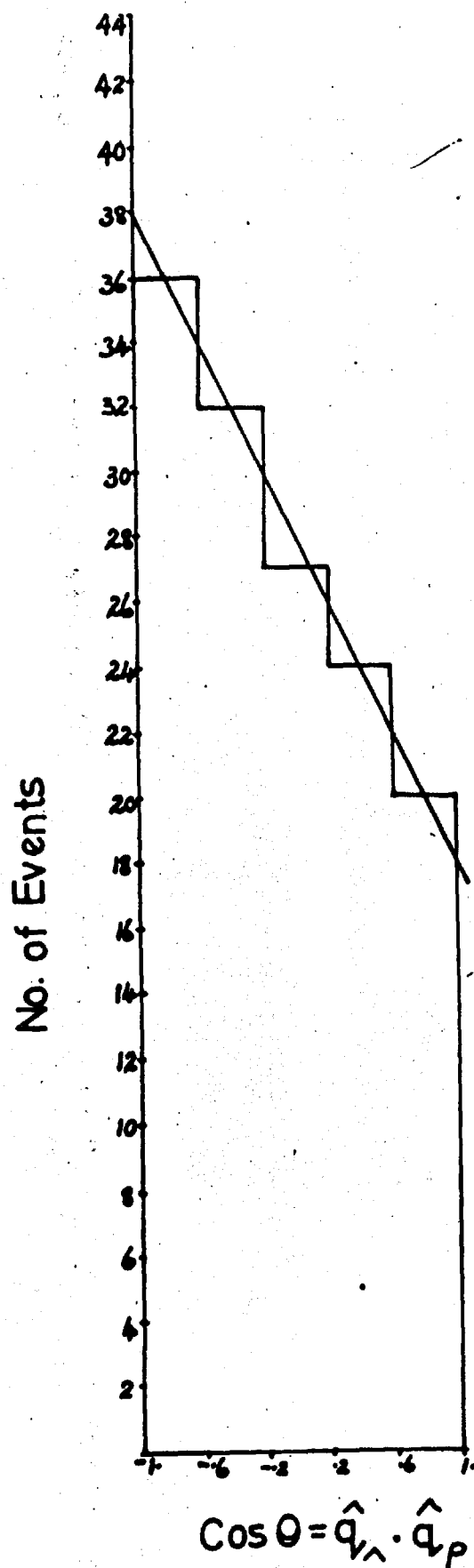
 $I=1/2$ systems

FIGURE 8.18



$$\mathcal{L} = d_{\Lambda} = -0.360 \pm 0.08$$

$$\mathcal{L}_{\Xi} = -0.58 \pm 0.15$$

139 Events

FIGURE 8-19

Section 8.8: Verification of the SU_3 predictions:

SU_3 predicts the following cross-section relation

$$(\pi^- P \rightarrow K^+ \Sigma^-) = (K^- P \rightarrow \Xi^- K^+) + (K^- P \rightarrow \Sigma^- \pi^+)$$

If we use the result for the $\pi^- P$ reaction at 3 GeV/c (72) and the $K^- P$ reaction at 3.5 GeV/c, we get

$$(15 \pm 5) = (9.4 \pm 3.2) + (11.0 \pm 3.0)$$

μb

If we assume that there is no abrupt change in the cross-section from 3 GeV/c to 3.5 GeV/c for the $\pi^- P$ interactions, the result given above is in agreement with the SU_3 prediction within errors.

Another SU_3 cross-section prediction is

$$(K^- P \rightarrow \pi^+ Y_1^{*-}) = (K^- P \rightarrow K^+ \Xi^{*-})$$

Both the cross-sections obtained at 3.5 GeV/c are less than $2\mu b$. SU_3 predicts that the cross-section for $\pi^- P \rightarrow K^+ Y_1^{*-}$ should also be equal to the above cross-section. The value obtained in 3 GeV/c $\pi^- P$ experiment is $11 \pm 5\mu b$. This is two standard deviations away from the above result.

The experimental angular distributions for the Σ^- and Ξ^- also show somewhat similar behaviour i.e. a forward peaking effect (see figures 7.1 and 8.10).

But if we take the $\Xi^- K^+ \pi^0$ and $\Sigma^- \pi^+ \pi^0$ channels the angular distribution of the Ξ^- and Σ^- look different (see figures 7.4 and 8.13). Ξ^- is still peaked forward whereas the Σ^- is peaking backward. As was explained in section 7.3 this backward peaking in the Σ^- distribution comes from the intermediate production of Y_0^* (1405). Ξ^- shows a very strong forward peaking when the $\Xi^- K^{*+}$ events are selected (see figure 8.13) but the $\Sigma^- \rho^+$ distribution looks almost flat (see figure 7.4a). The production of Ξ^{*-} in the 4 body Ξ^- channel is negligible, hence we can only compare the production angular distributions of Y_1^{*-} in $\Lambda \pi^+ \pi^- \pi^0$ (see figure 7.7) and that of $N_{3/2}^{*-}$ in $\bar{K}^0 \pi^+ \pi^- n$ (see figure 7.11). Y_1^{*-} distribution shows peaking in both the forward and backward directions while the $N_{3/2}^{*-}$ shows just a slight backward peaking. Hence we can draw the conclusion that the SU_3 predictions about cross-sections are obeyed within statistics whereas the experimental angular distributions are not always consistent with the theoretical prediction.

