

A thesis entitled

THE CHARGE EXCHANGE $K^- + p \rightarrow \bar{K}^0 + n$ AT 9.5 GeV/c

by

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ABSTRACT

This thesis is a report of an experiment performed on the charge exchange interaction

$$K^- + p \rightarrow \bar{K}^0 + n \text{ at } 9.5 \text{ GeV}/c.$$

This experiment was one of the first in which a large magnetic spark chamber was used. Part of the first chapter is a brief review of the principle types of apparatus used in High Energy Nuclear Physics, concentrating on their application to the study of strong interactions in order to show the advantages of a magnetic spark chamber. The rest of the chapter is devoted to a discussion of the charge exchange interaction and of its relation to elastic scattering. The second chapter contains a description of the apparatus used in the experiment, this being continued in Chapter 3 where the target and anticoincidence system are described and their properties discussed. Chapter 4 is an account of the scanning, measurement and analysis of the photographs taken during the experiment, concentrating on the particular problems of spatial reconstruction in the magnetic spark chamber. The determination of the total and differential cross sections for K^-p charge exchange is described in Chapter 5. The final chapter compares the results with those obtained in other experiments on charge exchange and with the predictions of some theoretical models.

PREFACE

I joined the High Energy Nuclear Physics Group at Imperial College in October 1960 and spent two years under the supervision of Mr. N.C. Barford assisting with the construction of a liquid hydrogen bubble chamber.

From October 1962 onwards I worked under the supervision of Dr. J.P. Astbury at CERN as a member of the CERN/ETH (Zurich) group. During the first few months I took part in the last of a series of experiments performed with a cloud chamber. A report of this experiment on the branching ratios of K_2^0 decays has been published in Physics Letters.

The cloud chamber was then dismantled and its magnet used for a large magnetic spark chamber designed for experiments on various π^- , K^- and $\bar{p}$ interactions in the momentum range 5 to 12 GeV/c. Having assisted with the initial design on these experiments, I was subsequently responsible for the design and development of the hydrogen target and associated counters used in the experiments. Early in 1964 the first experiment was performed on 10 GeV/c π^- , K^- and $\bar{p}$ interactions in which no charged particles or gamma rays were produced. I assisted with the preliminary testing of the apparatus and with the actual running of these experiments. I was then responsible for the final analysis of the K^- interactions. Preliminary results on the K^-p charge exchange cross section were reported at the Dubna Conference in 1964. Final results were published in Physics Letters in May 1965.

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Chapter 1. INTRODUCTION

1.1. Apparatus used in High Energy Nuclear Physics

The development of High Energy Nuclear Physics during the past ten years has been made possible by the construction of large, high intensity particle accelerators and the development of many new means of detecting high energy particles. A review of the principle types of detectors in current use can be found in reference ⁽¹⁾.

The variety of the apparatus used illustrates that no single technique can be used to perform all high energy experiments. This is because high energy interactions have a wide range of cross sections and vary greatly in complexity.

The majority of experiments performed can be roughly classified according to the type of apparatus used, as bubble chamber, counter or spark chamber experiments.

Use of bubble chambers

Since the discovery of the π^0 in 1959⁽²⁾, almost all the experiments in which new particles or resonances have been dis-

covered have been performed using bubble chambers. This is because all interactions taking place in the sensitive volume of the chamber are photographed. Thus even previously unknown interactions are recorded and can be accurately reconstructed as the spatial resolution of bubble chambers is high (of the order of 0.1 mm). A typical experiment performed using a large hydrogen bubble chamber produces of the order of 2×10^5 photographs taken in about two weeks. The number of beam tracks is limited to about 10 to 20 per photograph. There is on average one interaction per picture and during the experiment approximately 10^4 examples of an interaction are recorded per millibarn cross section.

The time needed to scan, measure and analyse bubble chamber photographs means that the above number of photographs cannot be greatly exceeded in a single experiment. A bubble chamber is therefore not a suitable instrument for an experiment in which the required number of events per millibarn cross section is much greater than the value quoted above.

Use of counters

If this is the case some selection of the events to be recorded must be made during the experiment. This cannot be done using bubble chambers as they are made sensitive before the interactions take place. The high time resolution of scintillation and Cerenkov counters permit electronic selection of required

events, even when the flux of particles through the apparatus is very high, an instantaneous flux of 10^6 particles/second being quite common. The selection is limited to interactions which can be represented by signals from a counter array and the measurements made must be simple and well defined. Thus counters can best be used in 'missing mass' or elastic scattering experiments where measurements of the momentum and direction of the incident particle and one outgoing particle are sufficient. Although the spatial resolution of counters is poor, this can be compensated by using long counter telescopes to maintain a reasonable angular resolution. This, however, causes a reduction in the solid angle of acceptance of the apparatus.

Some of the most advanced counter experiments performed to date are those of Lindenbaum et al⁽³⁾ using a counter hodoscope system in a series of high energy elastic scattering experiments. Each event was recorded in digital form and fed directly into a computer on line so that preliminary results were available during the actual running time of the experiments.

The data handling system limited the number of recorded events to 32 per machine pulse, i.e. 50,000 events per hour. By extending the memory capacity of the data system up to 10^6 events per hour could be recorded in suitable conditions.

Use of spark chambers

Spark chambers were first used at an accelerator by Cork and Cronin in 1959 and the name 'Spark Chamber' now refers to a wide range of devices in which charged particle tracks are detected by some form of localised gaseous discharge initiated by a pulsed electric field. An account of the properties of most existing spark chambers can be found in reference⁽⁴⁾.

The most widely used form of spark chamber consists of a number of thin parallel plates approximately 1 cm apart, the space between them being filled with a mixture of inert gases. If a high voltage pulse is applied to alternate plates within the order of 10^{-6} seconds the ionisation left in the gas by the passage of a charged particle causes sparks between the plates and along the line of the track.

The high voltage pulse is triggered by signals from a scintillation counter array so that the time resolution of a counter system can be used to select the recorded events. If the flux of particles through a spark chamber is high, unwanted tracks may be recorded as the sensitive time is of the order of 10^{-6} to 10^{-7} seconds.

The ultimate rate at which tracks can be recorded is limited by the time taken to disperse the ionisation after sparking which is of the order of 10^{-3} seconds. A more stringent

limitation is always the time taken to record the spark position, in particular to move on film if the chambers are photographed.

The spatial resolution is of the order of 0.2 to 0.5 mm parallel to the plates and is equal to the distance between the centres of adjacent sparks in the direction perpendicular to the plates. Bleuler et al⁽⁵⁾ have described several experiments which have features common to many experiments performed using this type of chamber. Spark chambers spaced by some distance were used to sample tracks at several points in order to obtain good angular resolution. Momentum measurements were made using bending magnets between the chambers and Cerenkov counters were used to identify the particles. Stereo views of all chambers were brought together on one film using mirrors in order to simplify scanning and measurement.

The greater simplicity of spark chamber pictures has made the application of automatic measuring techniques easier than for bubble chambers and many groups have developed automatic scanning and measuring devices (for example Anders et al⁽⁶⁾).

A logical extension of automatic measurement is the replacement of the photographic camera by a vidicon camera, the output of which can be stored on magnetic tape or be directly processed by an on line computer. Several systems of this type are being developed⁽⁷⁾.

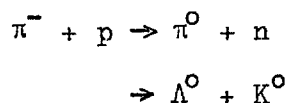
The acoustic waves generated by sparks can be used to give a digital record of the spark coordinates. An example of the use of acoustic chambers is the experiment of Cocconi et al⁽⁸⁾. They used a spark chamber hodoscope to study small angle elastic scattering. The sparks followed the line of the tracks within ± 0.3 mm and an angular resolution of ± 0.1 mrad was obtained. The momentum resolution was 0.2% at 20 GeV/c and the apparatus could record up to 12 events per pulse. These were checked by a small on line computer. As in most acoustic chambers only one spark per gap could be recorded.

Wire chambers being developed⁽⁹⁾ should be able to record up to 30 events per pulse which can be analysed on line. Their spatial resolution is of the order of 1 mm and they can record several tracks simultaneously.

1.2. Magnetic spark chambers

All of the above types of spark chambers can be used to detect interactions at a higher rate than bubble chambers but are limited in application to relatively simple interactions. The first spark chamber used which could record more complex interactions was that of Roberts et al⁽¹⁰⁾. Their apparatus consisted of a large spark chamber mounted in a magnetic field. The magnet used had a field of 15.5 Kgauss and a useful volume of

110 x 70 x 30 cm³. It was filled with a thin foil aluminium plate spark chamber with lead gamma ray converters inserted at intervals. Interactions of the type



were observed, a solid target being used. The spark chamber was triggered by a wide angle counter hodoscope when no charged particles emerged from the target but a V^0 decay or gamma ray conversion took place inside the spark chamber.

Thus although the trigger specified a certain class of events it allowed a considerable variation in their geometrical configuration. As the whole chamber was inside a magnetic field, momentum measurements were possible and a kinematic reconstruction could be made as in a bubble chamber.

Previous experiments on associated production had been performed only in bubble chambers and cloud chambers. This experiment demonstrated that a spark chamber could record such complex events. Although the above spark chamber was less precise than a bubble chamber of comparable size, it had the advantages of being counter controlled and able to operate in intense beams. It could therefore be used in experiments on interactions which were too rare to be investigated in bubble chambers and too complex to be uniquely identified in the normal type of spark chamber.

The CERN magnetic spark chamber

It was decided to construct a magnetic spark chamber at CERN similar to the one described above. The magnet available was somewhat larger than the one used above having a volume of $2 \times 1 \times 1$ cubic metres, with a field of 10.5 Kgauss.

The first experiments were performed on high energy interactions for which this apparatus seemed particularly suited.

In high energy interactions a large fraction of the secondary particles are concentrated in a narrow forward cone. In a simple parallel plate spark chamber these would all be almost normally incident on the plates so that best use was made of the anisotropic spatial resolution of the chamber. In these conditions the estimated momentum resolution for tracks 1 metre long was

$$\Delta P/P = P/P_0 \quad \dots 1.1$$

where $P_0 = 100 \text{ GeV}/c$. This was somewhat less than the corresponding figure for bubble chambers, but the use of an external target meant that much longer tracks could be measured than in a bubble chamber of comparable size and this would more than compensate for the inferior spatial resolution.

High energy bubble chamber experiments had been restricted to p and π beams because of the lack of high momentum separated beams of K mesons and antiprotons. Cerenkov counters could be

used with a magnetic spark chamber to identify particles in an unseparated beam so that high energy experiments could be performed to study K and $\bar{p}$ interactions.

Using known beam parameters and the estimated sensitive time of the chamber it was calculated that 10^3 events/hour/millibarn could be produced by K^- in an external target. The rate at which events could be observed would be less than this, depending on the nature of the interactions and on the efficiency of the triggering system.

1.3. Choice of experiment

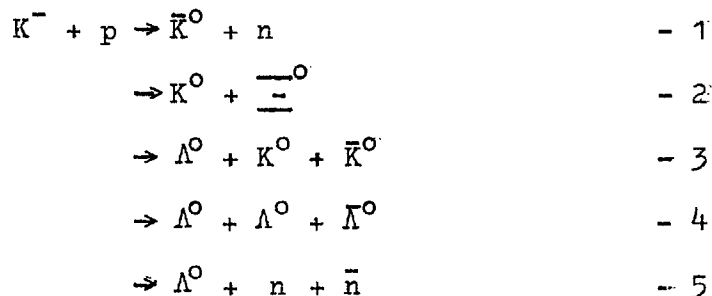
One of the established features of high energy p-p and π -p scattering in the above energy range was the large contribution of multiple meson production to the total cross section. This could be interpreted as the result of interactions in the meson cloud surrounding the nucleon. By studying interactions in which no pions were produced, it was hoped to obtain information on more fundamental interactions with the nucleon core.

The simplest way to eliminate interactions which had pions in the final state was to surround the target with an anticoincidence shield which could detect all charged particles and gamma rays.

Observed K^- interactions would be those which contained only neutral baryons and neutral K mesons in the final state.

Interactions in which a Σ^0 was produced would not be observed because of its rapid decay.

The K^- interactions which could be accepted by the trigger were therefore



These interactions could be detected by observing the charged decays of the unstable particles inside the spark chambers. Only charged K_1^0 decays of the K mesons could be observed as the K_2^0 decay length at high energies was much greater than the chamber dimensions.

The rate at which the above interactions could be observed depended on the detection efficiency of the apparatus for each interaction and on the total and differential cross sections. Little information on these was available when the experiment was designed. The measured cross section for reaction 3 was 70 microbarns at 2.24 GeV/c⁽¹¹⁾ and that for charge exchange in the range 1.5 to 4 GeV/c was of the order of millibarns⁽¹²⁾. The expected cross section for charge exchange at higher energies was considerably lower than this but it was expected to make up most of the

observed interactions as it could be most efficiently detected.

1.4. Theoretical interest of charge exchange

Relation between charge exchange and elastic scattering

The scattering amplitudes for the three interactions

$$K^- + p \rightarrow K^- + p$$

$$\rightarrow \bar{K}^0 + n$$

$$K^- + n \rightarrow K^- + n$$

are related by I spin conservation. If $A(0)$ and $A(1)$ are the scattering amplitudes of the $\bar{K}N$ system in the $I = 0$ and $I = 1$ channels then the three amplitudes can be written

$$A_{K^-p} = \frac{1}{2}A(0) + \frac{1}{2}A(1) \quad \dots 1.2$$

$$A_{\bar{K}^0n} = \frac{1}{2}A(1) - \frac{1}{2}A(0) \quad \dots 1.3$$

$$A_{K^-n} = A(1) \quad \dots 1.4$$

so that

$$A_{\bar{K}^0n} = A_{K^-n} - A_{K^-p} \quad \dots 1.5$$

The above equation 1.2 applies only within the limits of I spin conservation and so does not include electromagnetic effects. The imaginary parts of the forward elastic scattering amplitudes are related to the respective total cross sections by the Optical Theorem.

$$\text{Im}(A_{t=0}) = \frac{k}{4\pi} \sigma_T \quad \dots 1.6$$

The forward differential cross section for charge exchange obtained by combining 1.5 and 1.6 is

$$\frac{d\sigma}{dt}_{t=0} = \frac{1}{16\pi} (\sigma_T(K^-n) - \sigma_T(K^-p))^2 + (\text{Re}(A_{K^-n} - A_{K^-p})_{t=0})^2 \dots 1.7$$

where t is the momentum transfer. An equation of the same form relates $\frac{d\sigma}{dt}$ for π^-p charge exchange to the corresponding π^-p and π^+p parameters.

The above equations show the close relation of charge exchange to K^- nucleon elastic scattering. Being related to the difference in amplitudes of the two processes it might be expected to reflect fine structure effects in elastic scattering.

Theoretical models for elastic scattering

High energy elastic scattering was interpreted in terms of two models, the optical model and the Regge pole model. The optical model related the elastic scattering process to inelastic interactions which were known to predominate at high energies. Approximating the effect of the inelastic interactions to that of an absorbing disc, the elastic differential cross section was

$$\frac{d\sigma}{dt} = \left(\frac{d\sigma}{dt}\right)_{t=0} e^{(\frac{R}{2})^2 t} \dots 1.8$$

where R is the radius of the disc and t the momentum transfer. The scattering amplitude in this approximation is purely imaginary and R is related to the total cross section which would tend to

a constant value at high energies. The form of the differential elastic cross section was therefore predicted to be independent of energy.

The Regge pole model was based on the assumption that the scattering amplitude for elastic scattering was related to poles in the complex angular momentum plane. Each pole was characterised by a set of quantum numbers, isotopic spin, hypercharge etc. and its position varied with energy along a certain trajectory. ~~Bose~~ ~~Physical~~ particles and resonances were associated with points on the trajectories where the real component of the complex angular momentum had alternate integer values.

The Regge pole model was similar to the optical model in that it predicted exponential variation of the differential cross section with t , but it also predicted that the width should shrink with increasing energy. Elastic scattering was assumed to be dominated by the Pomeron trajectory which has quantum numbers I spin = 0, baryon number 0, parity and G parity both positive.

Exchange models for charge exchange scattering

In this section the quantum numbers are given of particles which can contribute to the scattering amplitude for charge exchange if a one particle exchange model is assumed. The conclusions also apply to the trajectories which can contribute to a Regge pole model.

If the mechanism of the three charge exchange interactions

$$\begin{array}{ll} n + p \rightarrow p + n & \dots 1.9 \\ \pi^- + p \rightarrow \pi^0 + n & \dots 1.10 \\ K^- + p \rightarrow \bar{K}^0 + n & \dots 1.11 \end{array}$$

is assumed to be a one particle exchange, then for small momentum transfer the exchanged particle has charge 1 and baryon number and strangeness both zero. The isotopic spin is therefore integer and greater than zero. Only $I = 1$ exchange will be considered.

For the first interaction the exchanged particle can have all combinations of integer angular momentum J and parity P as all particles have spin $\frac{1}{2}$. Consequently both the π and ρ can be exchanged. As the π and $\bar{K}$ both have spin 0, the spin parity of the exchanged particle for K^- and π^- charge exchange is restricted to the series 0^+ , 1^- , 2^+ ... excluding π exchange. Lee and Yang have shown⁽¹³⁾ that a two pion system has positive^G_A parity so that for π^-p charge exchange the ρ has the only permitted IPG quantum numbers $1-+$. This restriction does not apply to the K^-p charge exchange and a $1+-$ particle could also be exchanged. However, no particle with these quantum numbers had been discovered when the experiment was planned so that the mechanisms of π^-p and K^-p charge exchange were expected to be similar.

Conclusions

Measurement of K^-p charge exchange differential cross section was of interest as it could indicate the nature of the difference between K^-p and K^-n elastic scattering interactions. It would also provide a test of one particle exchange models as the ρ was the only known particle which could be exchanged. This restriction made it also a good test of a Regge pole model and it was possible that information could be obtained about the ρ trajectory.

Chapter 2. DESCRIPTION OF EXPERIMENTAL APPARATUS

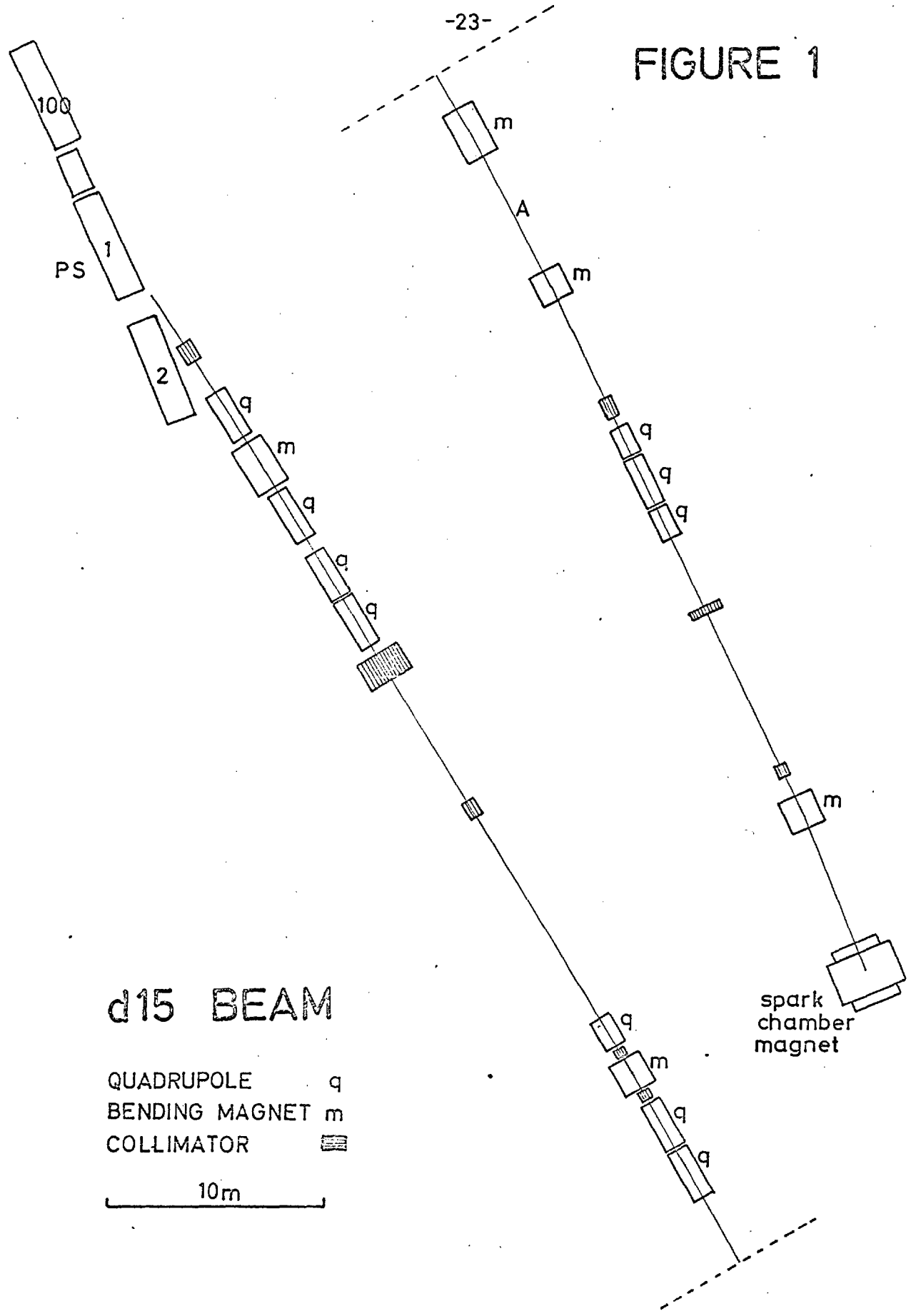
2.1. Beam and counter telescope

The beam used was an extended version of the d15 beam at the CERN proton synchrotron (PS). The beam is shown in figure 1; only the part of the beam after the point A will be described. The first part of the beam was used exactly as it had been set up for a previous experiment.

The extension of the beam consisted of two 1 m bending magnets to align the beam with respect to the spark chamber, and three quadrupoles to refocus the beam at the hydrogen target, the second bending magnet being also used for momentum analysis. The mean beam momentum was 9.5 GeV/c with an r.m.s. spread of ± 200 MeV/c. The total length of the whole beam from the internal target to the spark chamber was about 107 metres and the production angle was 40 mrad. The PS was operated at 18.1 GeV/c and gave a spill time of 300 m sec.

Figure 2 is a diagram of the counters and spark chambers used to define the beam. C_1 and C_2 are threshold Cerenkov counters of the Vivargent type⁽¹⁴⁾. C_1 was 4 m long and filled with hydrogen at a pressure of 7 kg/cm² abs. It detected pions and lighter particles but not kaons. C_2 was 2 m long and filled with ethylene at 4.75 kg/cm² abs. It detected kaons and lighter particles but not antiprotons.

FIGURE 1



d15 BEAM

QUADRUPOLE q
BENDING MAGNET m
COLLIMATOR 

10m

COUNTER SYSTEM

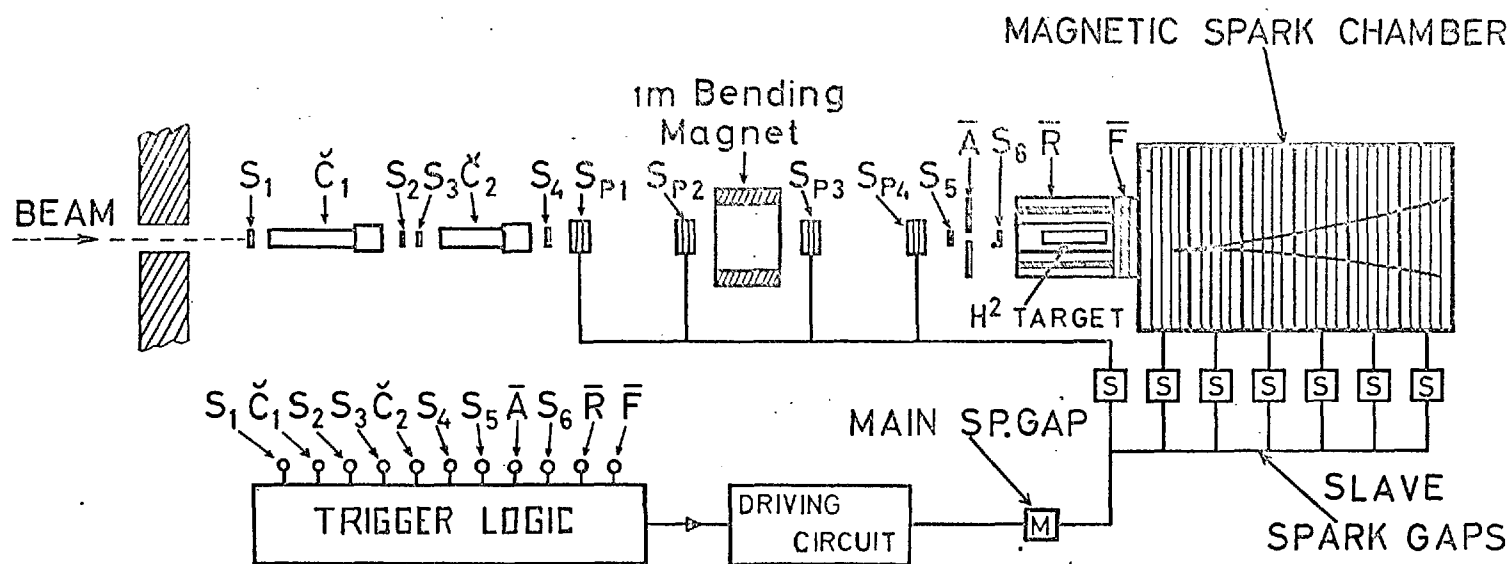


FIGURE 2

These two Cerenkovs were used to identify the particles in the beam. Denoting a coincidence count by C and a anti-coincidence by $\bar{C}$, the signatures of pions, kaons and anti-protons were then $C_1 C_2$, $\bar{C}_1 C_2$ and $\bar{C}_1 \bar{C}_2$ respectively. There was no evidence in the final data of events produced by misidentified beam particles, suggesting that the rejection efficiency for pions was better than $1 - 5 \times 10^{-5}$.