CHAPTER 9

DISCUSSION AND CONCLUSION

Section 9-1: Σ^+ channels, Y_1^* and $N_{3/2}^*$

$\Sigma^+ \pi^+$:

Figure 9.1 shows a plot of the total cross-section for $\Sigma^+ \pi^+$ production vs. the incident momentum. Though Σ^+ production is a dominant feature at low energies the cross-section falls rapidly with increasing incident momentum. This should be compared with the $\Sigma^+ \pi^-$ production cross-section (same figure) which does not fall so abruptly. The cross-section at 6 GeV/c⁽⁷⁷⁾ is a provisional figure. As was stated earlier this can be explained by a K^* exchange mechanism.

$\Sigma^+ \pi^+ \pi^0$, $\Sigma^+ \pi^+ \pi^+ \pi^-$ and $\Sigma^+ \pi^+ \pi^+ \pi^- \pi^0$

Table XII gives the cross-sections of these channels at different energies.

The mass and width of different resonances found in these channels tally quite well with those found at lower energies.

Y_1^{*-} (1385 Mev):

Though Y_1^{*-} production is the dominant feature of the three body channel $\Lambda^0 \pi^+ \pi^-$ up to an incident momentum of 1.5 Gev/c it becomes negligible at higher energies, see figure 9.2, where Y_1^{*+} production dominates indicating a K^* exchange. The dominance of the Y_1^{*-} production at low energies can be explained by a nucleon exchange in the t channel.

N^{*-} (1238 Mev):

The only indication of the production of N^{*-} is found in the $\bar{K}^0 \pi^+ \pi^- n$ final state. Again as in the other $\bar{K}^0$ channels the production of K^* (888 Mev) is the dominant feature. There is no evidence of a peripheral production of $N_{3/2}^{*-}$ in contrast with the peripheral mechanism in the production process of $N_{3/2}^{*+}$ in the $\bar{K}^0 p \pi^- \pi^0$ channel. This is not surprising in view of the negative charge of $N_{3/2}^{*-}$ which can only benefit from a nucleon exchange.

Section 9.2: Ξ^- Channels:

Ξ^- Mass:

Table XIII gives the mass of the Ξ^- determined in different bubble chamber experiments. The average value of Ξ^- mass from all these results is

$$M_{\Xi^-} = 1321.1 \pm 0.3 \text{ Mev}$$

The decay parameters of Ξ^- :

Table XIV gives the values of α_{Ξ^-} , β_{Ξ^-} , γ_{Ξ^-} and ϕ_{Ξ^-} found in different experiments. Our result only gives α_{Ξ^-} for reasons discussed earlier. Our value of α_{Ξ^-} agrees quite well with the average value of α_{Ξ^-} given by

$$\alpha_{\Xi^-} = -0.48 \pm 0.05$$

$\Xi^- K^+$:

Figure 9.3 shows the plot of total cross-section for $\Xi^- K^+$ production vs. incident momentum. The cross-section first rises from 1 GeV/c for the value of the incident momentum to a maximum at about 1.6 GeV/c, then it begins to fall. Figure 8.10 displays the most striking feature of $\Xi^- K^+$ production namely, the forward peaking of the Ξ^- .

$\Xi^{*-0} K^0$

The total cross-section is plotted against the beam momentum in the figure 9.4. Ξ^{*-} production cross-section is very small at our energy. There is a marked accumulation of events at high $\Xi\pi$ effective masses.

$\Xi^- K^0 \pi^0$:

The cross-sections of these channels are plotted against the beam momentum in figure 9.5. It rises from $P_K = 1.5$ GeV/c to a maximum at 2.1 GeV/c then falls slowly.

4 body Ξ^- channels:

Table XV gives the cross-sections of these channels at other energies. One would notice the slight increase in the cross-section as the incident beam energy increases. The dominant features at 3.5 GeV/c K^-P experiment are the Ξ^* (1530) and K^* (888) production. There is also some associated production of Ξ^* and K^* , see Table X.