The scintillation counters S_{1-6} were used as a counter telescope to define the trajectory of incoming particles and to reduce background. S_{1-4} were 1 cm thick and 100 cm^2 area counters placed near the ends of the Cerenkov counters. Their main purpose was to ensure that all particles accepted as beam particles passed through the Cerenkov counters and so were not misidentified. A second function was to reject beam particles passing close to the Cerenkov counter walls where they would interact and produce secondary particles which might simulate actual beam particles. The last two counters in the telescope S_5 and S_6 were 2 mm thick and 4 cm square. They were used to define a narrow beam entering the target which could not hit the target walls. S_6 was placed a few centimetres from the hydrogen cell inside the vacuum of the target to reduce background interactions in the target end windows. Subsidiary counters A_1 , A_2 and A_3 were used in anticoincidence to suppress triggers generated by particles scattered upstream which passed

through the light guides of S_5 and S_6 . The Cerenkov light they would produce would simulate unscattered beam particles.

The small spark chambers S_{P1-4} were used to define the trajectory of particles producing interactions in the target so that their momenta could be measured. The average beam intensity measured inside the counter telescope was 1.2×10^5 particles per burst; a roughly equal number of particles was registered in the beam which did not pass through all the counters and so could not contribute to accepted triggers. The proportion of K^- and $\bar{p}$ in the beam were respectively 0.0053 and 0.0009.

2.2. Target and anticoincidence counters

The hydrogen target was 40cm long and surrounded by a large anticoincidence counter consisting of a scintillator-lead sandwich. Four more scintillation counters S_7 , F_1 , F_2 and F_3 mounted downstream with interspaced lead sheets completed the anticoincidence shield around the target. The target and anticoincidence shield will be described fully in the next chapter.

2.3. Electronics and triggering logic

The triggering logic for the experiment was based on a system of electronic units designed by W. Beusch. Their design and testing has been fully described in reference ⁽¹⁵⁾. The

units were all D.C. coupled and standard transfer signals were used between units to make the logic system flexible and easy to use. All units had sufficient inputs and outputs for it to be possible to build a relatively complex logical system with a minimum of units, thus minimising the time delay in the electronics.

All counter outputs were connected via appropriate delays to bistable discriminators. Before receiving a counter signal the output voltage level of a discriminator was + 0.7 volts. A signal greater than the threshold of 0.4 volts changed the output level to - 1.2 volts so that the output signal was a negative step pulse. The discriminators were not sensitive to further input until reset. Each particle passing through S_4 generated its own reset pulse some 20 nsec before signals arrived from the counter telescope. When a particle had passed through a counter, the discriminator output voltage level remained at - 1.2 volts until the next beam particle reset all the discriminators. This memory property of the discriminators was used to record the nature of the trigger. Those discriminators connected to the Cerenkov and anticoincidence counters controlled an array of lights photographed with the spark chambers. These were used to identify the incoming particle, and to indicate when a second beam particle passed through the target just after the trigger had

been initiated.

The discriminator signals were combined in the system of coincidence units shown in figure 3. The coincidence units gave the same standard output signal as the discriminators when all connected inputs were at the - 1.2 volt level. Time resolution was controlled by means of clipping lines parallel to the inputs. The anticoincidence function was obtained by feeding the discriminator signals through a circuit which inverted the voltage levels.

As is shown, two coincidence units were used to combine the signals from S_{1-6} and the inverted signals from A_1 , A_2 and A_3 to give a signal for each particle passing through the beam telescope.

The Cerenkov signals were split and inverted as shown to give the K^- and antiproton signatures $\bar{C}_1 C_2$ and $\bar{C}_1 \bar{C}_2$. These were combined in parallel channels with the beam telescope signals to give an output signal for each K^- or $\bar{p}$, each $\bar{p}$ and each π^- in the counter telescope. The outputs of all the anticoincidence counters S_7 , F_1 , F_2 , F_3 and R surrounding the target were combined together and inverted. This anticoincidence signal together with the $K^- - \bar{p}$ coincidence gave the final trigger for the spark chambers.

Outputs from the various coincidence units were fed to

a bank of scalers which monitored the numbers of beam particles, triggers, etc; these were read out at the end of each roll of film taken.

The overall delay introduced by the triggering logic was of the order of 60 nsec. The logic was gated to introduce a dead time of 200 nsec after the passage of each particle through the beam telescope. This was used to reduce the number of background tracks on the photographs. Further gating stopped all the logic after the spark chamber had been triggered until the apparatus was ready to record another event.

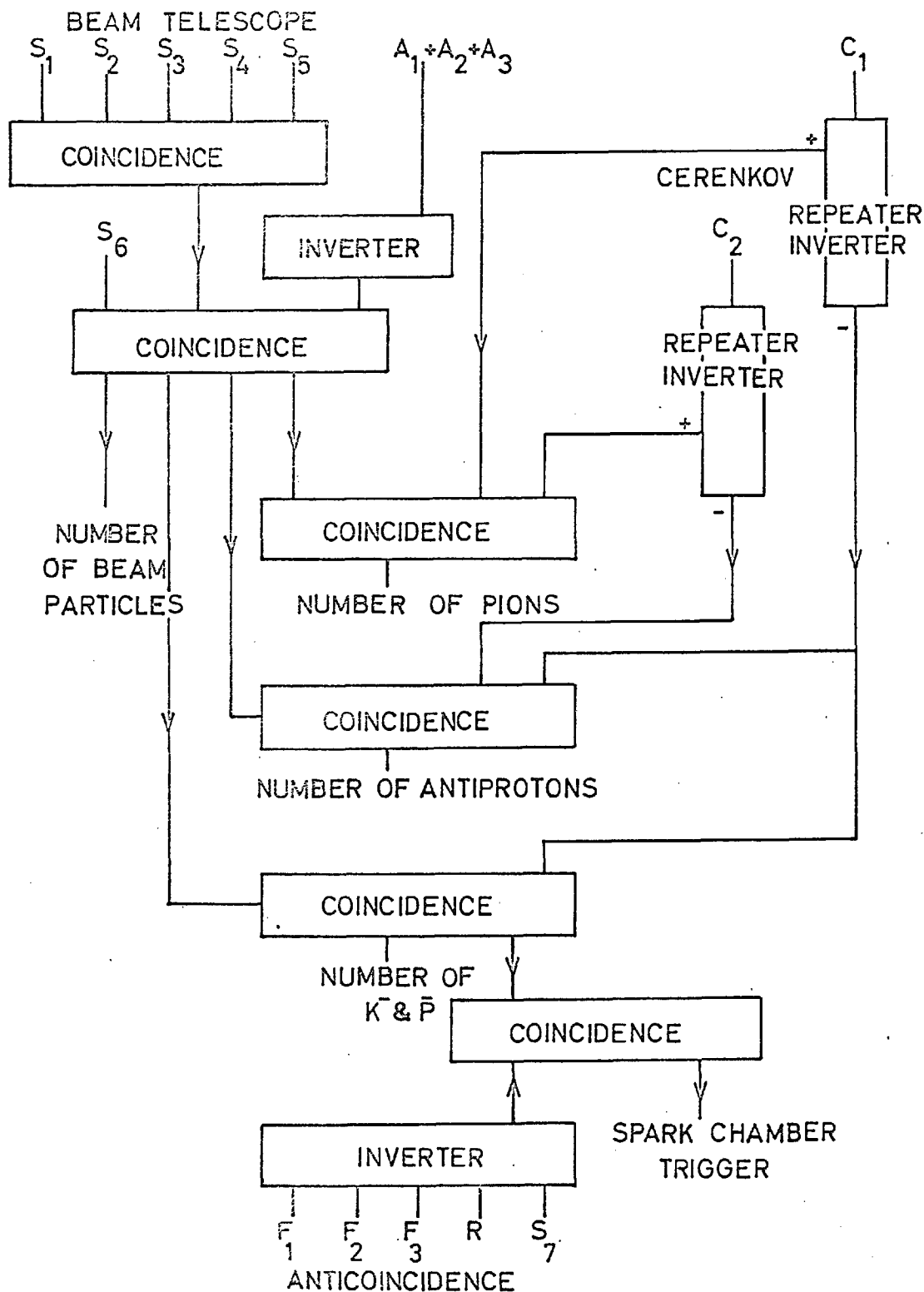
Anticoincidence losses

Not all of the events produced in the target and satisfying the trigger requirements actually gave a good trigger. A genuine trigger could be suppressed by excessive noise in the photomultipliers or a background flux of charged particles or gamma rays, which would simulate particles coming from the target. The loss of triggers depended on the time interval T in which pulses from the anticoincidence were accepted.

Assuming a uniform level of background this loss can be monitored by varying T . If in the experiment the value of T was T_1 , then the number of triggers observed in a given

TRIGGER LOGIC

FIGURE 3



time would be

$$N_1 = N_0 e^{-T_1/T_0}$$

where N_0 is the true number of triggers and T_0 is the mean time interval between background counts. If T is then increased by an amount T_2 , the number of triggers observed in a given time would be

$$N_2 = N_1 e^{-T_2/T_0}$$

from which N_0 can be determined. This principle was used in the experiment by delaying the beam telescope signal and comparing it again with the anticoincidence counter signal. The above argument assumes a uniform level of background in time. This was not the case in the experiment due to the 200 nsec dead time introduced to reduce the background. The monitor thus had to be calibrated. The true losses were measured by determining the ratio of the number of triggers to the number of beam particles as a function of the delay of the anticoincidence signal, the delay being large enough for the direct anti-signal to have no effect on itself. The losses were then found by extrapolating this ratio to zero delay.

2.4. Magnet and spark chambers

Magnet

The spark chambers were mounted in a large magnet formerly used for a cloud chamber. The complete assembly is shown in

figures 4 and 5. The magnet had a field of 10.5 Kgauss uniform within 10% in the useful volume of the spark chamber when the magnet operated at its maximum power of 2 MWatts. The total volume between the poles was approximately 2 x 1 x 1 cubic metres. The useful volume was somewhat less than this, being limited by the 170 x 60 cm² hole in the top of the magnet through which the chambers were photographed.

Construction of spark chambers

Each spark chamber plate consisted of a 74 cm square frame made from 12 x 40 mm aluminium. Aluminium foil 25 microns thick was glued to either side of the frame using araldite. Each foil was mechanically stretched while the araldite set to give it the required tension. This all metal construction gave the plates very good mechanical and thermal stability. Mylar sheet 0.8 mm thick was bent around the plates to prevent sparking at the edges. Thirteen plates were stacked together to make up a unit. The interplate spacing was 8 mm, given by small perspex spacers inserted at intervals around the edges of the plates.

The one disadvantage of this type of construction was the resulting large dead space between the sparks. This was not considered to be very serious for high energy interactions where most tracks would be almost normal to the plates and so

MAGNET SPARK CHAMBER
SECTION ALONG BEAM DIRECTION

FIGURE 4

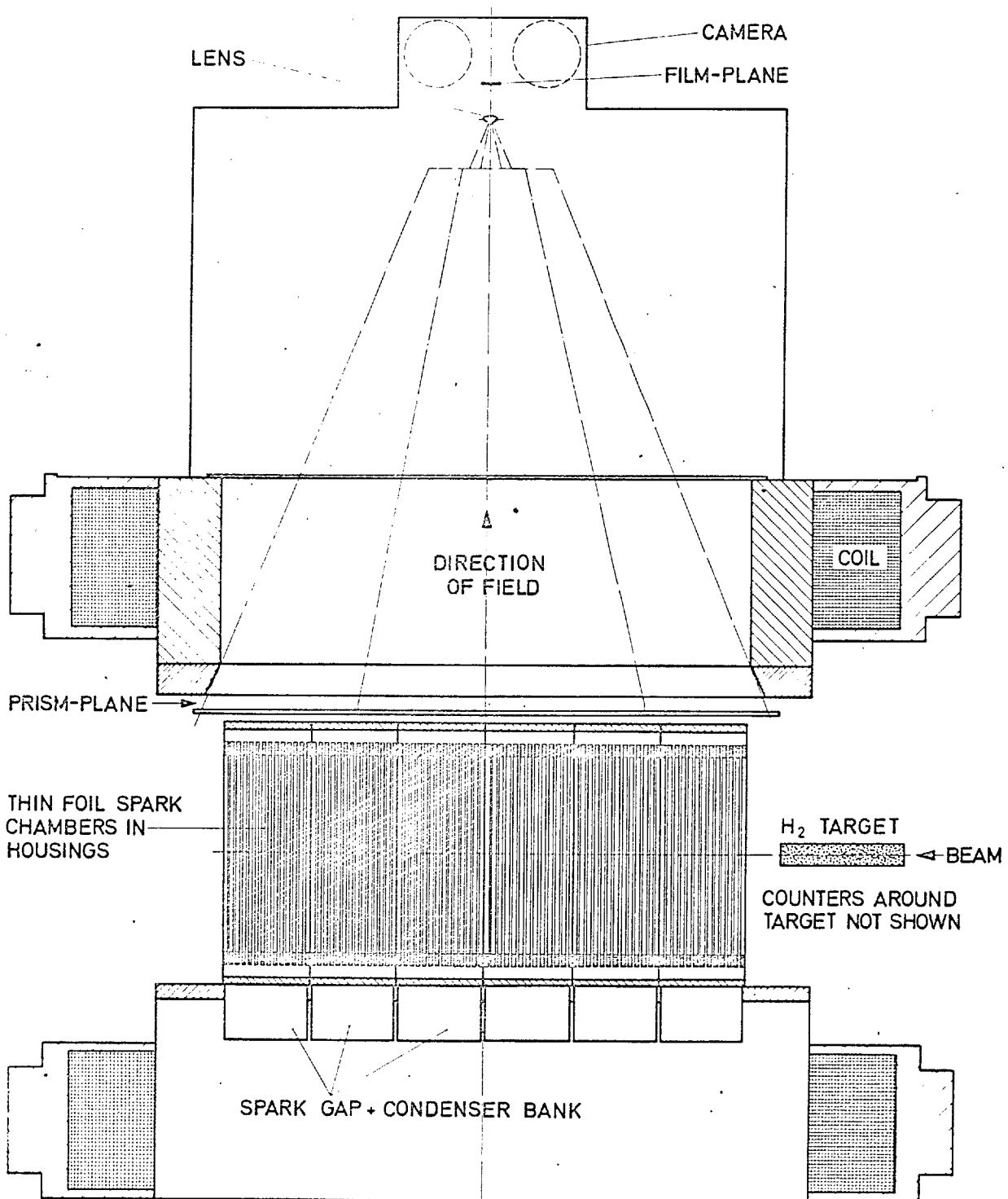
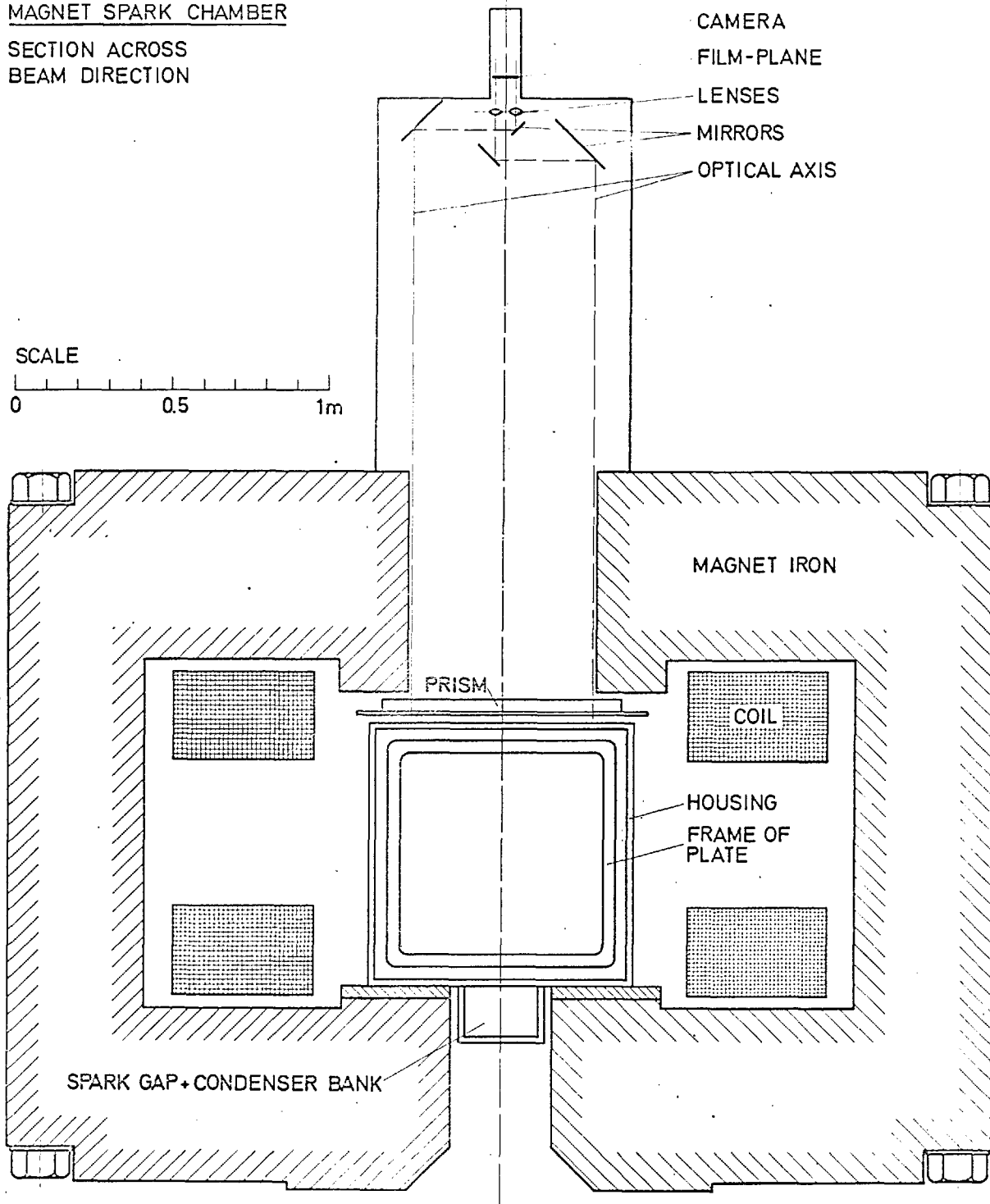


FIGURE 5

MAGNET SPARK CHAMBER

SECTION ACROSS
BEAM DIRECTION



have long path lengths in the chamber.

Each spark chamber unit was housed in an aluminium box with large mylar end windows to reduce interactions of particles passing through the chamber. The top of the box was plate glass to permit photography and all joints were sealed to make the container air tight. Condensers and spark gaps for the units were housed underneath. The complete spark chamber was made of 6 units and had a useful volume of $170 \times 60 \times 60 \text{ cm}^3$. It was mounted on a large iron trolley so that the spark chambers could be easily removed from the magnet.

2.5. Operation of spark chambers

The output signal from the logic triggered a driving circuit which fired the main spark gap. This was operated at 15 Kv and fired 7 slave spark gaps coupled one to each spark chamber unit and one to the small spark chambers in the beam. Alternate plates in the spark chamber units were connected to earth and to the high voltage, so that there were 12 active gaps in each unit, the electric field being in opposite directions in adjacent gaps.

The slave spark gaps were operated at 12 Kv in 2 Kg/cm^2 nitrogen and were coupled to each pair of live plates by a 4000 pf condenser. The risetime of the high voltage pulse measured at the plates was 30 nsec and breakdown occurred at

9 Kv. The capacity of each pair of plates was 1200 pf and the energy supplied to them was 0.21 joules.

The live plates were connected to earth through a 100 ohm resistor and the decay time of the pulse was 0.5 micro-seconds. A clearing field of 30 volts/cm was applied in the opposite sense to the high voltage pulse. This was well below the optimum value for minimum background for the following reason. The combined effect of the clearing field and the magnetic field caused a drift motion of the ions parallel to the plates. As the clearing field was in opposite directions in adjacent gaps this produced a 'staggering' of the sparks either side of the true track position. Using the optimum field of about 200 volts/cm, this staggering would have been large enough to make visual interpretation of the photographs difficult.

The gas mixture used in the chambers was a 80% neon 20% helium mixture and was not recirculated. The gas flow through the chambers was varied in the range 0.5 to 1.0 litres/minute as required.

The overall delay between the interactions and the firing of the spark chambers was of the order of 300 nsec, the major contributions to which were:- delays in cables 160 nsec; delay in counter logic 60 nsec and in the firing of spark gaps 80 nsec.

The sparking efficiency was 98% for one track and 68% for 8 tracks. The calculated radiation length of the chamber was 30 metres.

2.6. Optical system

Two views of the spark chamber were photographed side by side on 70mm film using two matched Symar objectives of 108.70 mm focal length. As shown in figure 5, the chamber was not viewed directly by the lenses, a system of mirrors being used to give an effective distance of 58 cm between the optic axes of the two lenses. The optical path length from the centre of the chamber to the lenses was 275 cm giving a demagnification of 24.2 at beam height. At this demagnification the grain of the film did not limit resolution. The proportionality constant for the depth coordinate Z determined from the co-ordinate difference $(Y_2 - Y_1)$ of the two views was 4.75 at the centre of the chamber.

As the light from sparks in a spark chamber can only emerge parallel to the plates a field lens is usually used to focus the light from all the gaps if the camera is close to the chamber. The dimensions of the apparatus in this case were such that this was not a practicable solution. A series of prisms of the same mean thickness were machined from perspex. These were mounted one per gap above the spark chamber on a

glass plate. Each one was computed to give the angle of bending of the light required to make it possible to view the whole depth of the gap from the camera lens.

The small spark chambers in the beam were photographed using a system of mirrors so that the images were recorded on the same film as those of the main chamber. The resulting definition was poor and many photographs showed multiple tracks which increased the problem of reconstruction. Thus although the small spark chambers were originally intended to be used to measure the momentum of the incoming beam particle, they served only to indicate when a second incident particle could have caused background interactions visible in the main chamber.

Figure 6 is a typical photograph taken during the experiment. A V^0 decay is clearly visible in the main spark chamber together with two beam tracks. The 'staggering' discussed in section 2.5. is most pronounced on the beam track on the left, identifying it as the track of a particle which passed through the chamber before the V^0 was produced. The small beam spark chambers are at the top of the left frame.

At the bottom of the photograph are the frame number and the discriminator controlled lights discussed in section 2.3. which were used to identify the beam particle and indi-

FIGURE 6 - Photograph taken during the experiment



cate when background particles passed through the anti-coincidence just after the trigger had been initiated.

Chapter 3. DESIGN AND PERFORMANCE OF THE TARGET AND ANTICOINCIDENCE SYSTEM

3.1. Introduction

In this chapter the hydrogen target and anticoincidence system are described. The parameters of the anticoincidence were the main factors determining the efficiency with which the charge exchange interactions could be detected and separated from the other interactions taking place in the target. The description of the counters is therefore followed by discussions of:-

1. The possible sources of background in the charge exchange data from the other interactions accepted by the trigger.
2. The experimental biases in the data caused by interactions of neutrons and neutral kaons in the anticoincidence counters.
3. The efficiency with which π^0 produced in interactions similar to charge exchange could be detected.

The conclusions reached will be used in the analysis of the data in Chapter 5.