Ξ^* (1600 MeV):

The 1600 MeV Ξ^* which according to Glashow and Rosenfeld⁽⁵³⁾ would be the doublet in the $3/2^-$ γ octet of the baryonic resonances was not found in the 3.5 GeV/c K^-P experiment. The upper limit on the cross-section of production of Ξ^* (1600) can be put as 2 μb . Two members of this octet (namely the Y_0^* (1520) and N^* (1512) which could be viewed as the "ground" (i.e. the lowest angular momentum) state of a different Regge trajectory have been found. The very low partial width for Ξ^* (1600) $\rightarrow \Xi\pi$ suggests that an alternative decay mode may predominate (such as $\Xi + \gamma$, $\Xi\pi\pi$ or ΛK). The spin parity of Y_0^* (1520) and N^* (1512) have been definitely established as $3/2^-$. Though some authors⁽⁵²⁾ favour a spin parity of $3/2^-$ for Y_1^* (1660), our data favours a positive parity [see section 7.3]. Hence, we do not agree with the assignment of the Y_1^* (1660) as the triplet in the $3/2^-$ octet. However, our result does not say anything about the spin of the Y_1^* (1660).

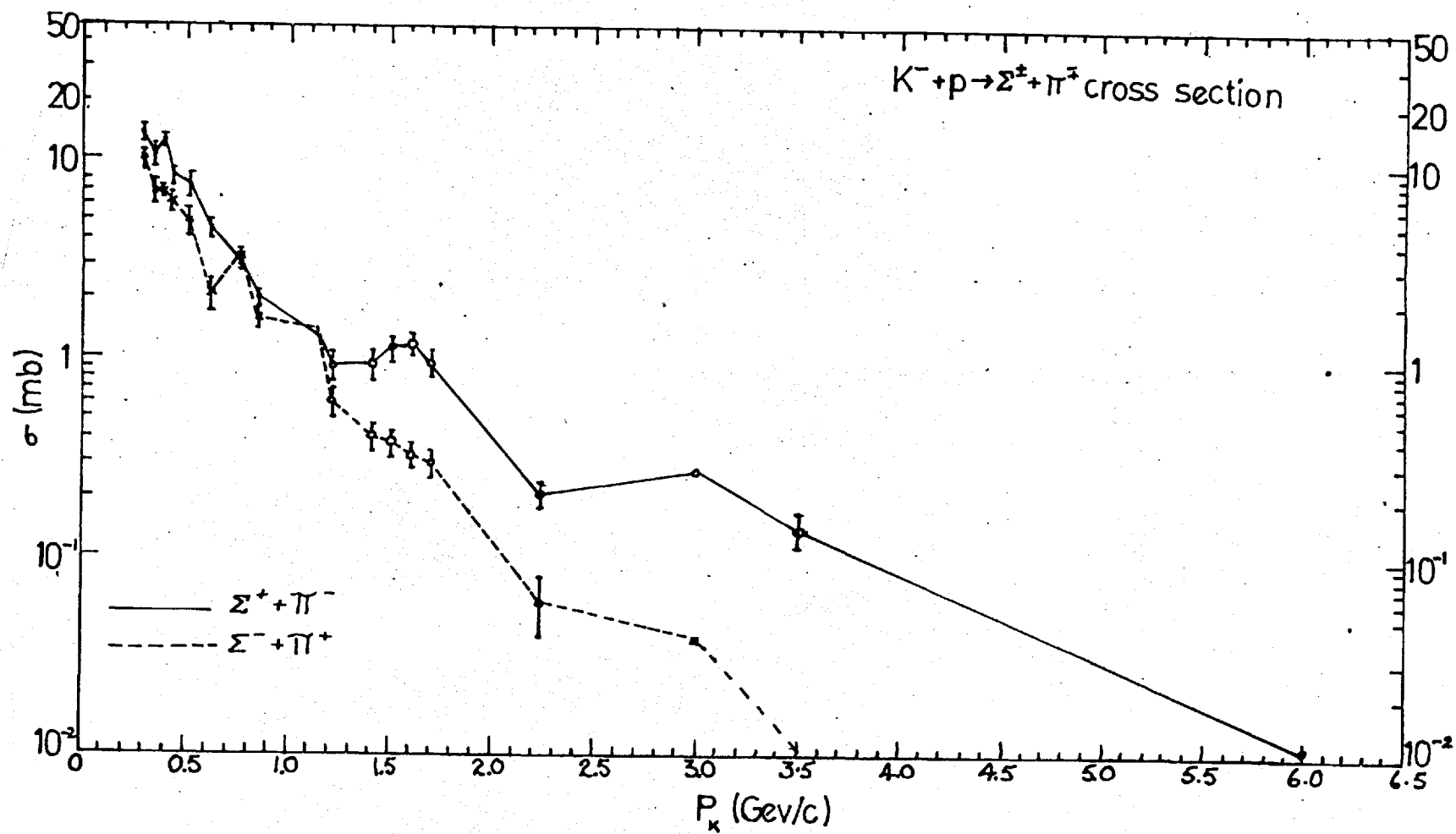


FIGURE 9.1

TABLE XII

Beam Momentum in GeV/c	$\Sigma^+ \pi^- \pi^0$	$\Sigma^- \pi^+ \pi^0$	$\Sigma^+ \pi^- \pi^+ \pi^-$	$\Sigma^- \pi^+ \pi^+ \pi^-$	$\Sigma^- \pi^+ \pi^- \pi^+ \pi^0$	$\Sigma^- \pi^+ \pi^+ \pi^- \pi^0$
	Cross-sections in mb					
2.24	0.67	0.49	0.15	0.18	0.09	0.06
1.47	1.2 ± 0.2	0.9 ± 0.2	0.2 ± 0.04	0.1 ± 0.04		
1.22	0.50 ± 0.04	0.45 ± 0.04	0.11 ± 0.2	0.08 ± 0.1		
1.51	0.93 ± 0.07	0.93 ± 0.07	0.25 ± 0.01	0.25 ± 0.01		
0.620	0.2 ± 0.13	0.4 ± 0.15				
0.762	0.7 ± 0.1	0.8 ± 0.1				
0.850	0.6 ± 0.1	0.7 ± 0.1				
3	0.37	0.24	0.24	0.21	0.18	0.18