3.2. Hydrogen target

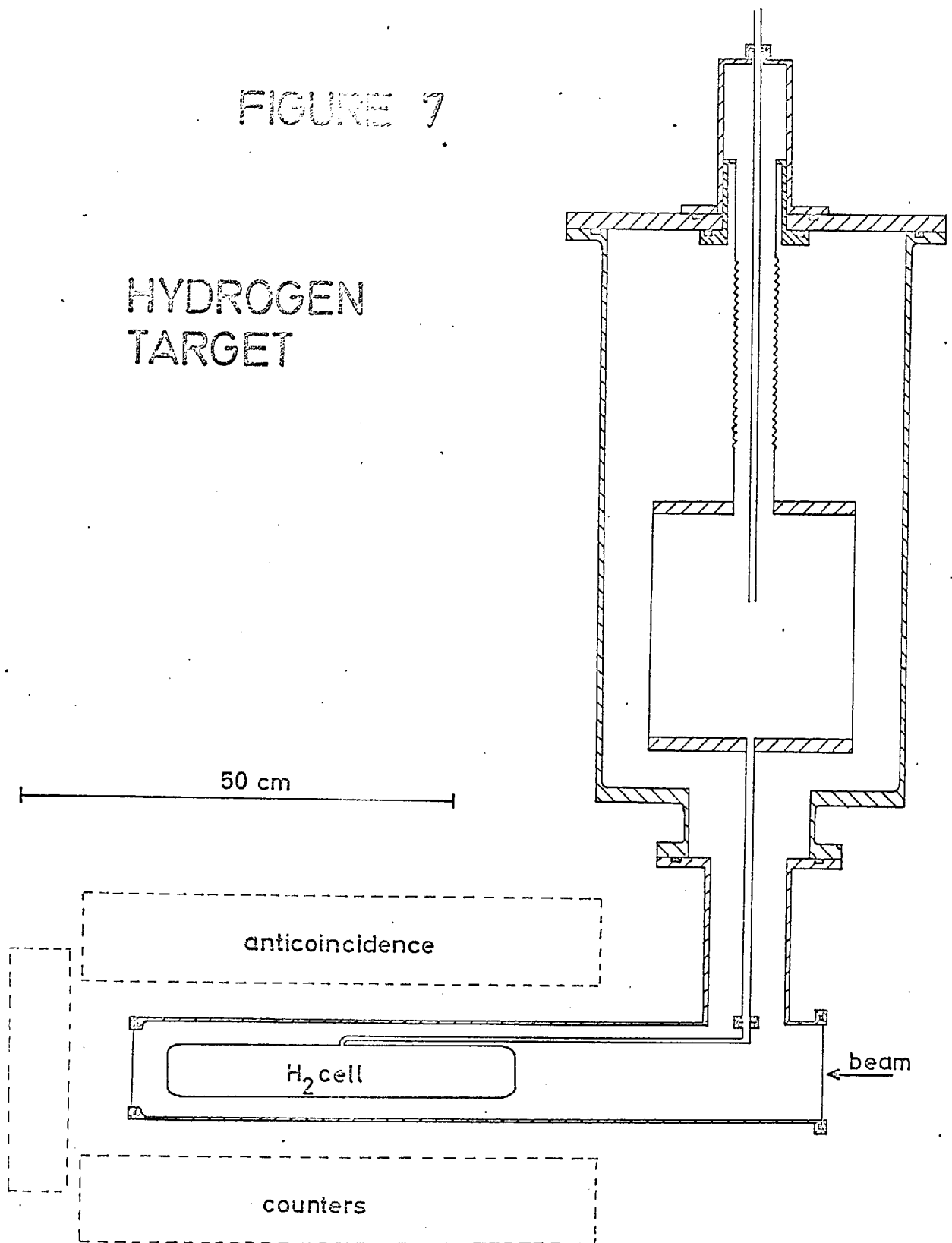
The liquid hydrogen target was designed to introduce a minimum of background due to K^- interactions with complex nuclei

in the target walls. It was also designed so that it could be quickly changed during an experiment. A very low rate of data taking could then be increased by replacing the hydrogen target by a solid one. If the rate of data taking was high, the length of the target could be changed to vary the relative rates at which the accepted interactions were recorded as the respective detection efficiencies were different functions of the target length. The length of the target chosen for this experiment was 40 cm. This was not so long that it unduly complicated the anti-coincidence system but was long enough to give a high rate of production of charge exchange events which could be detected in the spark chamber.

A section through the hydrogen target is shown in figure 7. The target cell was made of a 0.5 mm thick stainless steel tube of 6 cm diameter. The end windows were moulded from mylar 0.19 mm thick and were glued on using araldite. The target cell was supplied with liquid hydrogen from a 10 litre reservoir via a 1 cm diameter filling tube. Two further tubes removed the boil-off. Indium sealed joints on these tubes permitted quick replacement of the target cell. Both the cell and the reservoir were wrapped with 50 sheets of aluminised mylar to reduce radiant heat input to the target. The vacuum case around the cell was made of 0.3 cm thick aluminium and had 0.19 mm thick mylar end windows. The operating vacuum was

FIGURE 7

HYDROGEN
TARGET



2×10^{-6} mm.Hg. at which the boil-off rate was 1 litre/hr of liquid H_2 , resulting in an estimated 1% drop in the liquid density.

The rate of interactions produced in the carbon of the mylar windows was estimated to be 1% of those produced in the whole target. A short run during the experiment with the target empty gave no events, putting an experimental upper limit on this figure of 3%.

3.3. Anticoincidence system

The experiment was designed to study K^-p charge exchange and, if possible, the other four interactions listed in Chapter 1. The total cross sections for all of these interactions were expected to be small and it was therefore important that the interactions could be efficiently detected and that the background from the other K^- interactions in the target should be small. The main requirement of the anticoincidence counters was therefore that they should have a high detection efficiency for charged particles and gamma rays. It was also important that they should be compact so that the unstable particles produced in the required interactions should have a high probability of passing through them before decaying. A third requirement was that a minimum of the neutral particles produced in the target should be scattered in the anticoincidence counters. A counter

system satisfying the first requirement would consist of many layers of scintillator interspaced with thin lead plates. In this way the gamma conversion efficiency could be extremely high and the low energy electrons produced would not be absorbed in the lead before they were detected in the scintillator. Such counters would not, however, have the other characteristics required in this experiment. The counters described were considered to combine the above requirements in such a way that no excessive bias or contamination was introduced in the final experimental data.

3.4. Description of counters

The anticoincidence counters are shown in figure 8. Between the target and the spark chamber were the scintillation counters F_1 , F_2 and F_3 , each one being 28 cm square and 1 cm thick, F_1 being nearest to the target. Between F_1 and F_2 was a lead plate 8 mm thick and between F_2 and F_3 one 2 cm thick, these being used to convert gamma rays.

Surrounding the vacuum case of the target was a large counter R, 60 cm long and having a square cross section. Each side consisted of four 1 cm thick layers of scintillator between which were three 1 cm thick gamma ray converters, the one nearest the target being of copper and the others of lead. Each of the three F counters was coupled to a 2" photomultiplier by a perspex

ANTICOINCIDENCE COUNTERS

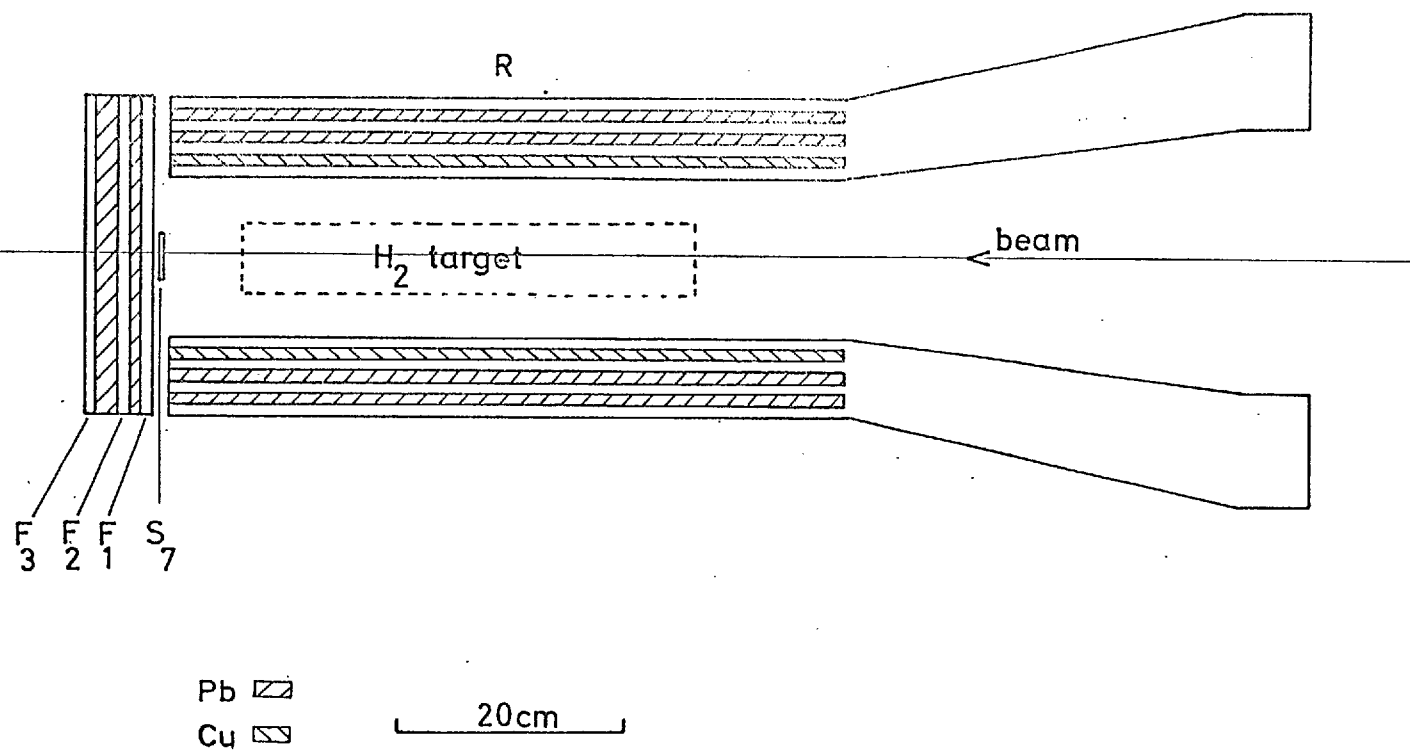


FIGURE 8

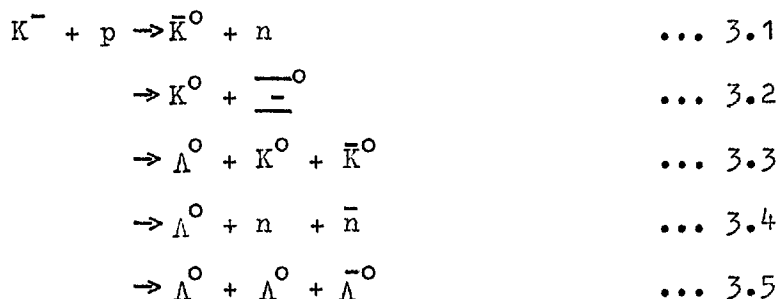
light guide. The four layers on each side of the R counter were coupled to a 5" photomultiplier using a single light guide. The positions of all the photomultipliers were determined by the fringing field of the magnet. At the centre of the target this was of the order of 2 Kgauss. The 2" photomultipliers for the F counters were located close to the magnet iron 1.5 metres from the centre of the scintillators. The photomultipliers for the R counter were mounted 2.5 metres back from the counter parallel to the beam. The fringing field in both these positions was of the order of 50 gauss and supplementary soft iron shielding was used to reduce it further. During the experiment tests were made with the magnet current off and on. The triggering rate was not significantly different, showing that the remanent field had little effect on the photomultiplier characteristics.

The uniformity of the light collection from different parts of the scintillators was high for counters of this size but the length of the light guides made the light collection efficiency low, particularly for the F counters. Consequently the operating voltages had to be high and the resulting high noise levels in the F counters caused most of the anticoincidence losses. The low light collection efficiency meant that there could be some background from interactions of beam particles in the first few millimetres of F_1 and for this reason a 2 mm thick 4 cm square anticoincidence counter S_7 was placed in the

line of the beam between the target and F_1 . The thresholds of all counters were set using a Co^{60} source and corresponded to 1 MeV (equivalent electron energy).

3.5. Detection of interactions accepted by the trigger

The two and three body interactions accepted by the trigger were



The efficiencies with which they could be detected were determined by the geometry of the target, anticoincidence and spark chambers and by the nature of the interactions which were largely unknown. As a result of the finite momentum resolution of the spark chambers, it was possible for the lambdas and kaons produced in the interactions 3.2 to 3.5 to simulate K_1^0 produced in the charge exchange interaction. This could only occur if all the unstable particles in the interaction decayed after passing the anticoincidence counters and, in the three body interactions, if the V^0 simulating charge exchange was produced with momentum approaching the kinematic limit in the centre of mass.

A Monte Carlo programme was used to generate a number of examples of each interaction from which the approximate detection efficiencies and momentum spectra of the secondary particles observed in the chamber were determined. The detection efficiencies (DE) were defined as the fraction of interactions produced in the target in which all unstable particles (excluding K_2^0) decayed via their charged decay modes inside a fiducial volume in the spark chamber.

In this section, as in the following two sections, it is assumed that the K_1^0 from the charge exchange interaction have momentum transfer less than about 1 (GeV/c)^2 . Only interactions were therefore considered in which the particle simulating a charge exchange event was produced forward in the centre of mass and had a transverse momentum of less than 1 GeV/c (corresponding roughly to a momentum transfer of 1 (GeV/c)^2 in the charge exchange interaction).

The three body interactions were considered as quasi two body interactions in which one particle was a resonance. In this way it was ensured that the other particle had a high centre of mass momentum.

It was found that neither interaction 3.2 nor interaction 3.3 could give K_1^0 which had momenta approaching that of charge exchange and which could be detected with reasonable efficiency.

DE was of the order of 10^{-4} and 10^{-3} for the two interactions compared with 0.26 for charge exchange. The interactions could give high energy lambdas if, as seemed unlikely at such high energies, the baryon was peaked forward in the centre of mass. For interaction 3.2 with the Ξ^0 produced forward and the K^0 decaying as K_2^0 . DE was of the order of 0.2 and the lambda momentum spectrum from 7.2 to 9.4 GeV/c. For interaction 3.3 considered as

$$K^- + p \rightarrow \Lambda + (K_2^0 K_2^0) \quad (\text{mass of } (K_2^0 K_2^0) = 1040 \text{ MeV})$$

DE was 0.25 and the lambda momentum spectrum was from 9.0 to 9.4 GeV/c. It therefore appeared that the K_1^0 produced in charge exchange should be well separated from the V^0 produced in the other interactions.

3.6. Detection of neutrons and neutral kaons in the anticoincidence

In order to determine the charge exchange total and differential cross sections it was necessary to estimate the biases caused by interactions of neutrons and neutral kaons in the anticoincidence counters.

The K mesons produced in charge exchange at 9.5 GeV/c with small momentum transfer all had momenta of the order of 9 GeV/c and were essentially normal incident on the F anti-coincidence counters. They therefore all had approximately the same probability of interaction in the material of the anti-

coincidence. Their interactions should have two effects on the charge exchange data. Firstly the number of observed events should be reduced due to the particles produced in the interactions giving an anticoincidence count. Secondly the scattering of the K mesons whose interactions were undetected might result in a bias in the observed differential cross section.

An estimate of the magnitude of the first effect was made assuming that an anticoincidence count could be caused by elastic scattering of the kaons in the hydrogen of the scintillator or inelastic scattering in the lead, copper or carbon. The K^0 and $\bar{K}^0$ inelastic cross sections in lead and copper were calculated from the K^0 - nucleon and $\bar{K}^0$ - nucleon total cross sections using the empirical formula of Williams⁽¹⁶⁾. The K^0 - nucleon and $\bar{K}^0$ - nucleon total cross sections were assumed to be equal to the K^+ - nucleon and K^- - nucleon cross sections respectively.

It was estimated that a fraction 0.14 ± 0.04 of the charge exchange events should be lost as a result of these interactions. The error takes into account the uncertainty in the calculated cross sections and in the estimation of the fraction of the inelastic interactions that would not be detected.

The effect of the undetected kaon interactions is difficult to estimate, but the majority of the interactions should be elastic diffraction scattering. The diffraction peak for complex

nuclei should be much narrower than that for nucleons so that the scattering of the kaons in the counters should only have a small effect on the overall scattering angle observed in the spark chamber. Whether or not the secondary scattering could alter the observed differential cross section will be discussed in Chapter 5.

The detection efficiency of scintillation counters for neutrons was known to be a function of the neutron energy. Measurements of the detection efficiency in the energy range 0 to 70 MeV have been made by Wiegand et al⁽¹⁷⁾ and a computer programme has been written by Kurz⁽¹⁸⁾ to calculate the detection efficiency in the energy range 0 to 300 MeV, the results being in good agreement with the above measurements as is shown in figure 9. The above results could not be used directly to determine the correction for neutron detection in the present experiment as the detection efficiency for a counter containing thick lead and copper plates was expected to differ from that of a homogenous scintillator.

The range of neutron energies which had to be considered extended from less than 1 MeV to more than 1 GeV and this together with the presence of the lead and copper greatly increased the number and complexity of the possible neutron interactions. Whereas Kurz was able to consider the contributions to the detection efficiency of each type of inelastic carbon

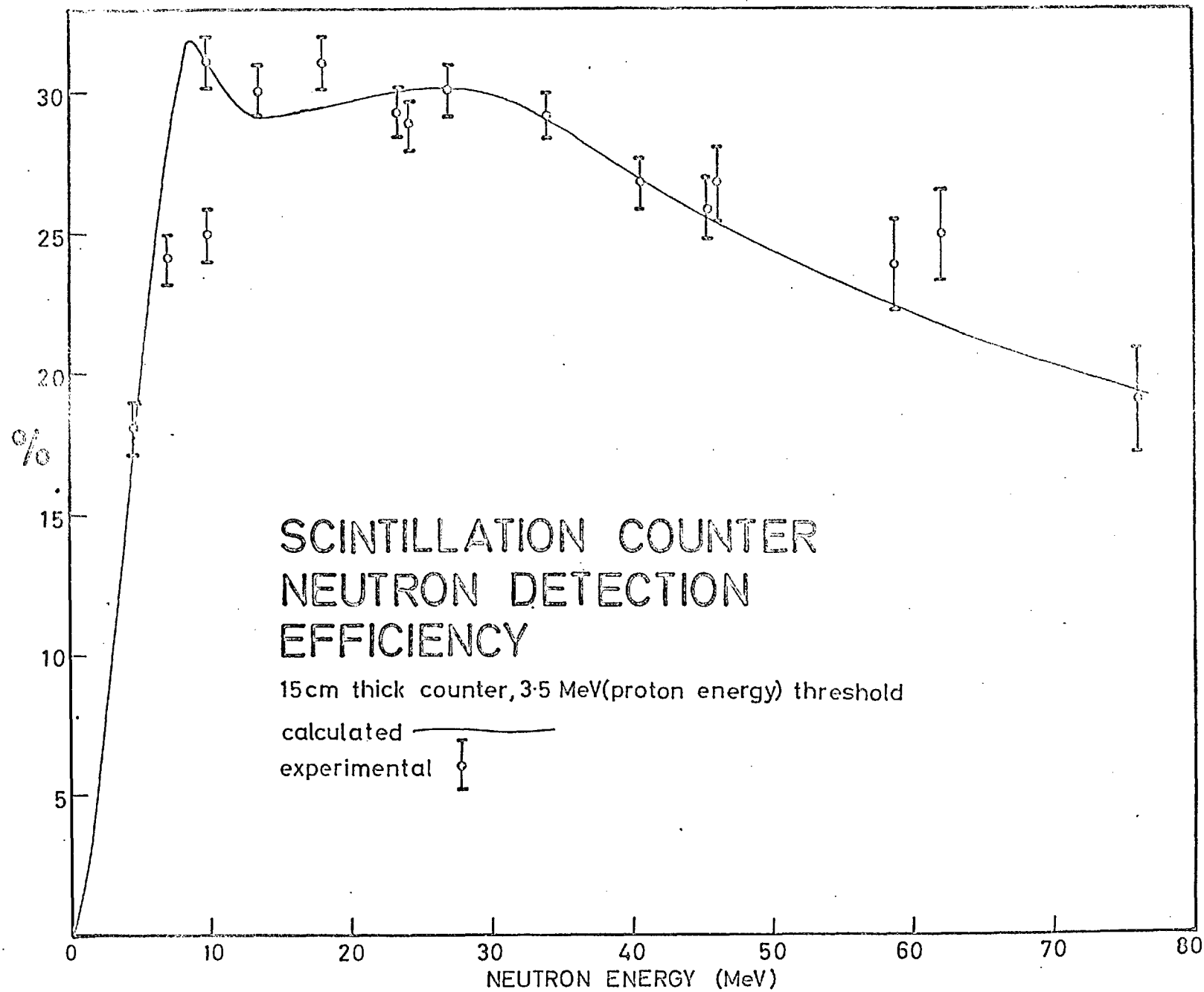


FIGURE 9

interaction, the lack of information available on neutron interactions in copper and lead made detailed calculation impossible for the counter used in the present experiment.

The estimate of the detection efficiency was therefore based on a simplified model of the inelastic interactions and a Monte Carlo programme was used to determine whether or not simulated neutrons interacted and were detected in the counters surrounding the target. In the programme neutrons were generated which were incident on the counters with energies and angles given by charge exchange kinematics. Random numbers determined where in the counter the individual neutrons interacted, the probabilities of interaction in the nuclei present being proportional to the cross sections for the interactions considered. The effect of elastic scattering in the complex nuclei was ignored as it was mainly diffraction scattering, the outgoing neutron being little changed in direction or energy. When a neutron interacted in hydrogen a recoil proton was generated, its kinematics were given by $n - p$ elastic scattering and the centre of mass angular distribution was assumed to be isotropic. At high energies essentially all recoils were detected so that the significant departure from isotropy had little effect on the results.

The energy loss of the proton along its path through the counter was calculated until it left the counter or came to

rest. The light output along the track in the scintillator was calculated using the formula of Birks⁽¹⁹⁾ for the specific fluorescence $\frac{dS}{dx}$, i.e.

$$\frac{dS}{dx} \propto \frac{\frac{dE}{dx}}{1 + B \frac{dE}{dx}} \quad \dots 3.6$$

where $\frac{dE}{dx}$ is the energy loss in MeV gram⁻¹ cm² and B is a constant determined as 10⁻² MeV⁻¹ gram cm⁻² by Evans and Bellamy⁽²⁰⁾ for a scintillator similar to the one used in the present experiment.

The contribution of the hydrogen interactions to the detection efficiency could be well determined so that the effect of the carbon interactions was included using the relative contributions of the carbon and hydrogen interactions as calculated by Kurz.

The main assumption made in determining the contributions of the lead and copper to the detection efficiency was that only interactions in which an energetic proton was produced could be detected. This was equivalent to assuming that all heavier particles produced were absorbed in the lead and that the probability of the gamma rays produced creating Compton electrons or electron pairs in the scintillator was small compared to the probability in lead.

The protons were assumed to be emitted as a result of direct neutron - proton collisions inside the nucleus,

consequently the cross section for their production at the higher energies considered was taken as

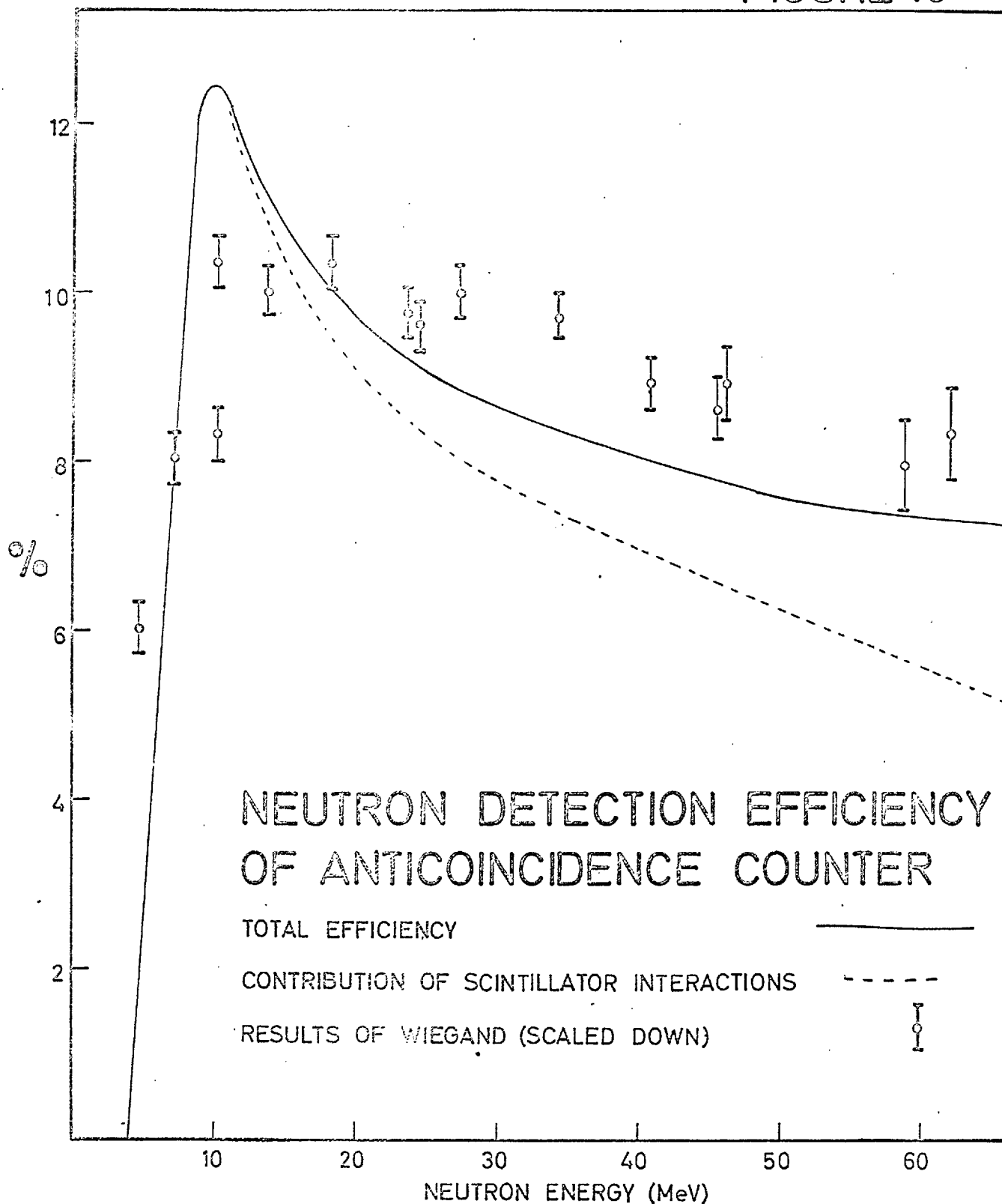
$$\sigma = \frac{Z}{A} \cdot A^{\frac{2}{3}} \sigma_{np} \quad \dots 3.7$$

where Z, A are the atomic number and weight and σ_{np} the n - p total cross section. At lower energies where this cross section exceeded the inelastic cross section, σ was fixed as being the same fraction of the inelastic cross section as at higher energies.

The neutron detection efficiency obtained is shown in figures 10 and 11. Figure 10 shows the calculated curve compared with the results of Wiegand at al⁽¹⁷⁾, scaled down so that the same total thicknesses of scintillator are compared. The present counter had a slightly lower threshold than that used by Wiegand so that a higher peak at 10 MeV was expected. Above this energy fewer neutrons interact in the scintillator as a result of the attenuation in the heavy plates. At high energies the lead and copper interactions give a large fraction of the detection efficiency. The rise at large momentum transfer shown in figure 11 is due to the greater efficiency of detection of these interactions and to the increased neutron path length in the counters.

The error in the neutron detection efficiency was

FIGURE 10



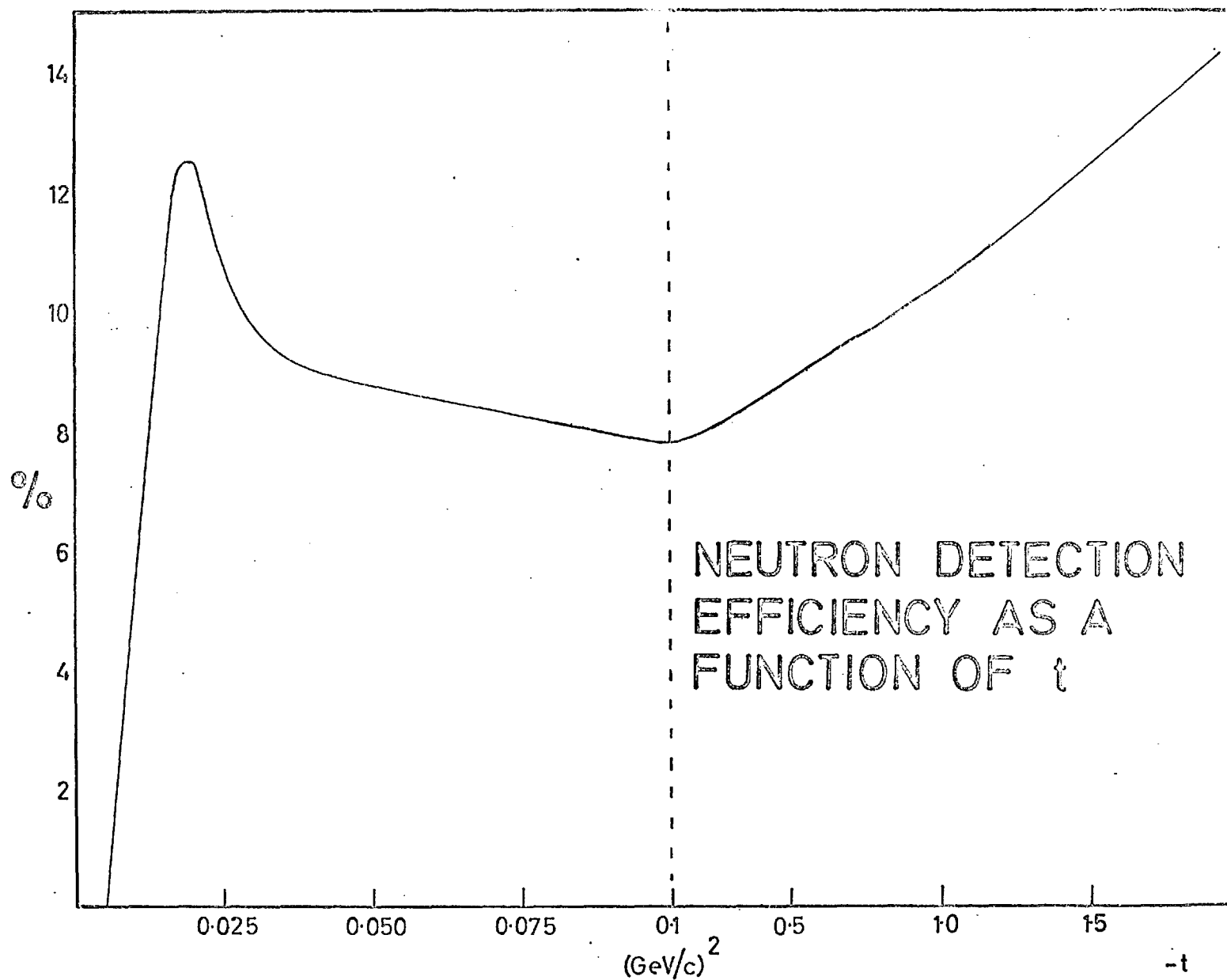


FIGURE 11

estimated as $\pm 20\%$ for the scintillator contribution and $\pm 50\%$ for that of the lead.

3.7. Gamma ray detection

As the anticoincidence counter was not a 100% efficient detector of gamma rays the interaction

$$K^- + p \rightarrow \bar{K}^0 + n + \pi^0 \quad \dots 3.8$$

was a possible source of background to charge exchange. The most serious background was from

$$K^- + p \rightarrow \bar{K}^0 + N^*(1238) \quad \dots 3.9$$

where $N^*(1238) \rightarrow n + \pi^0$

as this gave the lowest energy π^0 and had similar kinematics to charge exchange, the difference between the $\bar{K}^0$ momenta in the two interactions being only 300 MeV/c.

The estimate of the probability that both gamma rays from the π^0 decay were not detected was based on the calculations made by Crawford and Messel⁽²¹⁾ on the development of low energy gamma rays showers in lead.

A Monte Carlo programme was used to generate gamma rays produced by $N^*(1238)$ decay when the $\bar{K}^0$ was produced forward at 0° in the laboratory. The production vertex was uniformly distributed along the hydrogen target and the direction and energy of each gamma ray was determined, the energy spectrum

extending up to 280 MeV.

The copper plates in the R counter were assumed to be equivalent to 1 radiation length of lead. The showers of normally incident gamma rays were thus sampled at 1, 3 and 5 radiation lengths depth in the R counter and at 1.5 and 5.5 radiation lengths depth in the F counters.

Crawford and Messel gave values of the mean numbers of electrons with energy greater than 10 MeV present at various depths in showers produced by gamma rays with energies from 50 to 1000 MeV.

From these figures the probability P_e that no electron would be present in the shower at any of the sampled depths was calculated as a function of gamma ray energy assuming that there was no correlation between the electrons observed in successive layers of scintillator and that the number of electrons present in the shower at a given depth had a Poisson distribution.

The first assumption was a reasonable one as the mean electron energies were low enough for them to be absorbed in the lead between scintillator layers and because at all depths more than 65% of the shower energy was carried by gamma rays. The second assumption is somewhat arbitrary, but as the mean number of electrons present was less than one at most depths in the energy range considered, the results obtained should not be very

sensitive to the assumed form of the distribution.

As the efficiency for charged particle detection was high, P_e was the probability that the gamma ray would not be detected. The product of the values of P_e for the two gamma rays from each π^0 decay was the probability P_π that the π^0 would not be detected.

The mean value of P_π obtained was 4% assuming that all gamma rays were normally incident on the counters. This assumption was made as the considerable lateral spread of the showers meant that the results of Crawford and Messel could not be used to predict P_e for other than normal incidence. Most of the gamma rays were incident at quite small angles to the normal but for those incident at larger angles P_e could be underestimated by approximately a factor 2 for the high energy and a factor 1.2 for the low energy gamma rays. It therefore seems reasonable to assume that less than 10% of π^0 from $N^*(1238)$ decay would not be detected.

Chapter 4. SCANNING, MEASUREMENT AND ANALYSIS
OF THE PHOTOGRAPHS

4.1. Scanning

The 7000 pairs of photographs taken during the experiment were scanned twice for V^0 decays. A V^0 was defined as one positive and one negative track coming from a single point, provided there was no visible incident track. No restriction was placed on the apex position in the chamber or on the curvature of the tracks.

The events were easy to identify except for about 15% which had superimposed background tracks. Some of these events were more difficult to recognize but here the staggering of the sparks (discussed in Chapter 2) proved of great assistance as it gave a qualitative measure of the age of the tracks. Thus the two simultaneous tracks of a V^0 could be separated from the background and chance track configurations simulating real events could be eliminated.

The information recorded in the scanning consisted of the number of the spark gap in which the apex was situated, the frame number, the triggering information visible on the display unit and the number and nature of background tracks on the photograph. The first scan was made by a scanning girl and a physicist, the second by a girl alone.

A summary of the results of the scanning is given below.

The scanning efficiency E was defined as

$$E = \frac{\text{Number of events found in 1 scan}}{\text{Total number found in both scans}}$$

and was based only on events identified as charge exchange events in the final analysis. The overall figures were slightly worse, as some scanners had included events which others had rightly classed as interactions.

Scanning results

Number of photographs scanned	= 7000
Rate of scanning (frames/hour)	= 300-400
Total number of K^- produced events found	= 535
Scanning efficiency 1st scan	= 96%
Scanning efficiency 2nd scan	= 99%

During the final analysis, the events found on only one scan were closely examined. They were consistent with being an unbiased sample of the data except in that they were mainly in the part of the chamber where events were more likely to be obscured by background tracks. However, as the combined scanning efficiency was very high, no correction was made for events not found. The above

statistics do not include three events found with more than one V^0 on a photograph.

4.2. Measurement

The events found in scanning were measured on the CERN IEP measuring projectors. The operators were given a print of one view of each event indicating the points and tracks to be measured and their assigned labels.

Approximately 20 points were measured per track on each view. Whenever possible pairs of adjacent sparks were measured in order to reduce errors introduced by the staggering.

The measured apex of the V^0 was approximate and was only used to check the apex reconstruction (see section on THRESH). It was defined as a point on or midway between the first sparks on the two tracks according to whether or not they could be resolved.

The width of the spark images on the film varied according to the intensity of the spark but was typically of the order of 80 microns. As the resolution of the IEP was about 2 microns the operators measured what they judged to be the centre of the spark.

The coordinates of the measured sparks and fiducial marks were recorded on paper tape for input to the analysis

programmes. All first measurements were analysed; those badly measured or not fitting charge exchange were re-measured.

4.3. Analysis

The programmes used to analyse the measurements were those used at CERN for the analysis of bubble chamber photographs. Some modifications had to be made to take into account the differences between a spark chamber and a bubble chamber. The following section contains only brief descriptions of the programmes, concentrating on the modifications made and the determination of the resolution of the spark chamber system.

REAP

The paper tape output of the measuring machines was processed by the programme REAP. In this programme some measurement and labelling errors were detected. The data were then prepared for the next programme THRESH. A full description of REAP can be found in reference⁽²²⁾.

THRESH

The spatial reconstruction of the measured events was made in THRESH. The input to the programme consisted of general information about the experiment followed by the coded measurements of each event in turn.

The general information contained coordinates of fiducial marks and cameras, dimensions and refractive indices of all media between the camera lens and the tracks in the chamber.

Using these parameters THRESH reconstructed by a least squares method the best helix passing through the points measured in the tracks. A description of the programme can be found in reference⁽²³⁾ and of the least squares fitting in reference⁽²⁴⁾.

4.4. Modifications made to THRESH

A. Optical system

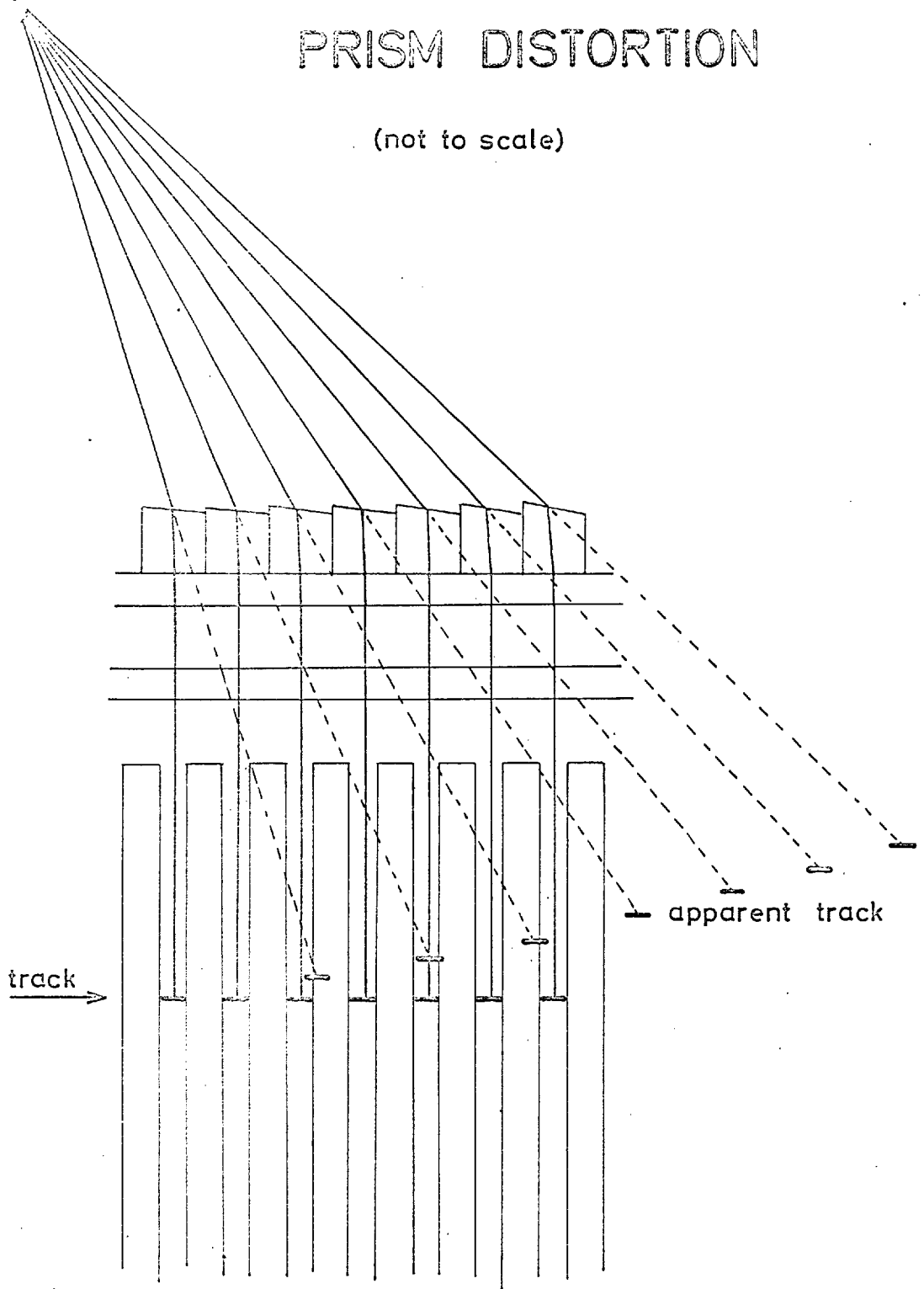
1. Effect of prisms

In a bubble chamber tracks are viewed directly by the camera. This was not the case in the spark chamber; the prisms bent the optical path and caused an apparent displacement of the spark as shown in figure 12. The effect on tracks was to elongate them and to give them an apparent curvature in the plane perpendicular to the plates and parallel to the magnetic field. The prisms had been optically tested before mounting and it was not found necessary to apply corrections other than for the obvious bending of the light and the increased optical path length.

FIGURE 12

PRISM DISTORTION

(not to scale)



2. Distortion

The distribution of sagittæ of 160 cm long tracks of 10 GeV/c beam particles measured with no magnetic field is shown in figure 13. In addition to the random spread of the distribution, a systematic error of 0.25 mm on the sagittæ is evident. The variation of this was investigated by measuring photographs of stretched wires at various positions inside the magnet. The mean value of the error was used to determine a correction applied to the sagittæ of all tracks reconstructed in THRESH.

The source of the error is unknown but is suspected to be curvature of mirrors or camera lens distortion.

B. Corrections applied for electron motion

During the time interval between the passage of the charged particle and the spark discharge the electrons in the gas were free to move under the influence of the magnetic field and the applied electric fields. As this drift motion was considerable, corrections had to be applied during the reconstruction to determine the track coordinates which each spark represented.

The electric field E referred to below is the average value of the clearing field and the high voltage field before spark breakdown.

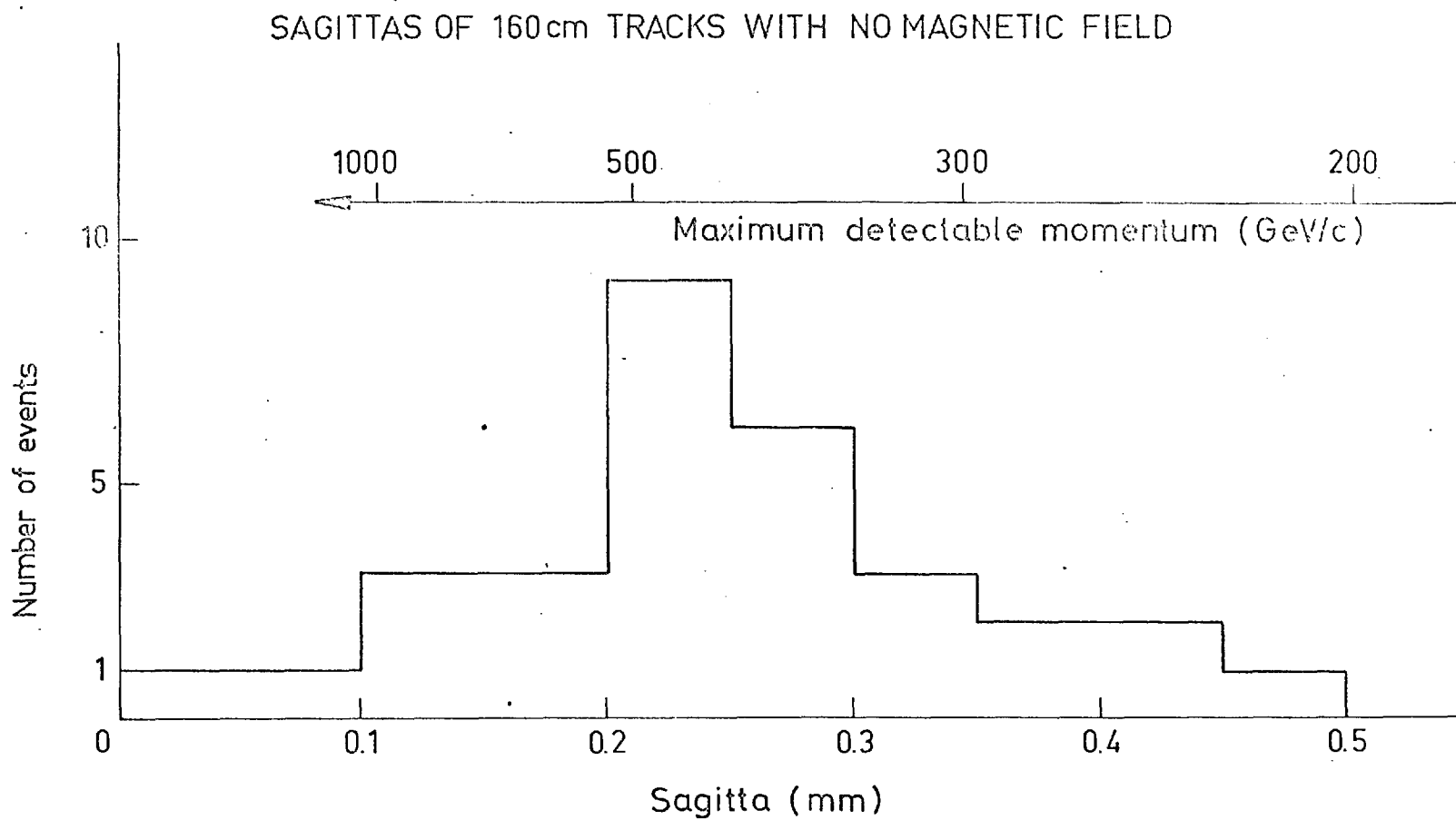


FIGURE 13

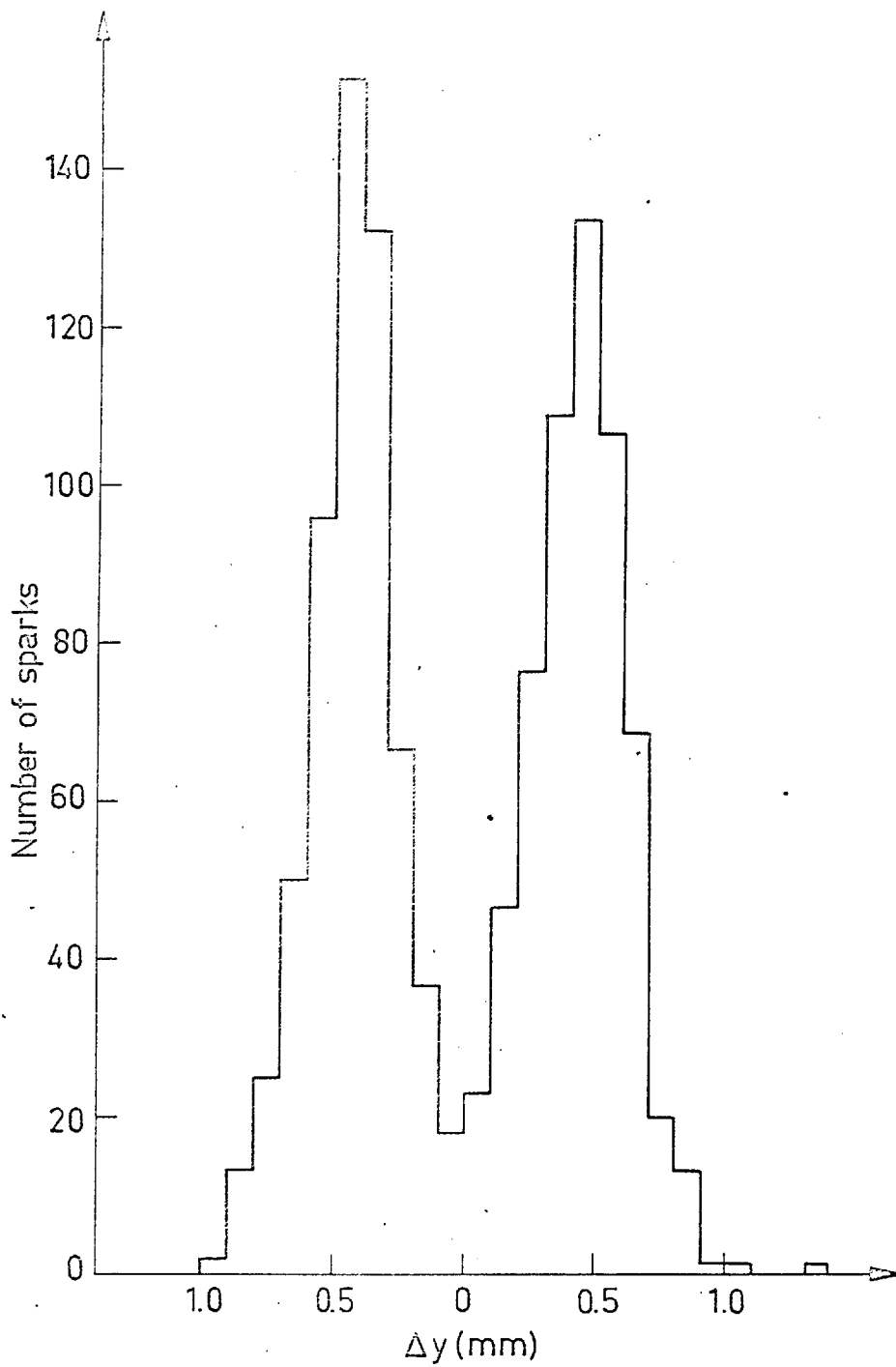
The motion of the electrons had two components. The first was proportional to E and directed towards the positive plate in each gap. The second was proportional to $\underline{E} \times \underline{B}$ and so was parallel to the plates (i.e. parallel to the Y axis). As the direction of E was reversed in adjacent gaps, both drift components were also reversed.

The drift motion of the electrons in the Y direction caused a corresponding displacement of the spark independent of the angle θ' between the track and the normal to the plates. In order to determine the corrections to be applied beam tracks were measured and the deviation ΔY calculated of each individual spark from the fitted curve through all sparks. The results obtained with a clearing field of 60 volts are given in figure 14. The magnitude of this drift was the mean value of ΔY in figure 15 obtained by reversing the sign of ΔY in alternate gaps.