$K^- + p \rightarrow Y^*(1385) + \pi$ Cross section

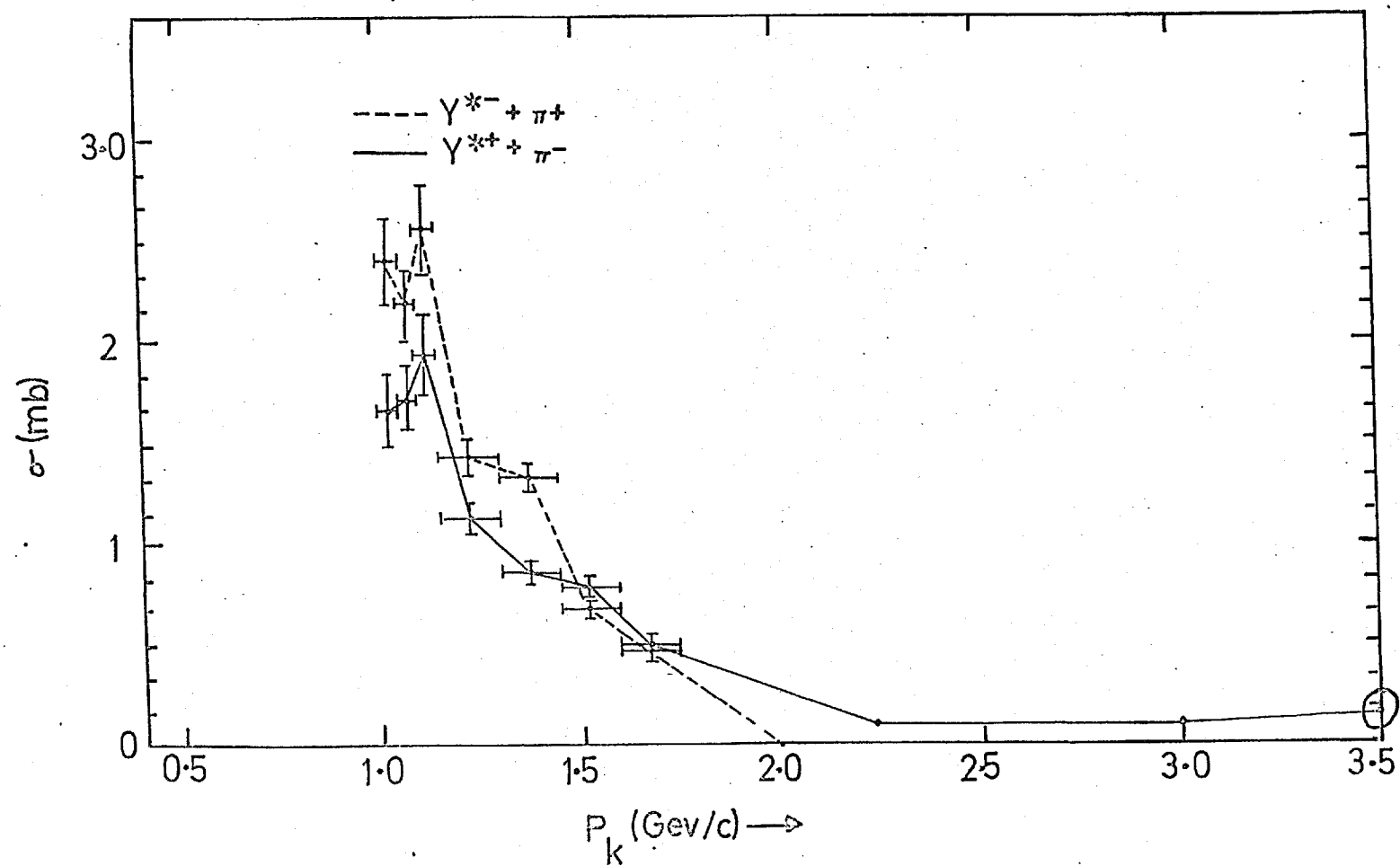


FIGURE 9.2

TABLE XIII

Laboratory	K^- beam momentum (Gev/c)	Mass of Ξ^- (Mev)
CERN	1.46	1321 ± 0.65
Ecole Polytechnique	1.45	1321.4 ± 0.6
Brookhaven	2.24	1321.0 ± 0.5
British Collaboration	3.5	1321.0 ± 0.2

TABLE XIV

Laboratory	Beam Momentum	α_{Ξ^-}	β_{Ξ^-}	γ_{Ξ^-}	ϕ_{Ξ^-}
CERN	1.46 GeV/c	-0.73 ± 0.21	0.44 ± 0.36	0.52 ± 0.44	$45^\circ \pm 30$
LRL	1.1 - 1.7 GeV/c	-0.41 ± 0.08	-0.08 ± 0.26	$0.91 \pm$	$-5^\circ \pm 15$
UCLA	1.80 + 1.95 GeV/c	-0.64 ± 0.13	0.65 ± 0.16	0.41 ± 0.28	$58^\circ \pm 24$
Ecole Polytech.	1.45 GeV/c	-0.44 ± 0.11	-0.24 ± 0.53	$+0.87 \pm 0.05$ 0.28	$-16^\circ \pm 37$
Brookhaven	2.24 GeV/c	-0.49 ± 0.16	-0.02 ± 0.22	0.87 ± 0.10	$-1^\circ \pm 15$
British Collab.	3.5 GeV/c	-0.58 ± 0.15			