If the track is inclined the motion of electrons perpendicular to the plates results in a displacement of the spark in the plane parallel to the plates. This is shown in figure 16. If the electrons in the gas move a distance $2x$ towards the positive plate then the centre of the gravity of the electrons remaining in the gas moves a distance x the same direction and a distance $Y = x \tan \theta'$ parallel to the plates. The mean alignment point of each spark with the track

Δy DISTRIBUTION
BEAM TRACKS
 $\theta=0$

FIGURE 14



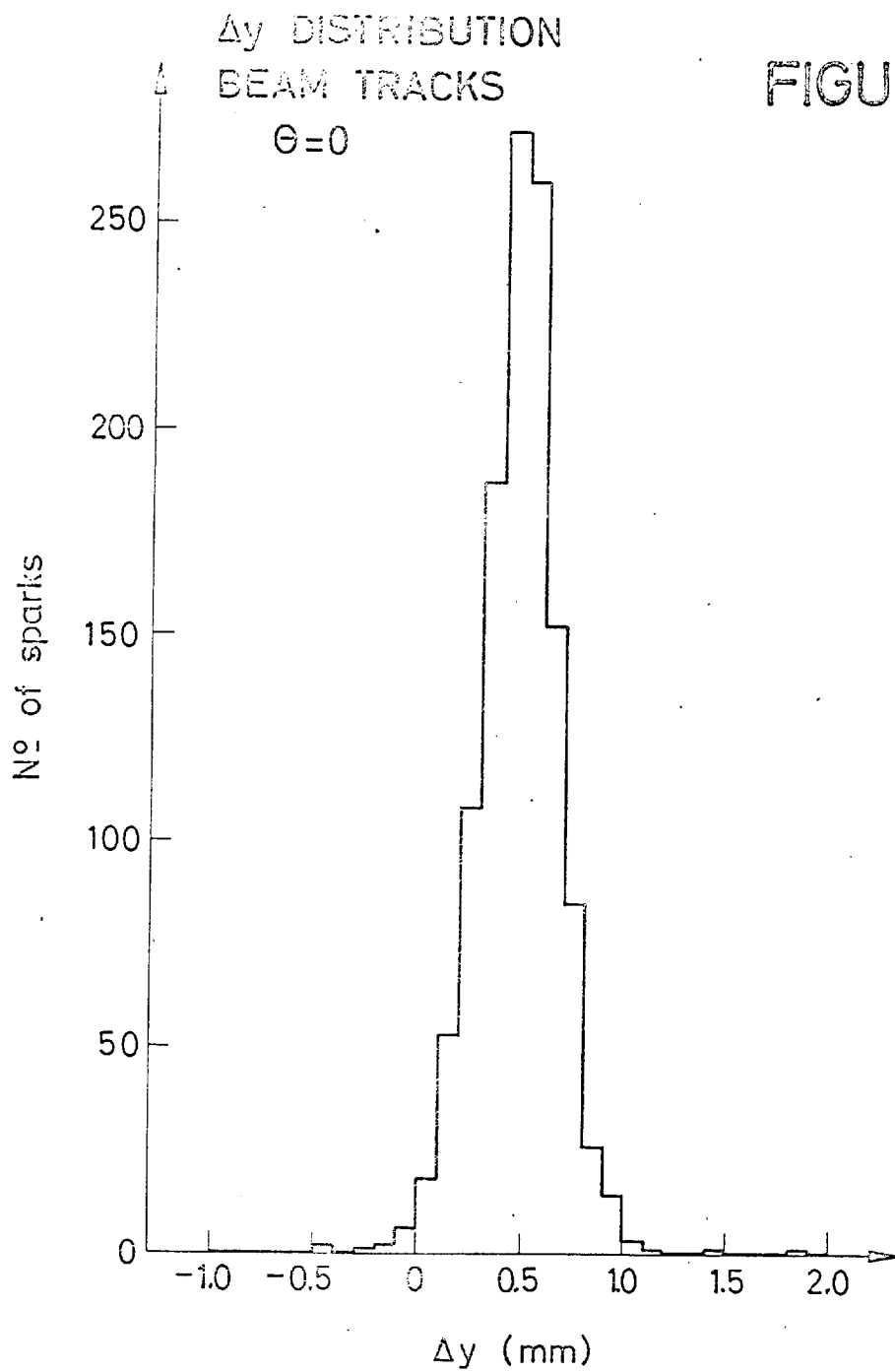
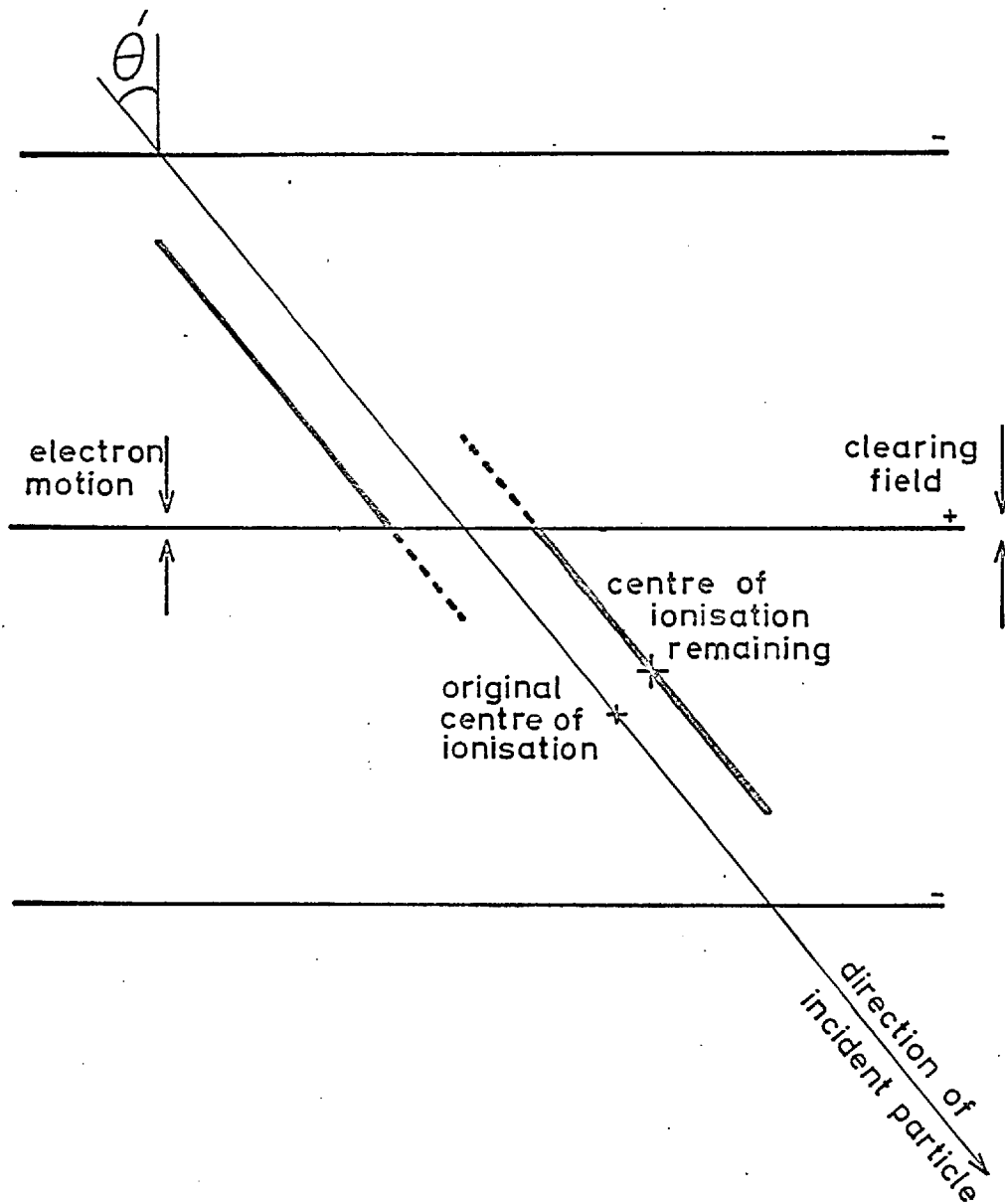


FIGURE 16

EFFECT OF CLEARING FIELD ON INCLINED TRACKS



was not the centre of gravity. However, the above discussion shows that the position of the spark relative to the track should be a function of θ , and so it was determined by measuring curved tracks in the spark chamber. The deviation of each spark from the fitted helix was found as a function of the angle θ between the normal to the plates and the projection of the track in the horizontal plane measured at the position of the spark. Whereas θ could have large values due to the curvature of the tracks, the angle between the normal to the plates and the projection of the track in the vertical plane perpendicular to the plates was small and therefore neglected as all tracks were peaked forward.

The results of these measurements, again with a 60 volt clearing field are shown in figure 17. The points $\overline{\Delta Y}$ uncorrected are the mean deviations of the centres of the sparks from the track after the $\underline{E} \times \underline{B}$ staggering correction has been applied. The slope of the line gave the mean alignment point as being 1.2 mm from the cathode. The points $\overline{\Delta Y}$ corrected are the deviations after the correction for the electric field drift has been applied. The corresponding mean deviations $\overline{\Delta Z}$ of the sparks in the Z direction are also shown.

Spatial resolution

When all the above corrections had been applied, the remaining deviations of the sparks from the tracks were due

FIGURE 17

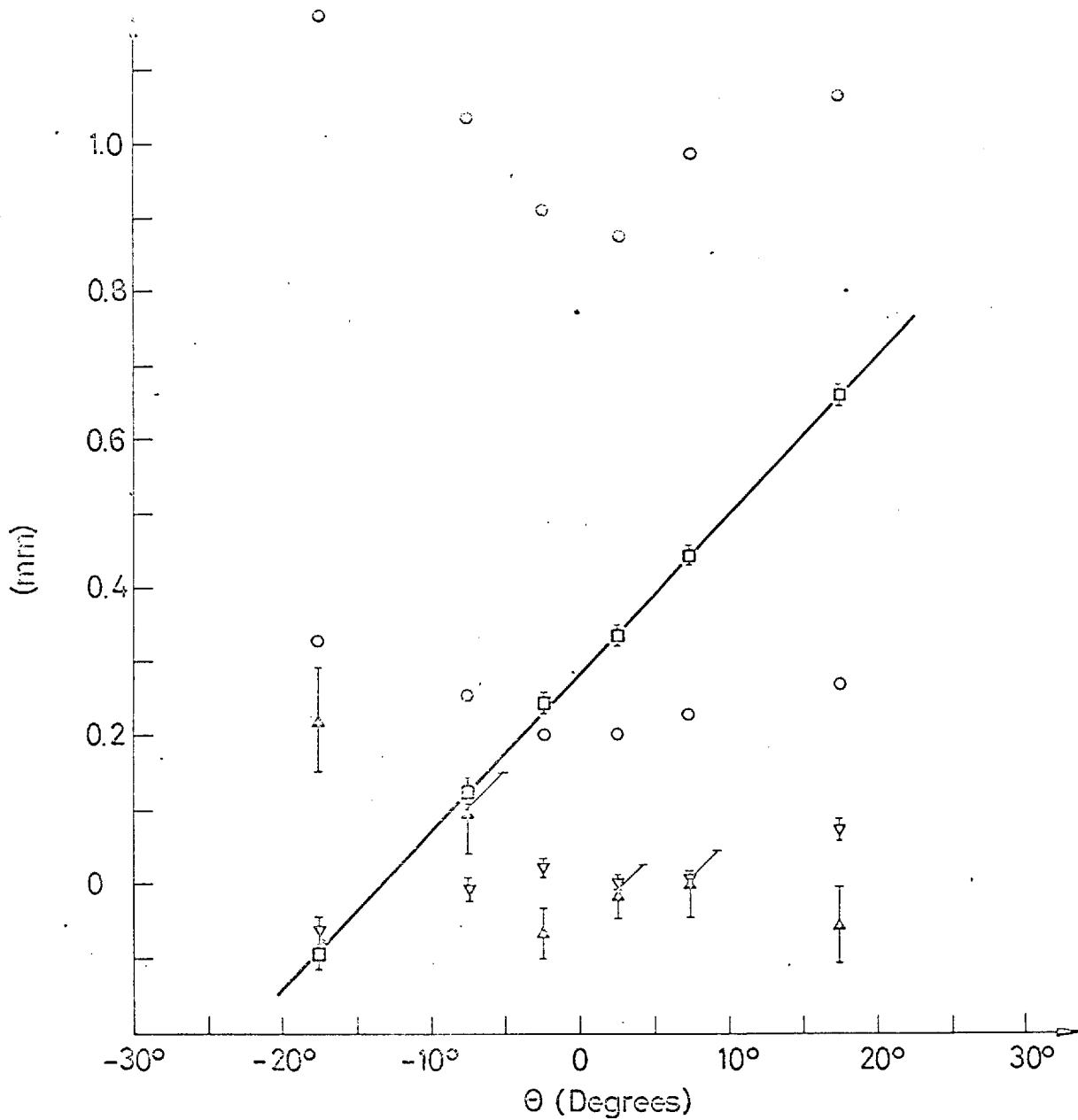
SPATIAL RESOLUTION vs ANGLE θ

hand measurements

corrections applied for:

staggering: $\overline{\Delta Y}$ ($\theta=0$) = 0.28 mmelectrons drifting: $\Delta X = 1.2$ mm

- $\overline{\Delta Y}$ uncorrected
- ▽ $\overline{\Delta Y}$ corrected
- △ $\overline{\Delta Z}$
- σ_Y
- σ_Z



to the diffusion of the sparks and the measurement errors, and had an approximately Gaussian distribution.

The spatial resolution is the combination of these two effects. In figure 17 the points σ_Y and σ_Z are the mean deviations of the sparks in the Y and Z directions respectively. Both show some increase with $|\theta|$.

The contribution σ_N of the diffusion of the sparks to σ_Y and σ_Z will be the same so that the difference in magnitude of σ_Y and σ_Z is given by the effect of the small stereo angle on the errors of measurement.

If the mean measurement error on each view is σ_m then σ_Y and σ_Z can be expressed as

$$\begin{aligned}\sigma_Y^2 &= \sigma_N^2 + 2 \sigma_m^2 \\ \sigma_Z^2 &= \sigma_N^2 + 40.5 \sigma_m^2\end{aligned}$$

At $\theta = 0$ the measured value of σ_Y is 0.23 mm and the contributions of measurement error and diffusion are respectively 0.15 mm and 0.18 mm. The diffusion of the sparks about the track is rather less than the values of 0.22 found by Mikhailev⁽²⁵⁾, 0.25 by Rutherglen⁽²⁶⁾ and 0.5 by Roberts⁽²⁷⁾, the third figure being also determined in a magnetic spark chamber.

Apex reconstruction

In order to reconstruct a nuclear interaction in a bubble chamber it is necessary to extrapolate the measured tracks to the interaction vertex. The error introduced due to the curvature of the tracks is small, as the spatial resolution is high and the vertex is well determined. This was not the case in the spark chamber as the minimum uncertainty in the measured position of the V^0 apex was ± 1 cm. This was the optimum value given by the inter-spark distance of 2 cm and was worse if the sparking efficiency was low or if the decay took place between units.

Use of the measured apex would therefore have introduced a considerable error, for example one of several percent in the calculated opening angle of a 9.5 GeV/c K_1^0 . For this reason the actual decay apex was determined by extrapolating the measured tracks to their point of nearest approach. It was required that this point should not be more than 1 cm before the measured apex, or more than 6 cm if the decay vertex was between spark chamber units.

4.5. Kinematic reconstruction. GRIND

The programme used to perform the kinematic reconstruction of the events was GRIND described in reference⁽²⁸⁾.

In GRIND the geometrically reconstructed V^0 was tested

to determine whether it was an example of one of the 4 processes

$$K_1^0 \rightarrow \pi^+ + \pi^-$$

$$\Lambda \rightarrow p + \pi^-$$

$$\bar{\Lambda} \rightarrow \bar{p} + \pi^+$$

$$\gamma \rightarrow e^+ + e^-$$

The momentum of both tracks was determined from their curvature using the field map of the magnet. For each of the above hypotheses small mass dependent correction were made to the momenta and their error due to multiple scattering and energy loss in the spark chamber.

Using the computed values of the vector momenta of the charged particles and assuming for each hypothesis the masses of the three particles, a one constraint fit was performed to determine the best value of the vector momentum of the neutral particle and the probability that the hypothesis was a reasonable interpretation of the event. In most cases the fit converged after two iterations. Whether or not the resulting fit was a reasonable interpretation was determined from the value of χ^2 obtained. The χ^2 was a function of the 'external' errors of the track parameters. In the standard version of GRIND, these errors are scaled according to an experimentally determined mean projected sagitta error DS.

In the version of GRIND used in the experiment the constant DS was replaced by a variable

$$DS' = DS (1 + A \tan\theta)$$

where A was a numerical constant and θ the angle between the track and the normal to the spark chamber plates at a point 0.6 of its length from the decay vertex.

This change took into account the increased spark fluctuation about the position of the track as the angle to the plates was increased.

The error assignment was checked using the χ^2 distribution for the whole data. At this stage a hypothesis was considered as a reasonable interpretation of the event if the χ^2 was less than 100. This limit will be discussed in the next chapter.

In normal circumstances the fitting would have been carried a stage further and a multivertex fit performed to test hypotheses for the production of the neutral particle. This was not done for two reasons. Firstly the incoming beam particle was not measured, so that its parameters were known only within broad limits; secondly the interaction vertex was not measured and so was only known to be in the volume of the hydrogen target.

In practice it was found that the V^0 decay was

sufficiently well measured for this extra information to apply practically no further constraint to the event.

4.6. Post GRIND analysis

The output of GRIND consisted of several records on magnetic tape for each event. These contained a great deal of information, much of which was not needed for the final analysis of the experiment. Moreover, parameters which were needed had not been calculated in GRIND.

A programme ABSTRACT was written to read the GRIND library tape, extract the required information, calculate the parameters necessary for final analysis and finally to write a data summary tape. This data summary tape was then used as input for the programme SUMX⁽²⁹⁾ which could plot histograms and perform tests on the whole data.

Provision was made in ABSTRACT for selection of events so that, for example, only the best of two measurements and only events produced by an incoming K^- were written on to the final data summary tape.

The quantities calculated in ABSTRACT consisted of detection probability, centre of mass decay parameters of the V^0 , missing mass etc. The momentum transfer and scattering angle were calculated with respect to the mean beam momentum and direction derived from measurements of beam tracks in the spark chamber.

Chapter 5. SELECTION OF EVENTS, ESTIMATION OF BACKGROUND
AND DETERMINATION OF TOTAL AND DIFFERENTIAL
CROSS SECTIONS

5.1. Criteria used in event selection

The analysed V^0 decays were selected as charge exchange events if the following criteria were satisfied:-

1. The reconstructed apex of the V^0 was in a certain fiducial volume inside the chamber.
2. The V^0 could be considered to be well measured.
3. The incoming particle beam producing the V^0 had been recorded as a K^- on the display unit.
4. The V^0 fitted the hypothesis

$$K_1^0 \rightarrow \pi^+ + \pi^-$$

in GRIND and its vector momentum was consistent with the kinematics of the reaction

$$K^- + p \rightarrow \bar{K}^0 + n.$$

If both measurements of an event satisfied the above criteria, which are discussed in greater detail below, the one which gave the best fit to a K_1^0 decay (i.e. had the lowest χ^2) was accepted.

Fiducial volume

Inspection of subsets of the whole data showed that the sample of events in which the apex of the V^0 was located in or

before the first gap of the spark chamber contained a disproportionately high number of badly measured and unidentified events. Many photographs contained visible interactions of beam particles either in the anticoincidence counters or in the wall of the chamber before the first gap. As the events with apices in the first gap could be contaminated by two prong interactions it was decided to accept only events with a visible apex after the first gap.

It was also found that the sample of events with apices in the last two spark chamber units contained a large number of badly measured, and ambiguous events. This was because the tracks of these events were not sufficiently long for accurate reconstruction. A further condition was therefore put on the position of the apex of accepted events to reject events in the last two units.

It was not found necessary to put lateral limits on the fiducial volume as all the observed events were close to the centre line of the spark chamber.

'Well measured' criterion

A V^0 was considered as being well measured if both the measured tracks were longer than 50 cm and if the error word computed in GRIND in subroutine EXTER⁽²⁸⁾ was less than a specified value.

The subroutine EXTER compares the internal errors of track

parameters calculated during the fitting, with external errors calculated from the track length, sagitta and orientation, scaled according to predetermined measured errors.

An upper limit of 8 was placed on the value of the error word calculated for both tracks. As is shown in⁽²⁸⁾ this applies the condition

$$\sigma(\text{INTERNAL}) < 3 \times \sigma(\text{EXTERNAL})$$

where σ refers to errors on the momentum, dip and azimuth of the tracks. The limit also excluded events having tracks which did not converge in the reconstruction. Events in which the internal errors on the reconstructed apex did not satisfy the above relation were not rejected by the limit used.

The dimensions of the chamber, together with the size of the fiducial volume and nature of the observed events, in practice imposed a lower limit on the lengths of tracks of accepted events. The limit of 50 cm was arbitrarily chosen to exclude events which had failed in the reconstruction programmes.

Identification of the incident particle

The combination of anticoincidence and Cerenkov counter outputs which had given the trigger was recorded on each photograph so that the incoming particle could be identified. The only remark to be made is that on about 6% of the photographs the display units did not function correctly so that it was not directly

known whether a K^- or $\bar{p}$ had given the trigger. The nature of the incoming particle had therefore to be inferred from the products of the interaction. Well identified antiproton events consisted almost entirely of $\bar{\Lambda}$ decays. The ambiguous triggers consisted of K_1^0 and Λ decays and so were all assumed to be produced by K^- .

Kinematic selection criterion

The well measured events in the fiducial volume which fitted a K_1^0 decay were considered to be charge exchange events if

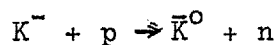
$$|\Delta| < 3 \text{ where}$$

$$\Delta = \frac{P_F - P_\theta}{\sqrt{(\sigma_B^2 + \sigma_F^2)}}$$

P_F was the fitted momentum of the K_1^0 and

θ its scattering angle

P_θ the momentum of a $\bar{K}^0$ produced in the reaction



at angle θ if the K^- momentum was 9.5 GeV/c.

σ_B was 200 MeV/c, the observed r.m.s. spread of the beam momentum and

σ_F the error on the fitted momentum of the K_1^0 .

The parameter Δ is thus a measure of the deviation of the momentum of the K_1^0 from the value expected if the observed event

were charge exchange, taking into account the spread in the beam momentum and the measurement error. An error in the scattering angle Θ would cause an error in Δ but as the momentum P_{Θ} only changes slowly with Θ in the range considered this error is neglected.

For a pure sample of charge exchange events the distribution of Δ should have mean zero and unit standard deviation. The above limit therefore corresponds to a three standard deviation cut-off and should exclude a fraction $1/370$ of the observed events.

The mean value of σ_F for the events selected as charge exchange was 106 MeV/c and the r.m.s. value of $P_F - P_{\Theta}$ was 240 MeV/c.

5.2. Discussion of selected events

The results of applying the above criteria are summarised in Tables I and II. Table I shows the effect of the fiducial volume and 'well measured' criteria. As can be seen, 20% of events outside the fiducial volume were bad measurements compared with only 6% inside. All following results apply only to the measurements inside the fiducial volume. Table II shows how the well measured events were identified and the number of charge exchange and low energy events.

The criteria defined above have not been strictly adhered

TABLE I

Summary of all events found in scanning

Total number of events	535
1. Number inside fiducial volume	412
comprising	
(a) well measured events	378
(b) badly measured events	26
(c) events lost due to labelling	
measurement errors etc.	8
2. Number outside fiducial volume	123
comprising	
(a) well measured events	86
(b) badly measured events	22
(c) events lost as above	15

TABLE II

Well measured events in fiducial volume

Total number of events	378
1. Charge exchange events	294
comprising	
(a) K and Lambda fits	24
(b) K and Antilambda fits	14
(c) K fits only	256
2. Other identified events not charge exchange	72
comprising	
(a) Lambda fits only	42
(b) K fits only	9
(c) K and Lambda fits	18
(d) K and Antilambda fits	2
(e) Antilambda fits only	1
(f) Gamma fits	0
No fit events	12

to in Table II, the range of Δ having been extended. The distribution of Δ is shown in figure 18. The agreement with the theoretical distribution, a Gaussian with unit variance, is good and the separation from the rest of the events very clear except for 8 events just outside the three standard deviation limit . As these events are well separated from the background of low energy events, they have been included in the charge exchange events.

The χ^2 distribution for the events selected as charge exchange is shown in figure 19. The theoretical distribution for a one constraint fit has mean 1.0 and less than 1% of the events with χ^2 greater than 7.0. The observed distribution contained 28 events (9.5%) with a χ^2 greater than 7.0.

For these events the changes made in the measured parameters during fitting were too large in relation to the measurement error and the probability that the fit was a good interpretation of the event was less than 1%.