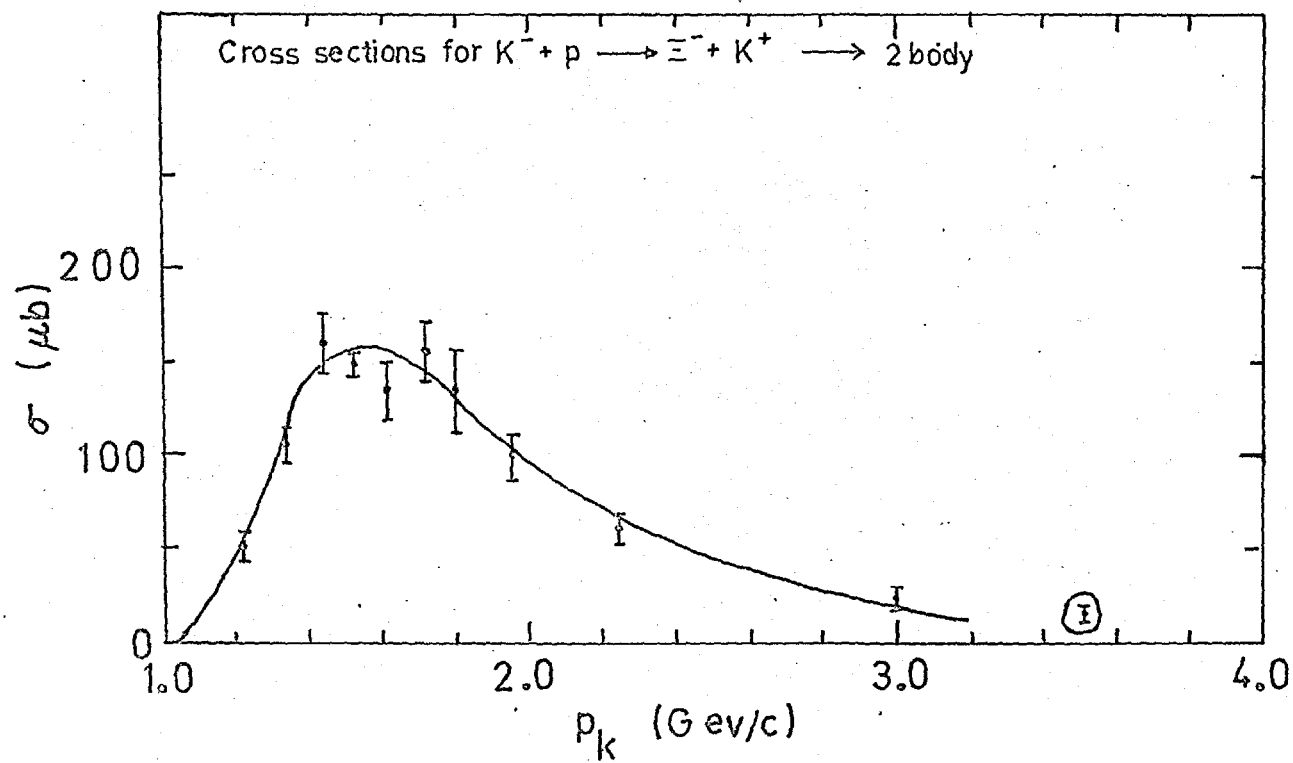


FIGURE 9.3

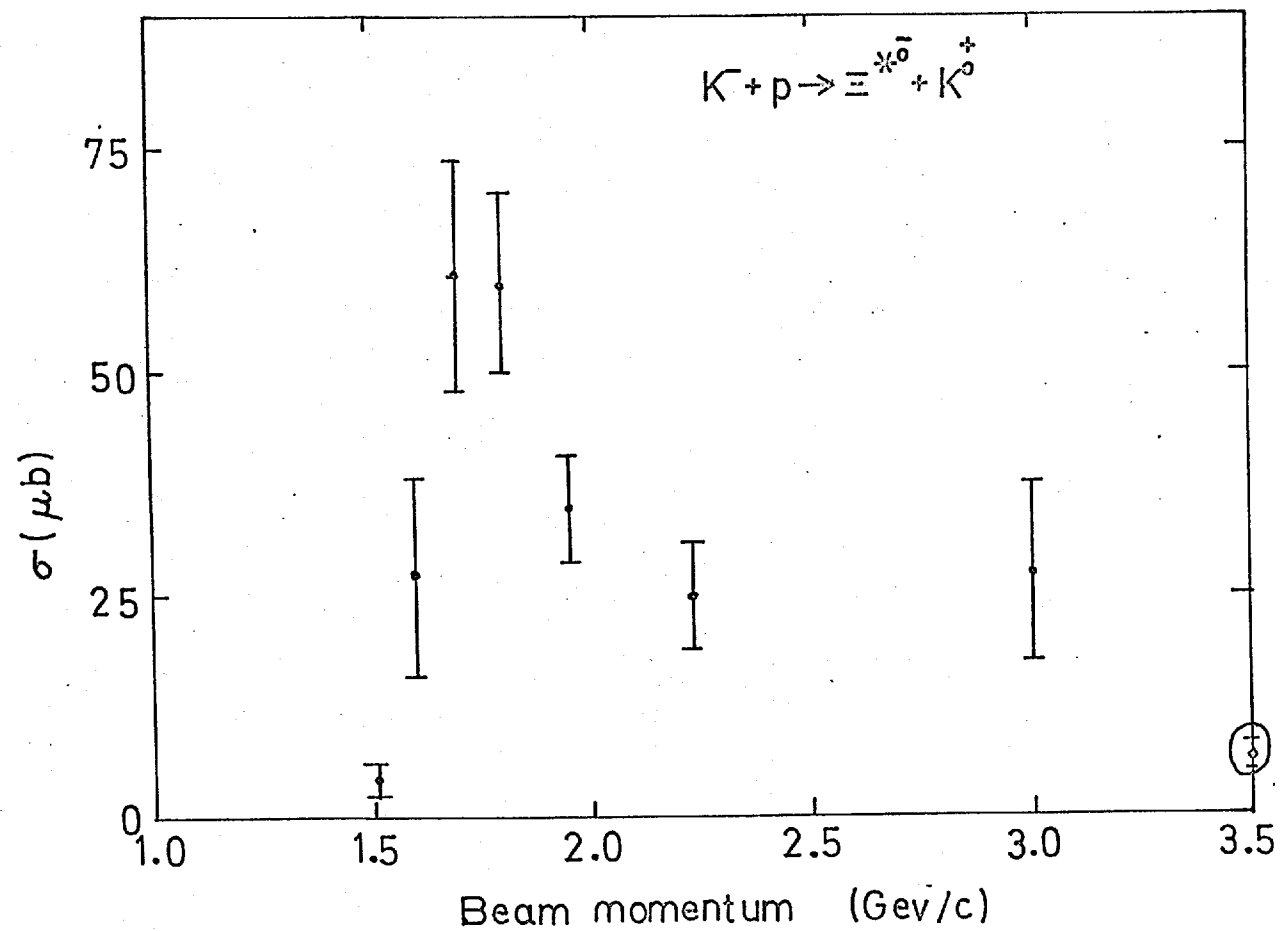


FIGURE 9.4

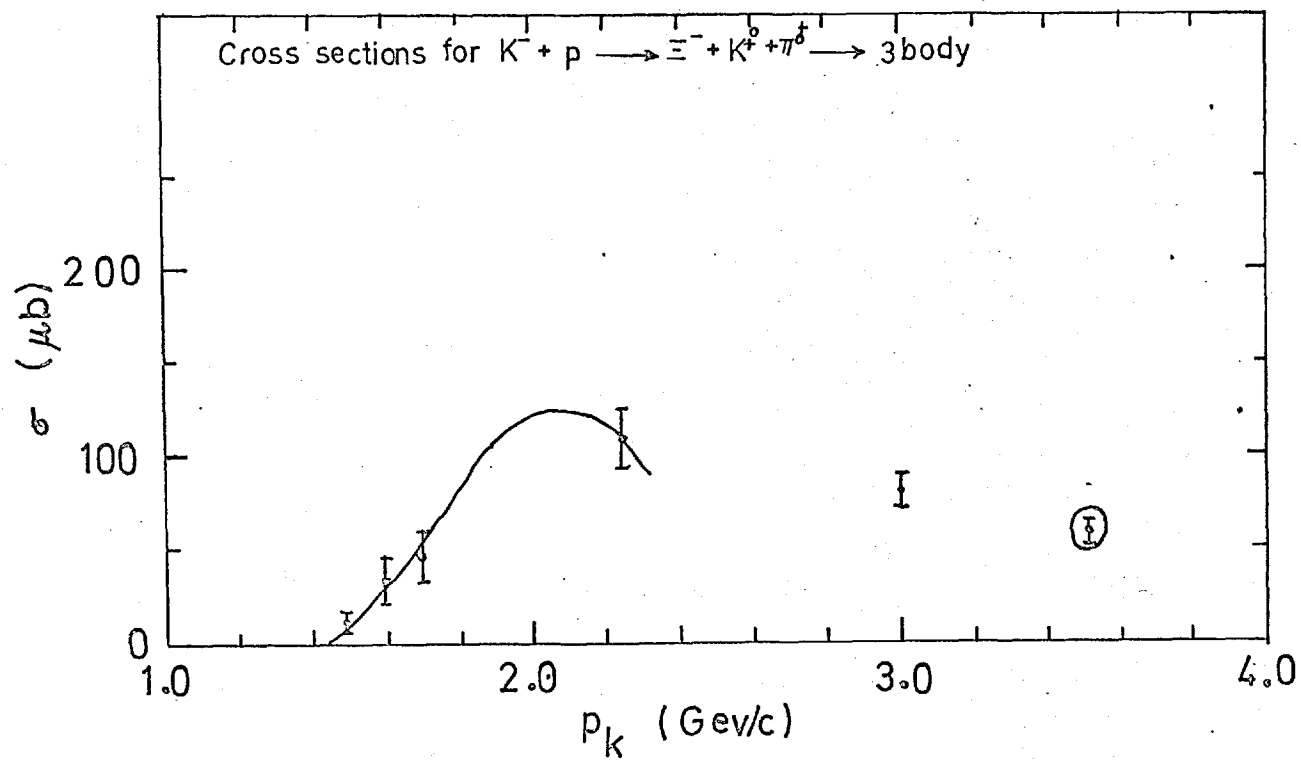


FIGURE 9.5

TABLE XV

Beam Momentum in GeV/c	$\Xi^- K^+ \pi^+ \pi^-$	$\Xi^- K^0 \pi^+ \pi^0$
	Cross-section in μb	
2.45 - 2.7	5.9	11.5
3.0	14 ± 4	14 ± 2
3.5	19.9 ± 4.1	36.9 ± 10.2

Ξ^* (1705) and Ξ^* (1810)

This experiment has shown no evidence for the existence of the Ξ^* (1705) and Ξ^* (1810). The upper limits of their production cross-section have been quoted before, (section 8.7). The $\bar{K}P$ experiment by the French-Dutch collaboration⁽⁷⁶⁾ at 3.0 GeV/c has observed