There were several possible explanations for the presence of a large number of high χ^2 events in the data. The first was that the measurement errors were underestimated. This seemed unlikely as if these events were discarded, the mean χ^2 of the remaining 266 events was 1.03. The second explanation was that they were misidentified events, either K_2^0 , Λ or $\bar{\Lambda}$ which had

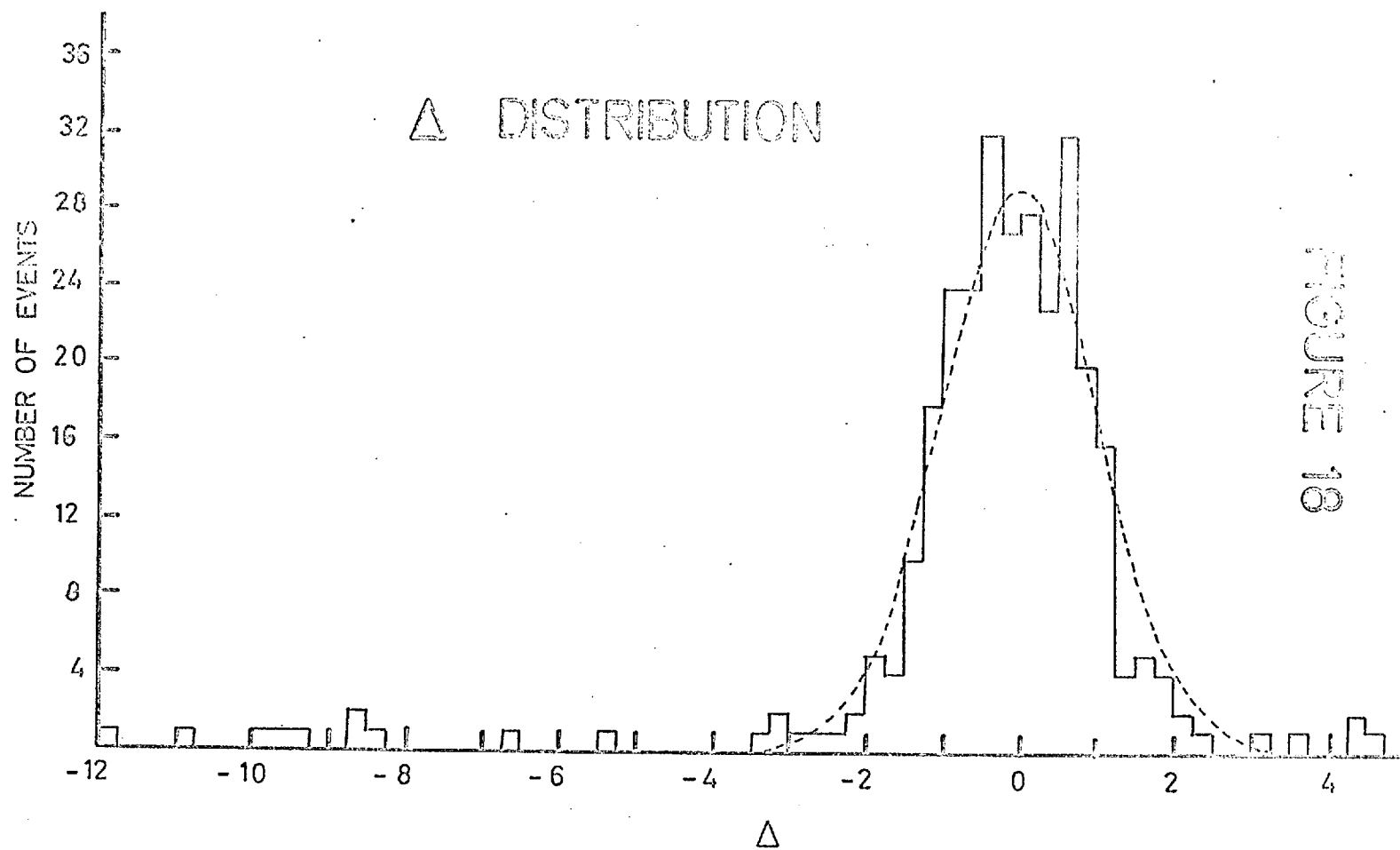


FIGURE 18

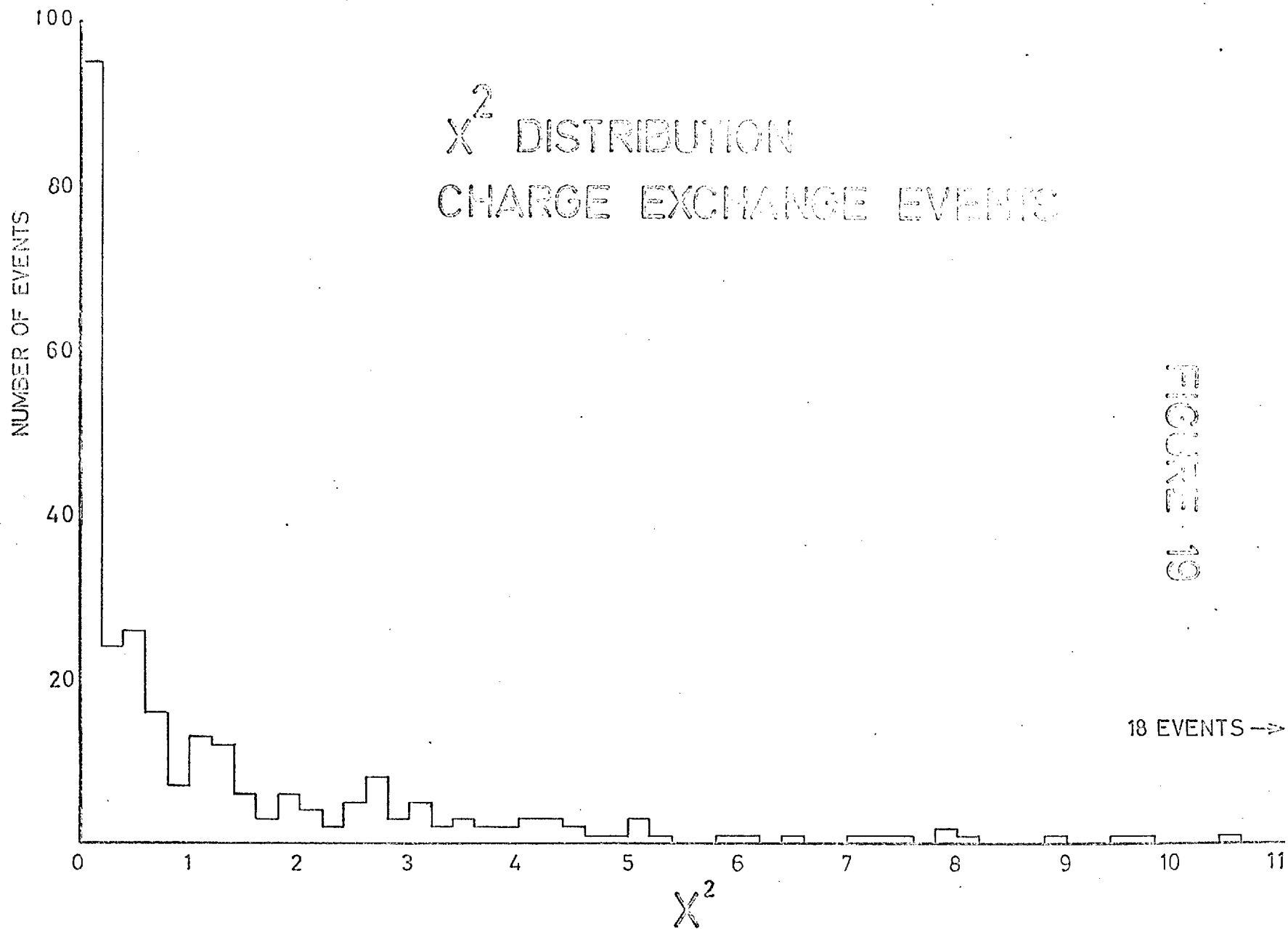


FIGURE 19

given a K_1^0 fit. However, only six of the 28 high χ^2 events fitted lambda or antilambda and the detection efficiency for K_2^0 was of the order of 10^{-3} so that it seemed improbable that most of these events were misidentified. The possibility of there being a small contamination of Λ is discussed below.

It was concluded that the majority of the 28 events had a high χ^2 as a result of some fault in the measurement or analysis and that consequently the calculated parameters for these events were not accurate. Subsequent analysis was performed on the data both with and without the high χ^2 events.

They appeared to be similar in all respects to the rest of the data, except that they had a slightly broader momentum transfer distribution than that of the rest of the data but the effect was not large enough to significantly change the results if they were included.

For the determination of the differential cross section it was desirable to place a limit on χ^2 to obtain a well identified and accurately reconstructed sample of events. Therefore no fit was accepted unless its χ^2 was less than 7.0. The effect of applying this limit to the whole data is shown in Table III.

TABLE III

Data of Table II with χ^2 limit of 7.0 imposed

1. Previous 294 events initially classified as charge exchange are now:-

Charge exchange events	266
comprising	
(a) K and Lambda fits	8
(b) K and Antilambda fits	6
(c) K fits only	252
also	
Lambda fits only	3
No fit (i.e. events for which all fits have $\chi^2 > 7.0$)	25
2. Previous 72 identified events not charge exchange:-

(a) K and Lambda fits	5
(b) K fits only	9
(c) Lambda fits only	47
(d) No fit	11

5.3. Possible sources of background in the charge exchange data

A. Misidentified Lambdas

The possibility of a contamination of misidentified high energy lambdas in the charge exchange data was discussed in Chapter 3. The appearance of three uniquely identified lambdas in the charge exchange data when the χ^2 limit was applied suggested that such a background might be present. Closer examination of the data showed that this was unlikely. All three of these events had also given K_1^0 fits with χ^2 between 7.0 and 10.0. There could therefore only be a significant background if all high energy lambdas had a high probability of also giving a K_1^0 fit. This was certainly not the case for the low energy events (i.e. those with momenta less than 8 GeV/c). The majority of these only gave a lambda fit and the 13 ambiguous events which became unique lambda fits when the χ^2 limit was applied gave a K_1^0 fit with a mean χ^2 of 45.0. Of the 14 antiproton events found in the fiducial volume 12 were identified as being antilambdas with momenta up to 9 GeV/c and only two were ambiguous. It therefore seemed improbable that the three 'unique' lambda fits in the charge exchange data indicated a real contamination of lambdas, this was confirmed by the distributions of the polar angles of decay of the V^0 s.

The $\cos\theta^*$ distribution for the events fitting charge

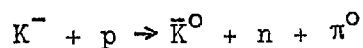
charge exchange in Table III are shown in figure 20, θ^* being the angle between the positive particle and the V^0 line of flight in the V^0 centre of mass, and the suffixes referring to the hypothesis considered. The $\cos\theta_K^*$ distribution contains all events fitting K_1^0 , the $\cos\theta_\Lambda^*$ and $\cos\theta_{\bar{\Lambda}}^*$ contain only the ambiguous events except that the three uniquely identified lambdas have also been included in the $\cos\theta_\Lambda^*$ distribution.

Although there is a slight excess of events near $\cos\theta_K^* = + 1.0$ as might be expected if misidentified lambdas were present it is not statistically significant. The $\cos\theta_\Lambda^*$ and $\cos\theta_{\bar{\Lambda}}^*$ distributions are similar apart from a difference of sign and both are anisotropic as is expected if all the ambiguous events were K_1^0 . The $\cos\theta^*$ distributions for the charge exchange data without the χ^2 limit applied were similar to those discussed above.

It was therefore concluded that there was no evidence of any background of lambdas in the charge exchange data.

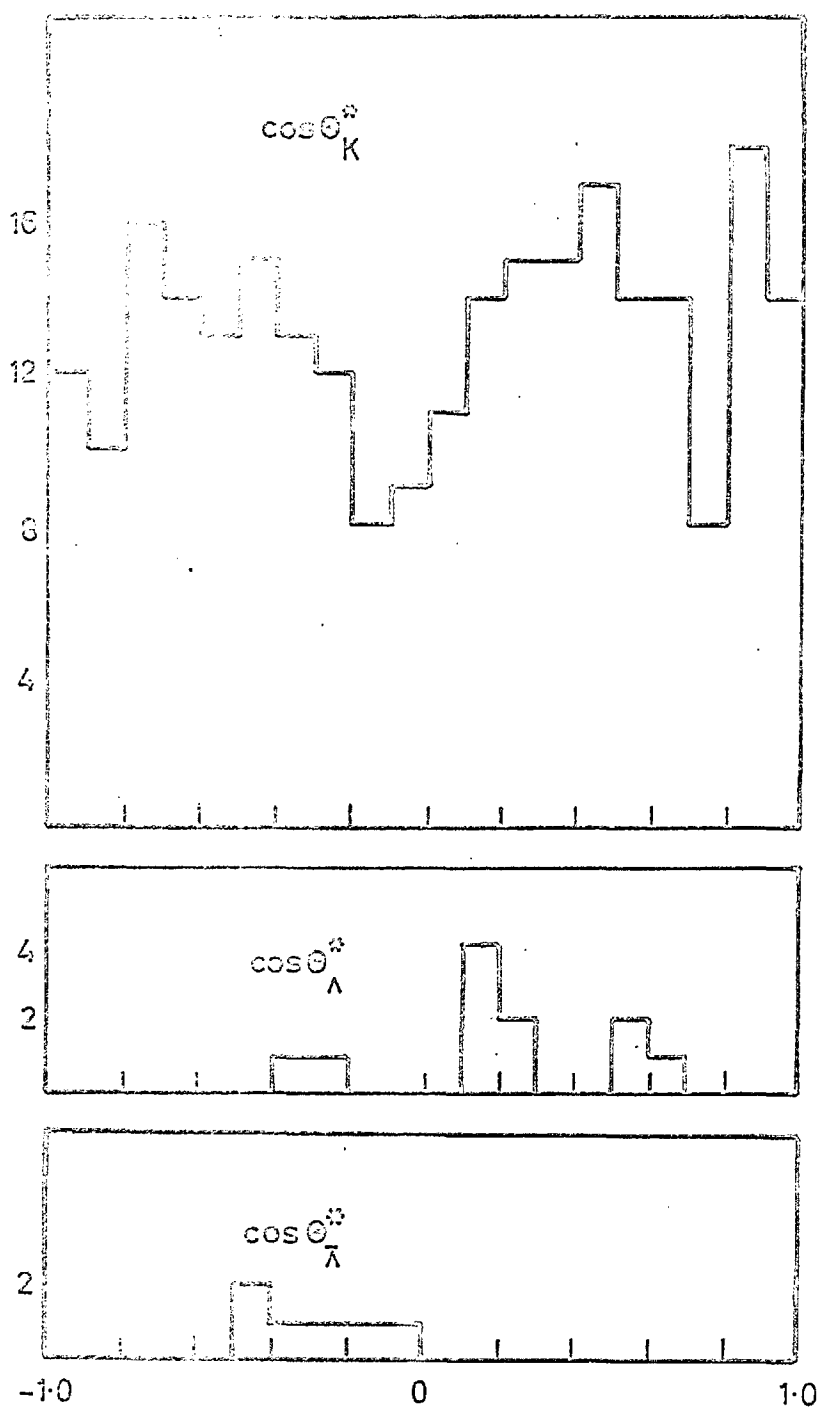
B. K_1^0 associated with N^* production

As discussed in Chapter 3 a background of K_1^0 from the interaction



could be present in the charge exchange data if the n and π^0 were produced from $N^*(1238)$ decay. A large background should show up

FIGURE 20



$\cos \Theta^*$ DISTRIBUTIONS

as an excess of events in the Δ distribution in the region of $\Delta = -1$ as a consequence of the difference in the kinematics of the two processes. Neither in the Δ distribution of figure 18 for the whole data, nor in that of figure 21 for the data with the χ^2 limit applied, is there any significant excess of events. However, the total number of events is small and a 10% contamination might not be detected in this way. From the conclusions reached in section 3.7 a contamination of this magnitude could be present if the cross section for $N^*(1238)$ production was comparable to that of charge exchange. Available experimental evidence suggested that it should be considerably less than this at 9.5 GeV/c. The cross section for the related interaction

$$K^- + p \rightarrow \bar{K}^0 + p + \pi^-$$

had been measured at 3.5⁽³⁰⁾ and at 6 GeV/c⁽³¹⁾. The total cross sections were 880 ± 50 microbarns and 248 ± 23 microbarns respectively. In both cases the interaction was dominated by K^* production, the total contributions of all N^* production to the above cross section were 6% and 10% respectively. The drop in cross section between 3.5 and 6 GeV/c suggests that background from the $N^*(1238)$ interaction should be negligably small at 9.5 GeV/c.

C. Background from other interactions

Another possible source of background was that of high

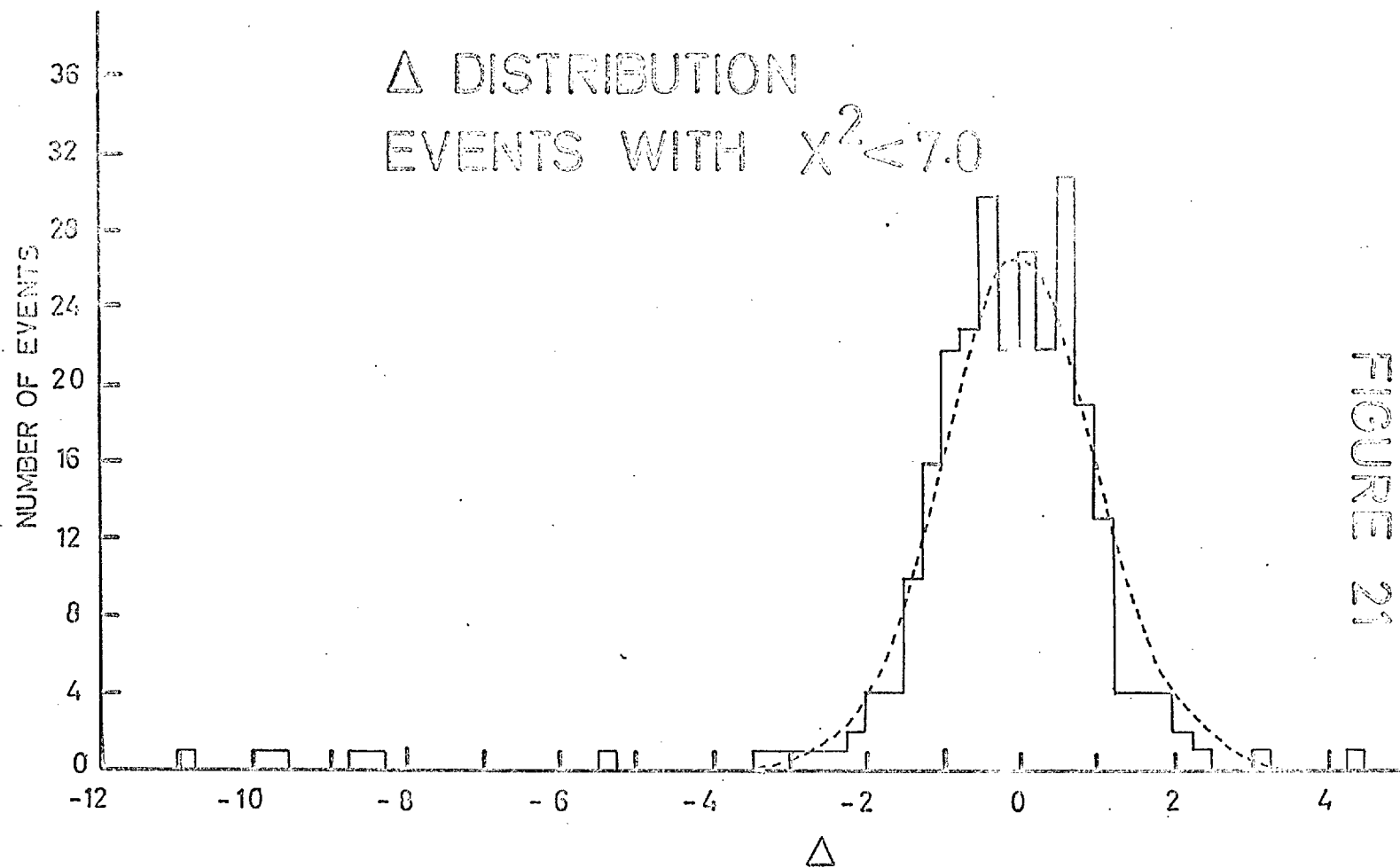
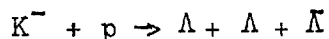


FIGURE 21

energy $\bar{K}^0$ or K^0 produced in the other interactions accepted by the trigger. The probability of detecting high energy K_1^0 decays has been discussed in Chapter 3 and was shown to be small. The presence of a small background would have been detected from the low energy events in the chamber as, with the exception of charge exchange events, the interactions accepted by the trigger which could give high energy K^0 or $\bar{K}^0$ would simultaneously give low energy Λ or $\bar{\Lambda}$.

Figure 22 is a plot of P_T against P_L for the uniquely identified events not classified as charge exchange (Table III) where P_T and P_L are the transverse and longitudinal laboratory momenta of the V^0 . There are no lambdas present with momenta less than 1 GeV/c. Three events consisting of two V^0 were found in scanning. The only one identified was a lambda-antilambda pair so was presumably an example of



One V^0 was identified in each of the other two events, one was a 5 GeV/c Λ and the other a 7 GeV/c $\bar{\Lambda}$.

In the events not classified as charge exchange there was therefore no evidence that the other interactions accepted by the trigger gave high energy K_1^0 which could be interpreted as charge exchange events.

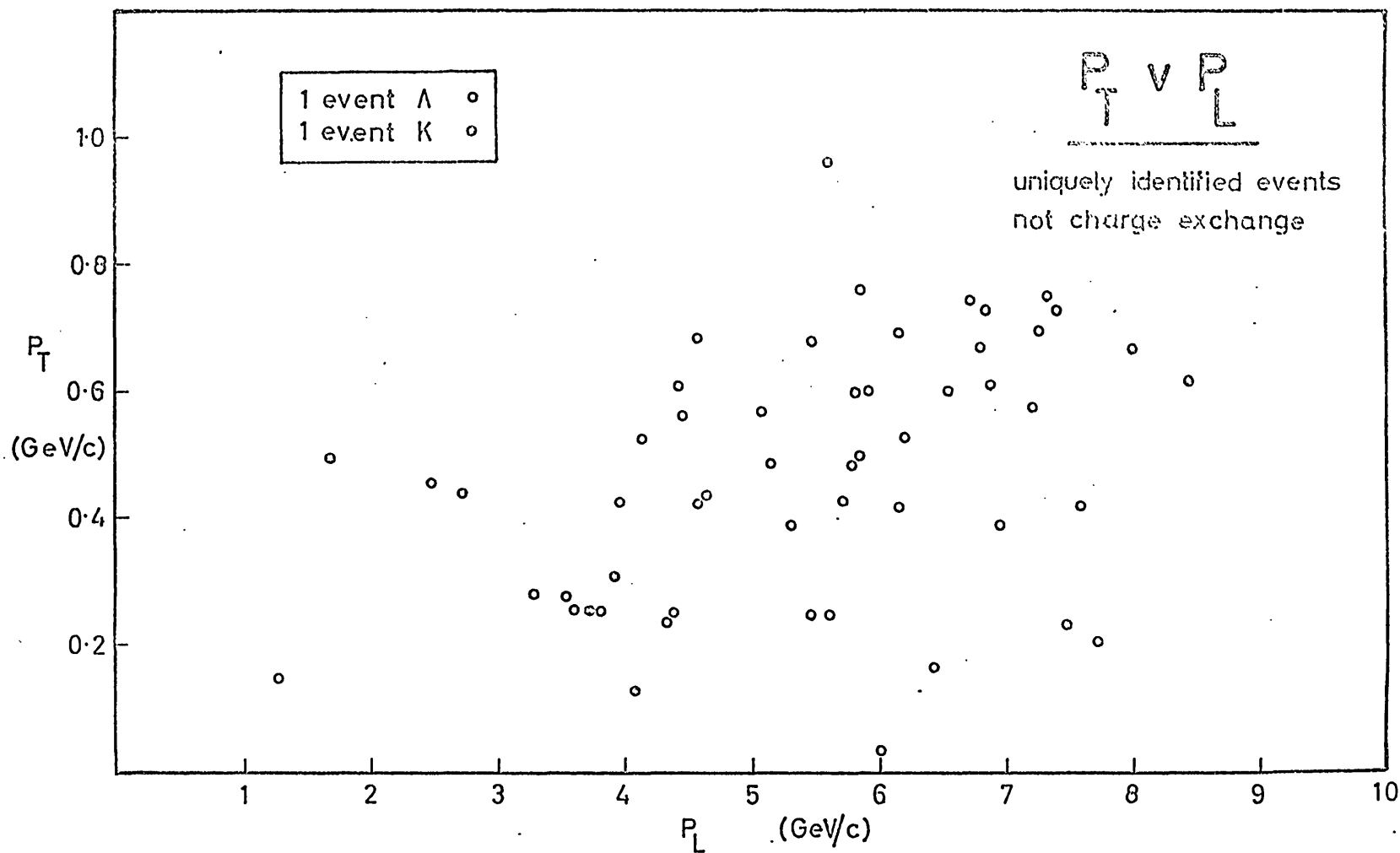


FIGURE 22

D. Background from $\bar{p}$ and π^- interactions

Misidentification of the beam particle could result in a background of high energy K_1^0 from interactions produced by π^- and $\bar{p}$ in the beam. It was shown during a later experiment that few of the K_1^0 produced in π^- interactions had high enough momentum to be confused with charge exchange events. As discussed above the V^0 produced by antiprotons were almost entirely antilambdas. Misidentification of the beam particle should therefore give a negligably small background.

5.4. Determination of the total and differential cross section for charge exchange.

The total cross section was based on the 294 charge exchange events given in Table II. The high χ^2 events were included as there was no evidence that they were not charge exchange events. Corrections were made for badly measured and lost events, i.e. those in Table I section 1.(a) and 1.(b), assuming they were an unbiased sample of the whole data. Three of the No Fit events had momenta consistent with their being charge exchange and were included as charge exchange events. The resulting total number of events was multiplied by the correction factors listed in Table IV to obtain the number of charge exchange events produced by the K^- incident on the target.