the $\Lambda\bar{K}^0$ decay mode of the Ξ^* (1810). The best values of the parameters given for this resonance in their paper are

$$M = 1814 \pm 4 \text{ MeV}$$

$$\Gamma = 12 \pm 4 \text{ MeV}$$

The production cross-section quoted for the different possible decay modes of the Ξ^* (1810) are:

$$\Lambda\bar{K}^0 = 11 \pm 3 \mu\text{b};$$

$$\Xi^- \pi^+ = 1.5 \pm 1.5 \mu\text{b}$$

$$\Xi^- \pi^+ \pi^0 = 0.0 \pm 1.5 \mu\text{b}$$

These values should be compared with the values given by the Berkeley group.^(67,68) They are

$$M = 1817 \pm 7 \text{ MeV}$$

$$\Gamma = 60 \text{ MeV}$$

and for the cross-section,

$$\Lambda \bar{K}^0 \pi^+ = 11.4 \pm 2.6 \mu\text{b}$$

$$\Xi^- \pi^+ = 10.8 \pm 2.7 \mu\text{b}$$

$$\Xi^- \pi^+ \pi^0 > 1.1 \mu\text{b}$$

$$\Xi^{*-} (1530) \pi^0 = 3.0 \pm 1.5 \mu\text{b}$$

The results for the $\Lambda \bar{K}^0$ and $\Xi^- \pi^+ \pi^0$ modes for the two groups are in agreement. There is some disagreement on the $\Xi \pi$ mode, where the Berkeley group finds a larger branching ratio. Also in the French result, the $\Lambda \bar{K}^0$ effective mass does not show any enhancement in this region in contrast with the Berkeley result. These discrepancies make the existence of the $\Xi^{*-} (1810)$ quite doubtful.

$\Xi^{*-} (1970 \text{ Mev})$:

Because the first Regge recurrences of some members of the $\frac{1}{2}^+$ octet and $3/2^+$ doublet have already been seen, one predicts the existence of a $\Xi \pi$ resonance at a mass of ~ 1970 with $J^P = 5/2^+$. This can be included in the octet containing $Y_0^* (1815)$, $N^* (1688)$ and $Y_1^* (188?)$.⁽⁵³⁾ The $K^- p$ experiment at 3 GeV/c⁽⁷⁶⁾ has observed a bump at this region in the distribution of $\Xi^- \pi^+$ effective mass from

$\Xi^- \pi^+ K^0$ events. The best estimates of the parameters of this resonance that they give are

$$M = 1933 \pm 16 \text{ Mev}$$

$$\Gamma = 140 \pm 35 \text{ Mev}$$

In our data we get a slight bump at $2050 \text{ Mev}/c^2$ (see the $\Xi^- \pi^0$ mass distribution in $\Xi^- K^+ \pi^0$ channel in figure 8.9b). Also in the $\Xi^- \pi^+$ mass distribution we notice a concentration of events in the higher mass values of the $\Xi^- \pi^+$ combination. These might be the indications of the production of the Ξ^* (1933) considering the finite width of the resonance.

Section 9.3: Ω^- production:-

All the film was searched for the evidence of the production of Ω^- and its subsequent decay. But no event which could be interpreted as the production and decay of Ω^- was found. The upper limit on the cross-section of Ω^- production in 3.5 GeV/c K⁻P interactions can be put as $1\mu\text{b}$ with 90% confidence.

So far, only a few examples of Ω^- production have been observed. Therefore the Ω^- spin is still left to be determined. (of course, if we believe in SU₃ it must have a spin parity of $3/2^+$). A measurement of its parity would be more difficult. The Ω^- has a parity non conserving weak decay so the decay cannot be used for parity determination. Therefore one has to design a strong interaction experiment whence the parity can be determined. But in the meantime we hope that the statistics on Ω^- production will improve and a spin determination can be made. If the spin is found to be $3/2$ there will be very little doubt about the fact that it has a positive parity.

To summarise all the results presented in the thesis we conclude:

In two and three body final states Σ^+ and Y_1^{*+} productions dominate over those of Σ^- and Y_1^{*-} indicating a possible K^{*} exchange. The negative hyperon production in the above cases might be mediated through a baryon exchange.

The angular distributions for the negative and positive cases are very different. In higher multiplicity final states we get an almost equal amount of negative and positive Σ 's and Y_1^* 's. They also show similar angular distributions.

The masses and widths of different resonances found in our data are consistent with the accepted values. A positive parity for the Y_1^* (1660) has been suggested.

Within errors SU_3 predictions about cross-sections for different multiplets in the $U = \frac{1}{2}$ doublet and $U = 3/2$ quartet are consistent with the experimental results. However, though SU_3 predictions about angular correlations are obeyed in two body Σ^- and Ξ^- cases, they are violated in the three body channels and also in the angular distribution of Y_1^{*-} and $N_{3/2}^{*-}$ in the four body final states.

The production of Ξ^- is most probably mediated via a hyperon exchange. We have determined the value of the Ξ^- mass and its decay parameter α_{Ξ^-} . They are in excellent agreement with the accepted values. ⁽⁷⁵⁾ The cross-section for neutral Ξ^* production is larger than for charged Ξ^* in both the three and four body channels. Ξ^* production cross-section is much higher in four body final state than that in the three body. K^* is also produced strongly in three and four body channels. The masses and widths of Ξ^* and K^* from our data agree well with the accepted values.

We have not seen an example of Ω^- production. The upper limit on its production can be put as $1 \mu b$.

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FIGURE CAPTIONS

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- Fig. 8.19 Distribution of $\cos \theta$, where

$$\cos \theta = \hat{q}_\Lambda \cdot \hat{q}_p$$

$\hat{q}_\Lambda$ is the direction of Λ in the rest frame of Ξ^- and $\hat{q}_p$ is the direction of the proton in the rest system of Λ .

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