In correction (1) the K_1^0 branching ratio of 2:1 for

TABLE IV

Correction factors used in determination of the
total cross section

	<u>Source of correction factor</u>	<u>Value</u>
1.	Decay ratio $\frac{\text{all } K_1^0 + K_2^0 \text{ decays}}{K_1^0 \rightarrow \pi^+ + \pi^-}$	3.0
2.	Anticoincidence losses (section 2.3.)	1.42 ± 0.06
3.	Mean value of $1.0/(\text{detection efficiency})$	2.57 ± 0.04
4.	Neutron interactions in anticoincidence (section 3.6.)	1.09 ± 0.03
5.	Neutral Kaon interactions in anticoin- cidence (section 3.6.)	1.16 ± 0.05
6.	Neutral Kaon and K^- attenuation in target	1.03 ± 0.01

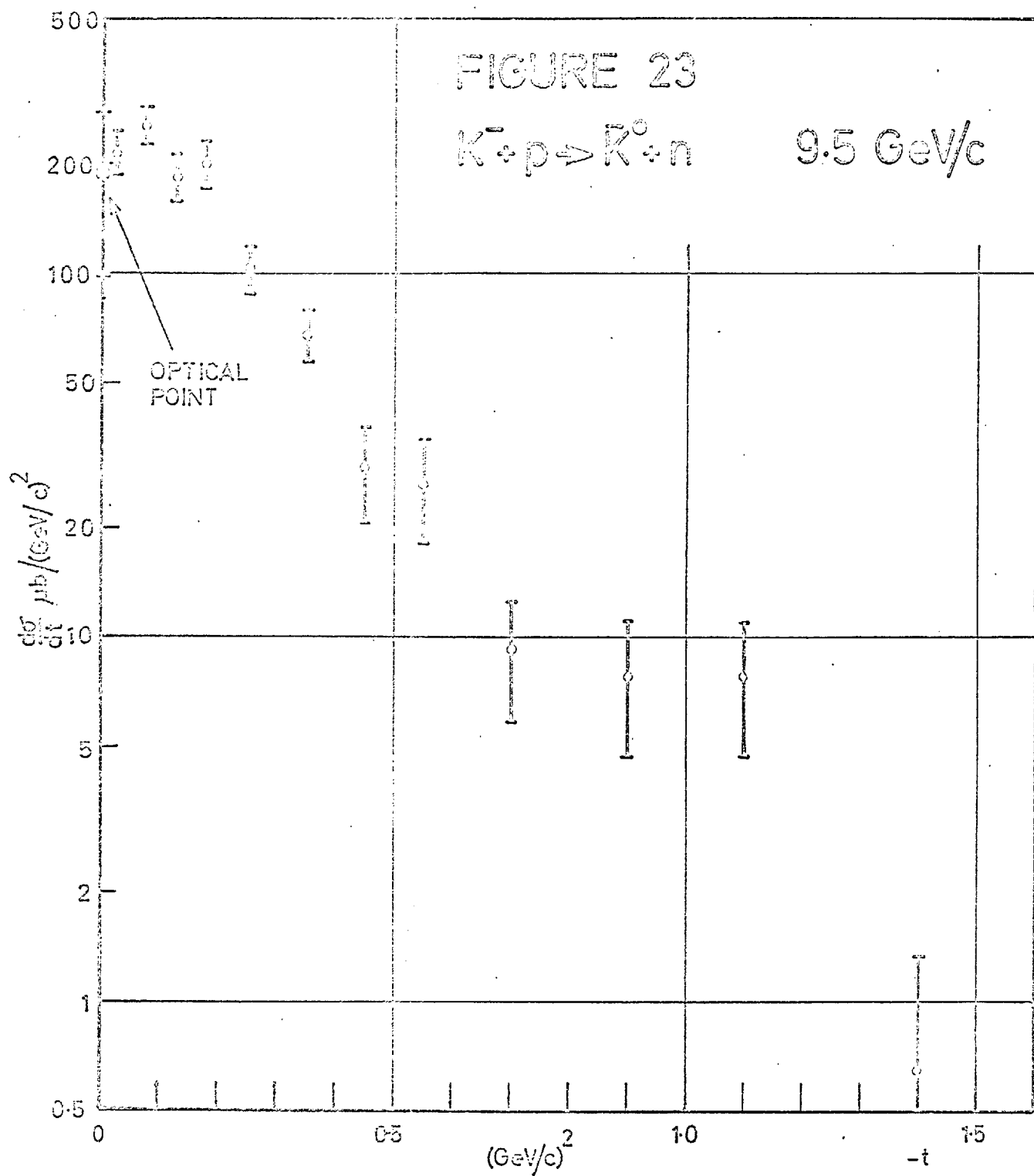
charged: neutral decays has been assumed. This is the value given by the $\Delta I = \frac{1}{2}$ rule, neglecting the small difference due to phase space. The detection efficiency (correction 3) was calculated for each event from its momentum, direction and decay point in the chamber. Correction (6) for attenuation in the target was determined using the measured K^-p total cross sections⁽³²⁾. The other corrections have been discussed as indicated.

From the corrected number of events and the total number of incident K^- which was monitored during the experiment, the total cross section σ_T was determined as

$$\sigma_T = 70 \pm 10 \text{ microbarns.}$$

The value of the cross section given above does not include the contribution of a backward peak. The efficiency for detecting decays of $\bar{K}^0$ produced in a backward peak was very small so that no conclusion can be made as to the magnitude of such a peak. At this energy it should however only be a small fraction of the total cross section.

The differential cross section was based on the 266 well identified events and is shown in figure 23. Appropriate t dependent correction have been applied for the loss of events due to the neutrons detected in the anticoincidence counters. The error in t calculated for each event was approximately 0.005 at $t = -0.05$ and increased linearly with t to 0.04 at $t = -1.0$.



The differential cross section at $t = 0$ was estimated to be

$$\frac{d\sigma}{dt}_{t=0} = 200 \pm 40 \text{ microbarns}/(\text{GeV}/c)^2.$$

The Optical Point, the contribution of the imaginary part of the scattering amplitude was calculated from the K^-p and K^-n total cross section measurements of Galbraith et al.⁽³²⁾ using equation 1.7. The value obtained was $188 \pm 85 \text{ microbarns}/(\text{GeV}/c)^2$ and is shown in figure 23. From this and the measured differential cross section at $t = 0$, the ratio of the real to the imaginary part of the scattering amplitude at $t = 0$ was calculated to be

$$\alpha = 0.09^{+0.7}_{-0.09}$$

5.5. Discussion of differential cross section

The differential cross section exhibits a drop in cross section towards $t = 0$. The error flags are based on the statistical errors so that the effect is a little more than one standard deviation and the possibility that the differential cross section is constant near $t = 0$ cannot be ruled out. It is, however, unlikely to be increasing. Before considering the implications of the observed drop in the differential cross section it is necessary to consider whether or not the effect could be a result of a systematic error.

The narrowness of the forward peak meant that all the events observed were of uniformly high momenta and close to the centre

line of the chamber, it is therefore inconceivable that there is a scanning or measurement bias that could significantly alter the shape of the differential cross section. The only correction discussed above which had a significant t dependence was that for neutron interactions in the anticoincidence counters and although the magnitude of the correction is not known with great precision, the variation at small t is unlikely to be substantially different from the form assumed and is certainly too small to produce the observed effect.

Two systematic errors which could influence the form of the differential cross section remain to be discussed. The first is that introduced by undetected scattering of neutral kaons in the anticoincidence, this having been mentioned in section 3.5. The average change in direction of the kaons was expected to be small as the effect should be dominated by elastic scattering on complex nuclei. It is, however, possible that a small percentage of the observed events could be scattered enough for their momentum transfer to be changed by the order of 0.05 so that the events could be shifted from one point in the distribution to the next. The effect should, however, be a uniform one throughout the range of t observed and the net effect would be to reduce by a few percent the difference between the magnitude of the differential cross section at adjacent points in the distribution. This effect could therefore not produce a dip towards $t = 0$ but would

in fact tend to reduce the dip by a small amount.

The second systematic error could change an exponential t variation of the differential cross section into one similar to that observed. This could happen if the direction of the incident beam had been inaccurately measured. However, to produce the observed effect, the error would have to be of the order of 20 mrad, and the mean direction of the K_1^0 observed in the chamber agreed with the mean beam direction within ± 2 mrad.

It was therefore concluded that the dip found in the forward direction was a small but real effect.

Chapter 6. INTERPRETATION OF RESULTS

6.1. Introduction

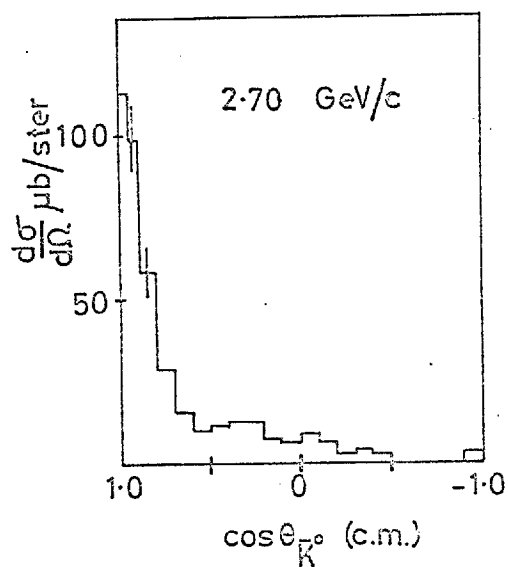
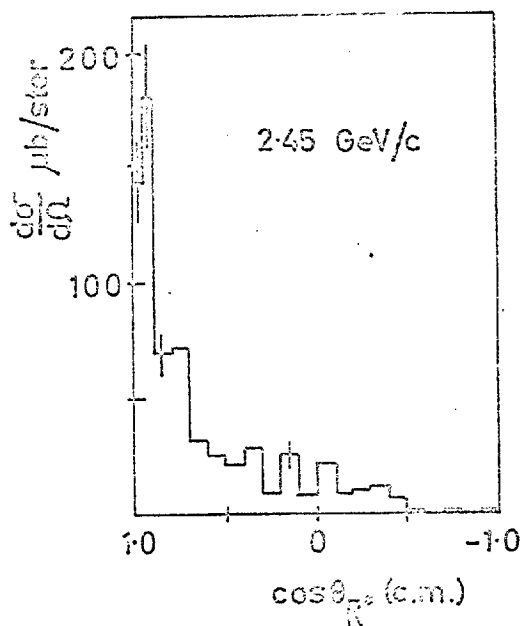
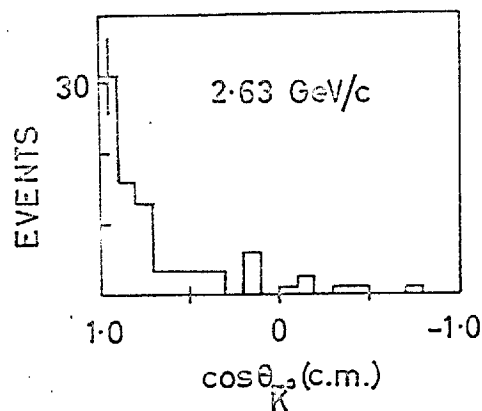
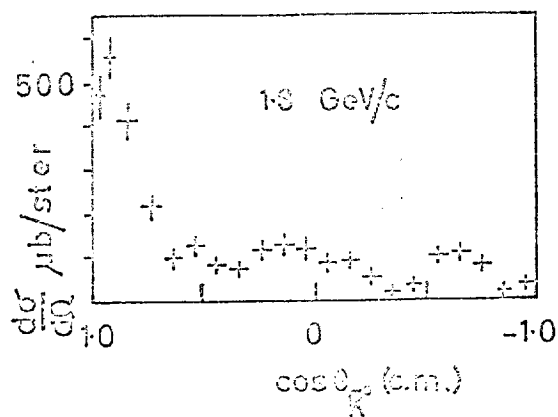
In this chapter the results of the previous chapter are compared with those of other experiments on charge exchange. A review is then given of the predictions of various theoretical models of the interaction.

6.2. Comparison with previous K^-p charge exchange experiments

Most experiments on K^-p charge exchange have been performed at low energies where the interaction is dominated by Y_0^* production. The total cross section⁽³³⁾ shows large peaks at centre of mass energies corresponding to resonant Y_0^* (1520) and Y_0^* (1815) production; above 1.1 GeV/c it decreases with increasing energy.

The differential cross section⁽³³⁾ at low energies has a peak in the backward direction which decreases with increasing energy and is not significant above 1.6 GeV/c. A dip in the forward direction is only found in data at higher momentum (figure 24), at 1.8 GeV/c⁽³⁴⁾ and 2.45 GeV/c, however, at 2.63 GeV/c the dip is no longer significant and at 2.70 GeV/c is replaced by an increase in the differential cross section. The last three experiments were all part of

FIGURE 24



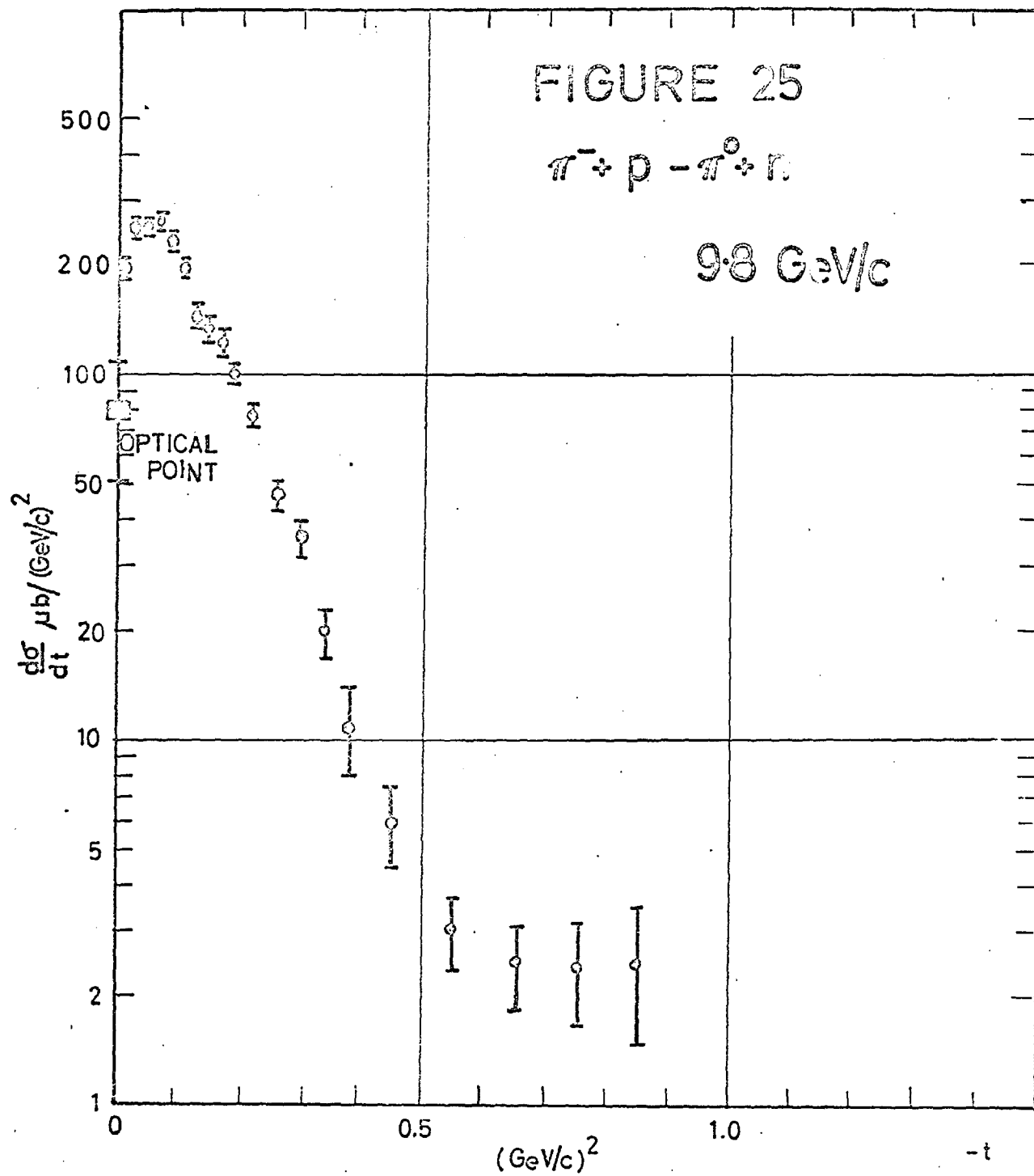
DIFFERENTIAL CROSS SECTIONS

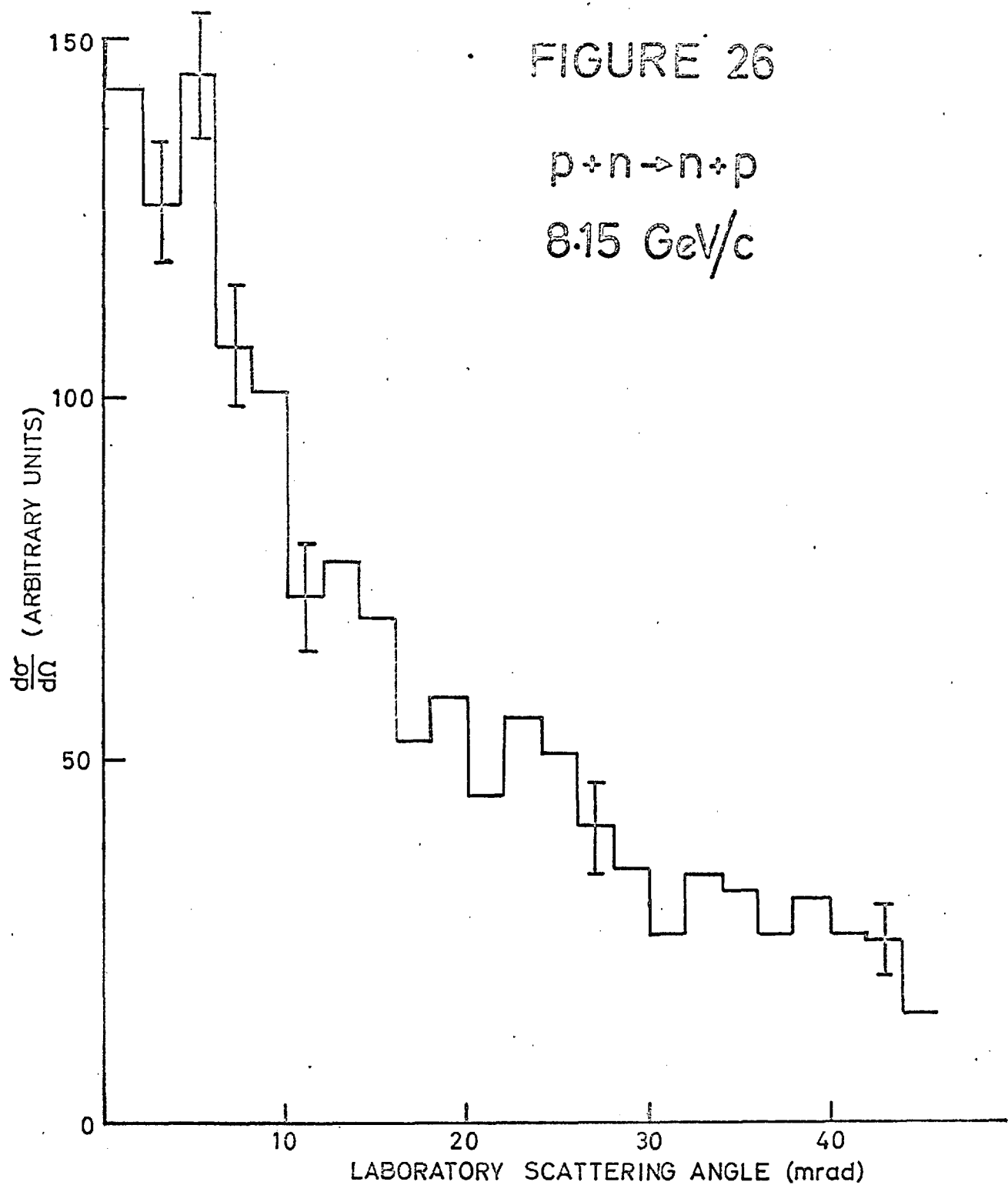
the same experiment⁽³⁵⁾ so that it is unlikely that this change is a result of an experimental bias.

The variation in the charge exchange differential cross section between 1.8 and 2.7 GeV/c may be a consequence of the relation of the interaction to elastic scattering given by equation 1.7. The diffraction peak in elastic scattering is mainly due to shadow scattering resulting from inelastic collisions. In the above momentum range where the number of ^{IN-}elastic channels is limited, changes in one or more inelastic interactions are large enough to produce the observed effects in charge exchange. Thus although the dip in the forward direction found in the present experiment has also been found in some previous experiments, the interaction at lower energies appears more complicated than is expected at 9.5 GeV/c where resonance production and individual inelastic channels should have little effect.

6.3. Comparison with π^-p and np charge exchange at high energies

The present results can be compared with the differential cross sections for π^-p charge exchange at 9.8 GeV/c⁽³⁶⁾ shown in figure 25 and that for np charge exchange at 8.15 GeV/c⁽³⁷⁾ shown in figure 26. None of the three charge exchange interactions had a differential cross





section similar to the respective elastic interactions at similar energies which all have differential cross sections of the form

$$\frac{d\sigma}{dt}_{EL} = e^{a+bt+ct^2} \quad \dots 6.1$$

The np charge exchange has a width consistent with that expected if a pion is exchanged; in the forward direction the angular distribution is flat. The π^-p charge exchange is superficially similar to the K^-p . The differential cross section also drops at $t=0$ and the value at $t=0$ is similar to that of the K^-p . It is, however, considerably narrower than the K^-p and this produces a lower total cross section 48 ± 2.5 microbarns compared with the K^-p value of 70 ± 10 microbarns.

The differences between the differential cross sections for the three interactions reflects the differences in exchange mechanisms discussed in Chapter 1. The π^-p and K^-p are similar and a ρ exchange mechanism was expected to be important in both interactions. Several particles could be exchanged in the $n - p$ interaction, as a consequence its differential cross section was expected to differ from those of the other two interactions.

The value of a calculated for the π^-p is 0.95 ± 0.25 showing that the imaginary and real amplitudes contribute

almost equally to the forward differential cross section.

This is consistent with recent measurements of the real amplitudes of the π^-p and π^+p elastic scattering⁽³⁸⁾. The large contribution of the real amplitude in the charge exchange is obviously related to the difference in the real amplitudes of the elastic scattering interactions, the values of α obtained being $-0.300 \pm .045$ for the π^-p and $-0.109 \pm .024$ for the π^+p . The value of α for the K^-p charge exchange suggests that the K^-p and K^-n real elastic scattering amplitudes are more equal than the π^-p and π^+p , but α is not well enough determined to allow any definite prediction.

6.4. Relation to KN elastic scattering

Although the K^-p charge exchange differential cross section is quite different to that of K^-p elastic scattering it can be interpreted as resulting from a difference in slope of the K^-p and K^-n elastic cross section. At small t the K^-p elastic differential cross section is

$$\frac{d\sigma}{dt}_{K^-p} = e^{a_1 + b_1 t} \left[\frac{(\sigma_{K^-p})^2}{(4\pi)^2} \right] [\text{mb}(\text{GeV})^2] \quad 6.2$$

where $a_1 = 3.62$ and $b_1 = 10.5/(\text{GeV}/c)^2$ (39).

Assuming the K^-n elastic interaction has the same form and that the ~~imaginary~~ ^{REAL} parts of both scattering amplitudes are small, the charge exchange differential cross section can

be written

$$\frac{d\sigma}{dt}_{K^0n} = (e^{\frac{1}{2}(a_2+b_2t)} - e^{\frac{1}{2}(a_1+b_1t)})^2 \quad \dots 6.3$$

Using the Optical Theorem

$$e^{\frac{1}{2}a_2} = \frac{k \sigma_{T K^0n}}{4\pi} \quad \dots 6.4$$

so that the only unknown parameter is b_2 , which is related to the slope of the K^0n differential cross section at small t . A fit to determine b_2 gave a value of $12.5/(\text{GeV}/c)^2$. The charge exchange differential cross section given by inserting this value of b_2 in 6.3 is shown in figure 27. This shows that the dip in the charge exchange cross section at $t=0$ is consistent with the observed experimental behaviour of K^0p elastic scattering at small t if it is assumed that the K^0n elastic scattering has the same form, but has a different slope.

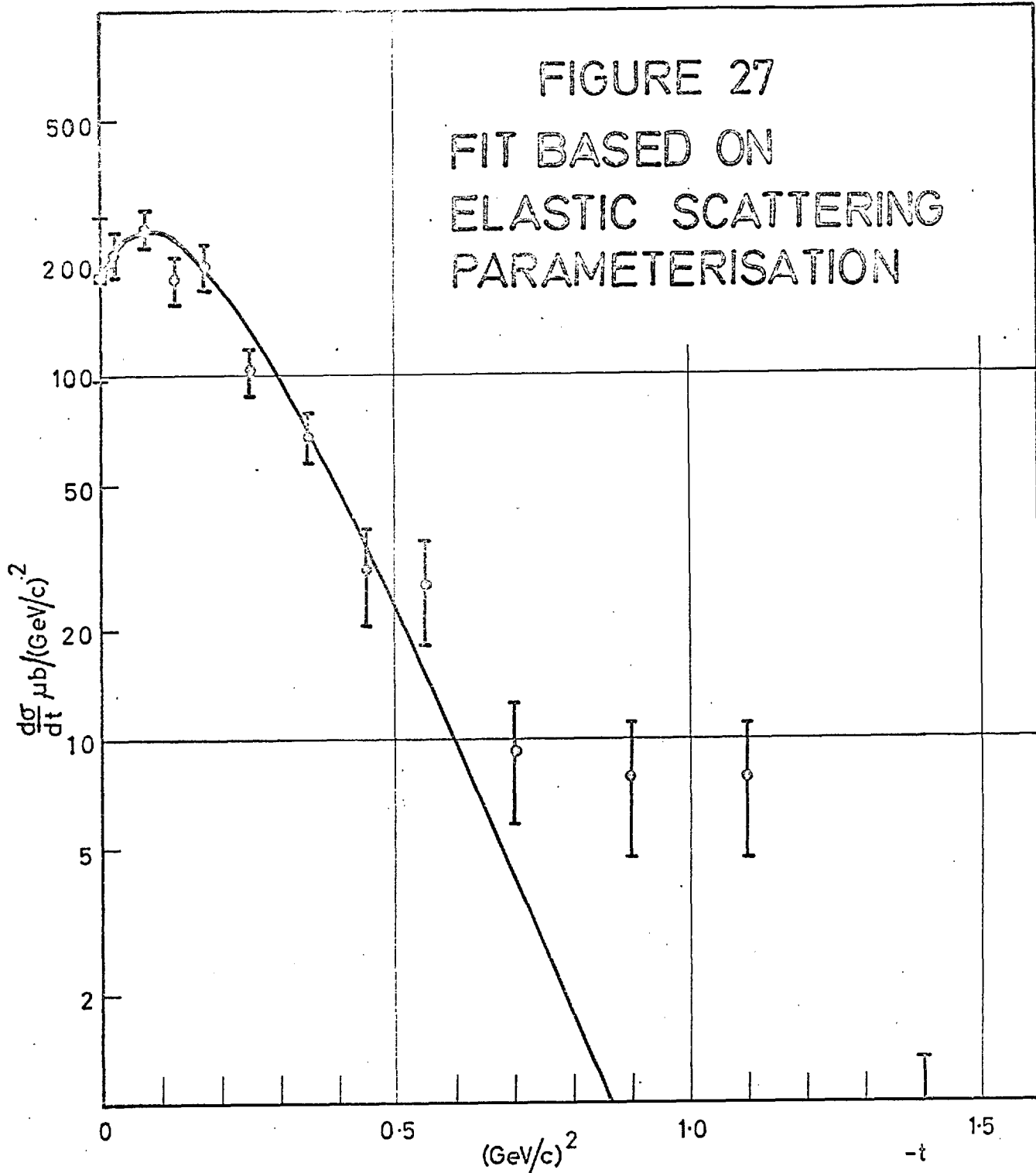
6.5. Spin effects in charge exchange scattering

It has been suggested by both Lovelace⁽⁴⁰⁾ and Phillips⁽⁴¹⁾ that the slope of the charge exchange differential cross section at small t can be explained by a large spin flip amplitude.

The scattering amplitude for the interaction of a spin $\frac{1}{2}$ nucleon with a spin zero particle is

$$A(t) = A_{nf}(t) + A_{sf}(t)$$

FIGURE 27
FIT BASED ON
ELASTIC SCATTERING
PARAMETERISATION



where $A_{nf}(t)$ and $A_{sf}(t)$ are respectively complex non spin-flip and spin flip amplitudes.

$A_{sf}(t)$ has the form

$$A_{sf}(t) = \underline{g} \cdot \underline{n} \cdot f(t)$$

where $\underline{g}$ is the spin direction and $\underline{n}$ the normal to the production plane. Consequently $A_{sf}(t)$ disappears at $t=0$.

The spin-flip and non spin-flip amplitudes can be expressed in terms of helicity amplitudes $G(t)$ and $H(t)$ of the t channel⁽⁴²⁾.

$$A_{nf} = \left\{ G(t) \left(1 - \frac{t}{4M(E+M)} \right) - H(t) \frac{W}{M} \frac{t(t + 4q^2)}{4(E+M)(4M^2 - t)} \right\} \quad \dots 6.5$$

$$A_{sf} = \sin\theta \frac{E-M}{2M} \left\{ -G(t) + H(t) W \left(1 + \frac{4ME}{4M^2 - t} \right) \right\} \quad \dots 6.6$$

where W, E, q, θ are the total energy, nucleon energy, momentum and scattering angle in the centre of mass system.

Amplitudes of this form give a differential cross section

$$\frac{d\sigma}{dt} = \frac{\pi}{q^2} \left[\left(1 - \frac{t}{4M^2} \right)^2 |G(t)|^2 - \frac{t(t+4q^2)W^2}{4(4M^2 - t)M^2} |H(t)|^2 \right] \quad \dots 6.7$$

Lovelace⁽⁴⁰⁾ suggested using helicity amplitudes of the form

$$|G(t)|^2 = G_0^2 e^{at} \quad \dots 6.8$$

and

$$|H(t)|^2 = H_0^2 e^{at} \quad \dots 6.9$$

The differential cross section obtained by inserting these amplitudes in equation 6.7 was used in a maximum likelihood analysis to determine G_o , H_o and a . The results obtained were

$$G_o^2 = 229 \text{ microbarns/steradian}$$

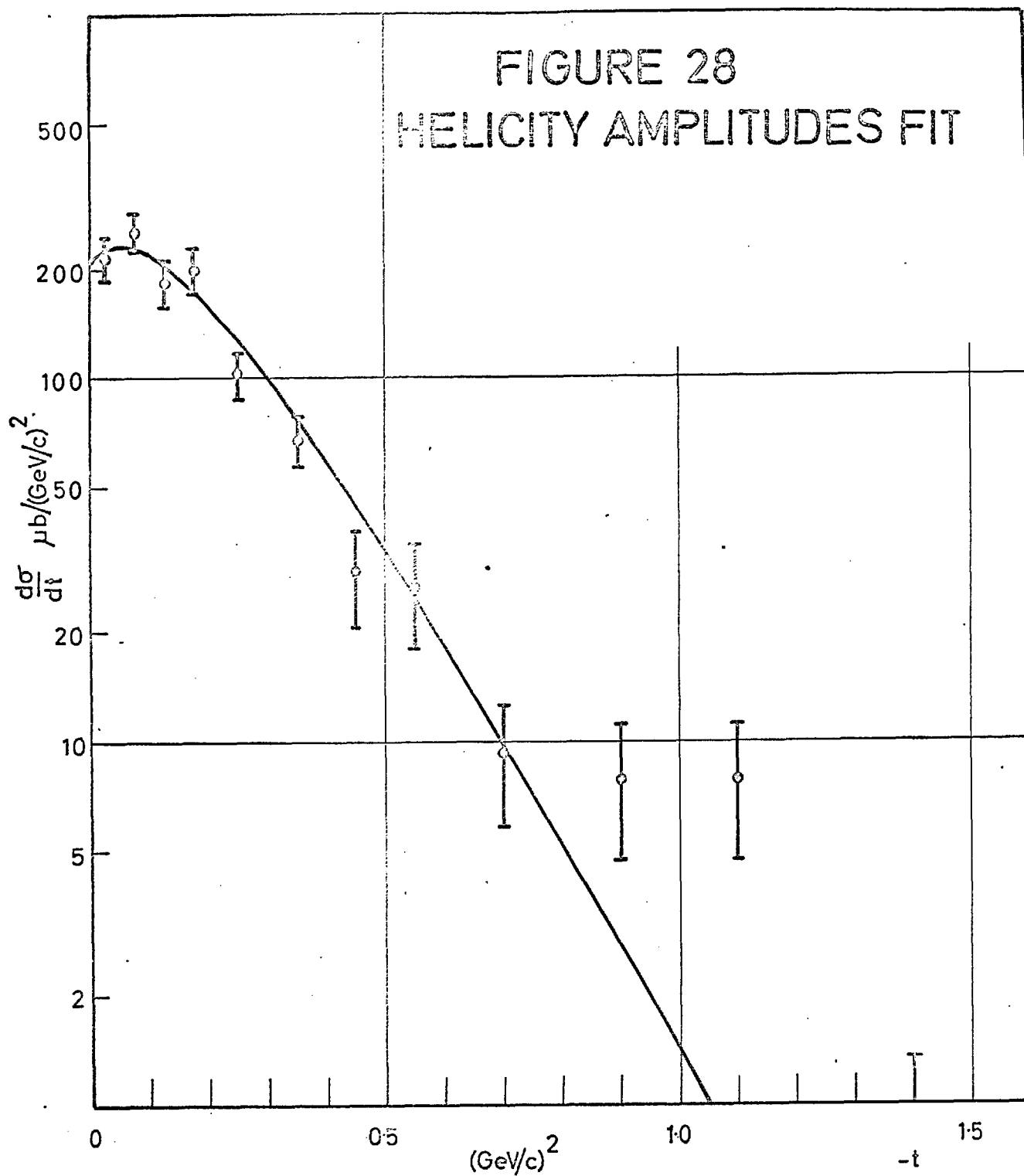
$$H_o^2 = 114 \text{ microbarns/steradian}$$

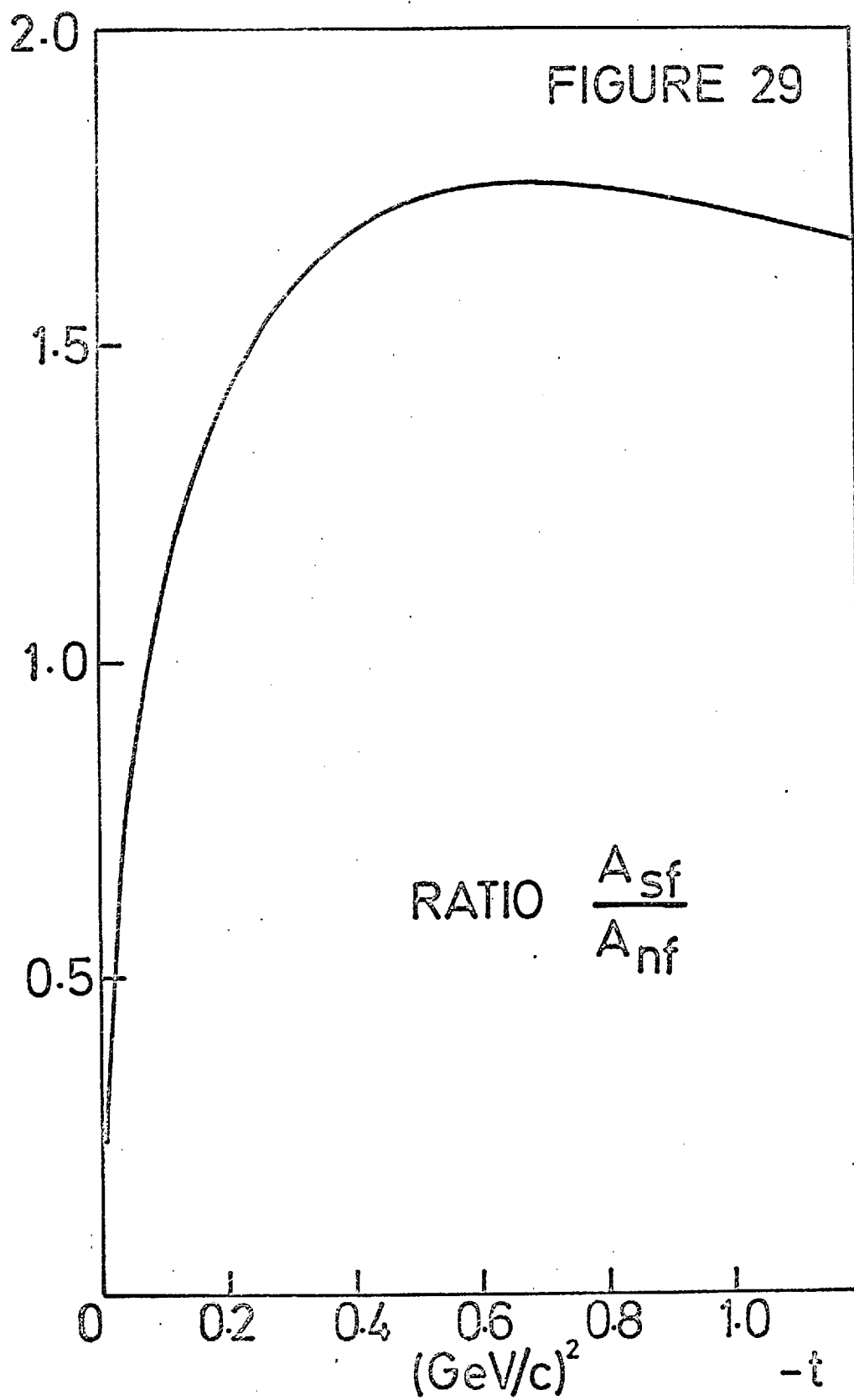
$$a = 7.4 \text{ (GeV/c)}^{-2}$$

The differential cross section is shown in figure 28 and the ratio of the amplitudes A_{sf}/A_{nf} in figure 29. The dip in the experimental distribution is well reproduced and the values of G_o and H_o obtained mean that the spin-flip amplitude makes a large contribution to charge exchange scattering. Both A_{nf} and A_{sf} are much smaller than the corresponding elastic scattering amplitudes so that this is not in contradiction with the assumption that the non spin-flip amplitude dominates elastic scattering.

6.6. One particle exchange model including absorption effects

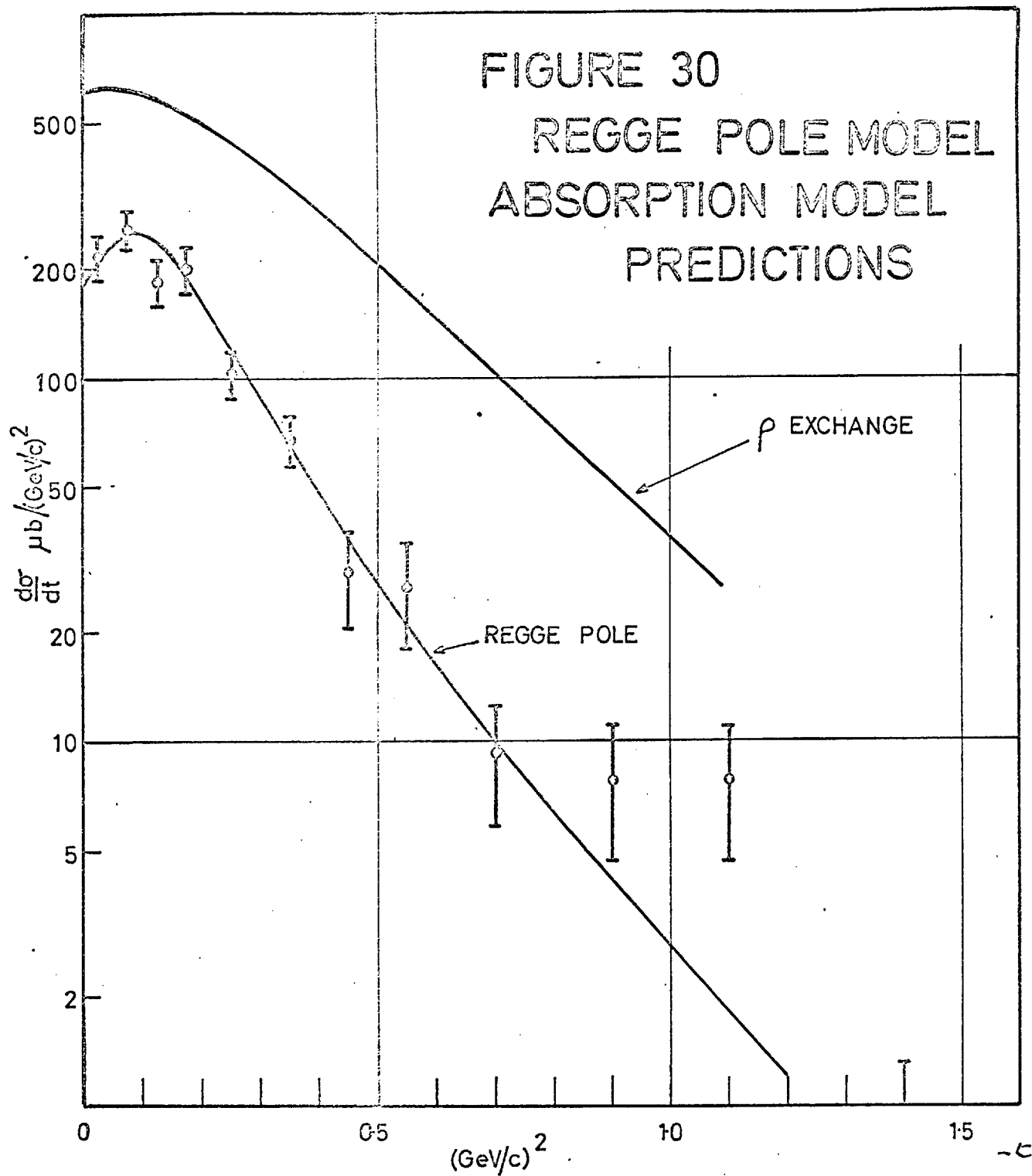
The differential cross section for π^-p and K^-p charge exchange has been calculated by Hogaasen and Hogaasen⁽⁴³⁾ assuming ρ exchange in both cases. The model used was that described by Gottfried and Jackson⁽⁴⁴⁾ namely a Born approximation modified to take into account initial and final





The forms of which state interactions were given by parameters derived from elastic scattering and were assumed to be spin independent. The calculated differential cross section for K^-p charge exchange is shown in figure 30. Although this model is better than the unmodified Born approximation, the cross section is still much too high, particularly at large t . The dip in the forward direction is predicted by the model, but Hogaasen and Hogaasen state that it would disappear if the t dependence was modified to agree with the experiment. The failure of the model in this particular case is considered to be due to the relation of charge exchange to elastic scattering, the model is only expected to be valid for true inelastic interactions whose probabilities are small. ^{In} general the model has only been successfully applied to interactions in which a spin 0 particle is exchanged, when a non-zero spin particle is exchanged the model fails at high energies because of the divergence of the Born amplitude⁽⁴⁵⁾.

Another failure of the model is that it predicts that the K^-p and π^-p charge exchange differential cross sections should have similar form, although the magnitude could differ as a result of the difference in the $\rho\pi\pi$ and ρKK coupling constants, the SU_3 prediction of the ratio of the coupling constants⁽⁴⁶⁾ suggests that the K^-p cross section should be a factor 2 less than the π^-p .



This does not depend on the detailed mechanism of the absorption. Henley and Muzinech⁽⁴⁷⁾ using a different absorption model have made a similar prediction. It therefore seems difficult to explain the observed differences between the two interactions using a one particle exchange model.

6.7. Regge pole model for charge exchange

This has been described in detail in two papers by Phillips and Rarita⁽⁴⁸⁾. In the first one, the effect of the R Regge trajectory on K^-p charge exchange is discussed and in the second a fit is made to all high energy meson - nucleon scattering data using a multi-Regge pole model.

The R trajectory

The R trajectory is one member of an even signature Regge pole octet, proposed by Pignotti⁽⁴⁹⁾. It has I spin 1, parity + 1 and G parity - 1, so that it can in principle contribute to K^-p charge exchange scattering. The R trajectory is close to that of the ρ , so that no spin 0 particle lies on it. The first physical particle on the trajectory was therefore expected to have $J=2$ with a mass of the order of 1500 MeV. The A_2 meson has the required quantum numbers and a mass of 1310 MeV and it has been proposed that it lies on the R trajectory⁽⁵⁰⁾. Ahmadzadeh⁽⁵¹⁾ has shown that the p-p and n-p total cross section differences, together with n-p charge

exchange can be explained using the ρ and R trajectories together but not by the ρ alone. In their first paper Phillips and Rarita show that the same is true for the K^+n and K^+p total cross section differences. The prediction using ρ alone, that

$$\sigma_T(K^-p) - \sigma_T(K^-n) = \sigma_T(K^+p) - \sigma_T(K^+n)$$

is not consistent with experimental results.

Application of R to charge exchange

The K^-p and π^-p charge exchange differences can be explained if the R trajectory is considered. The R cannot contribute to π^-p charge exchange because of G parity. Using the ρ alone a Regge pole model predicts that the forward cross section should be twice the optical limit, in good agreement with experiment. In K^-p charge exchange the real amplitudes of the ρ and R are of opposite sign and the imaginary amplitudes are of the same sign because the two trajectories have opposite signature factors. This means that the forward scattering cross section is dominated by the imaginary contribution, the predicted value being 205 ± 40 microbarns/(GeV/c)² to be compared with the experimental value of 200 ± 40 microbarns/(GeV/c)², the optical limit of 185 ± 88 microbarns/(GeV/c)² and the forward cross section if ρ alone is considered of 370 ± 176 microbarns/(GeV/c)². The figures here are somewhat different to those of Rarita and Phillips which are based

on preliminary cross section data.

In their second paper Phillips and Rarita use a Regge pole model including spin effects to fit all high energy meson total cross section, elastic and charge exchange scattering data. Three poles are used to fit the πN data, the Pomeranchuk pole, a second vacuum pole, and the ρ . For the KN and $\bar{K}N$ data the ω and R in addition are used.

The fit to the data determined various parameters in the assumed forms of the trajectories and residue functions. Constraints were applied so that the final solution did not violate unitarity. A good fit consistent with SU_3 predictions was obtained and several predictions were made including the sign and magnitude of the real amplitude of πp elastic scattering which gave good agreement with experiment. The fit obtained to the K^-p charge exchange at 9.5 GeV/c is shown in figure 30. The fit to the π^-p charge exchange was equally successful.

6.8. Conclusions

The measured differential cross section for K^-p charge exchange at 9.5 GeV/c has a form different from but consistent with that of K^-p elastic scattering. The differential cross section cannot be explained unless a significant spin flip amplitude is assumed, indicating the presence of a small

spin flip amplitude in elastic scattering. A one particle (ρ) exchange model including absorption effects does not give the magnitude or form of the differential cross section or explain the observed differences between K^-p and π^-p charge exchange interactions at this energy. A Regge pole model including contributions both from the ρ and the R trajectory proposed by Pignotti is however successful in all three respects.

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THE CHARGE EXCHANGE $K^- + p \rightarrow \bar{K}^0 + n$ AT 9.50 GeV/c*, **

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We have measured the total and differential

cross sections for the reaction $K^- + p \rightarrow \bar{K}^0 + n$.
The data were obtained during a three-and-a-half

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days' run at the CERN proton synchrotron, using a large magnetic spark chamber in a negative particle beam of $9.50 \text{ GeV}/c \pm 0.20 \text{ GeV}/c$.

A counter telescope defined the beam, and the K^- were selected by two gas threshold Čerenkov counters of the Vivargent type [1]. The average beam intensity was 1.2×10^5 particles per pulse; the ratio of $\pi^- : K^- : \bar{p}$ was $1 : 0.0053 : 0.0009$.

A 40 cm long hydrogen target was mounted inside a 60 cm long anticoincidence counter to discriminate against charged particles and γ rays emitted forwards and sideways. The counter consisted of alternate layers of scintillator and lead (2.8 cm Pb in the forward direction, 2 cm of Pb and 1 cm of Cu at the side).

Thus the trigger system accepted K^- interactions in which no charged particles or π^0 mesons were produced. The accepted interactions were observed in a magnetic spark chamber starting 22 cm downstream from the end of the hydrogen target. The chamber had a useful volume of $60 \times 67 \times 170 \text{ cm}^3$; it consisted of seventy-two 8 mm gaps defined by 25μ aluminium foils, giving a radiation length of 30 m. The magnetic field in the chamber was 10.5 kG, and a typical momentum resolution of $\Delta p/p = 0.017$ was obtained on 160 cm long, 9.5 GeV tracks. With two charged particles passing through the chamber, the percentage of visible sparks was 95%, and with eight particles 60%.

The 7000 photographs taken were scanned twice for V^0 decays; the scanning efficiency on the two scans being estimated as 96% and 99%. In a fiducial volume of $106 \times 60 \times 50 \text{ cm}^3$, 412 events were measured at CERN on IEP measuring projectors and analysed by a modified version of the THRESHGRIND series of programmes.

The charge exchange events were identified by the following criteria:

- 1) The counter logic must indicate an incoming K^- and no outgoing charged particles or π^0 's.
- 2) The V^0 photographed in the spark chamber must fit kinematically the decay of a K^0_1 .
- 3) The momentum and scattering angle of the K^0_1 must fit kinematically the process $K^- + p \rightarrow \bar{K}^0 + n$.

The observed V^0 's were tested for consistency with the hypotheses K^0_1 , Λ^0 , $\bar{\Lambda}^0$. Of the 412 events, 323 satisfied criterion 2), 42 were identified as Λ^0 , 1 as $\bar{\Lambda}^0$, 12 gave no fit and 34 were bad measurements.

The 323 events fitting K^0_1 decay were considered as candidates for charge exchange. To apply the criterion 3), a parameter Δ was defined as:

$$\Delta = (P_{K^0_1} - P_\Theta) / \sqrt{(\sigma_{K^0_1}^2 + \sigma_{K^-}^2)}$$

where $P_{K^0_1}$ and $\sigma_{K^0_1}$ are the fitted momentum of the K^0_1 observed in the spark chamber and its error, P_Θ is the momentum of a K^0 produced in a charge exchange interaction of a $9.50 \text{ GeV}/c$ K^- at the observed scattering angle Θ , and σ_{K^-} is the momentum spread of the beam.

The distribution of Δ is shown in fig. 1, together with a normal distribution which has a standard deviation of 1.0. The 286 events having a value of $|\Delta|$ less than 3.0 have been accepted as a charge exchange, together with a further eight which did not quite satisfy this criterion, but on closer inspection could not be given an alternative interpretation.

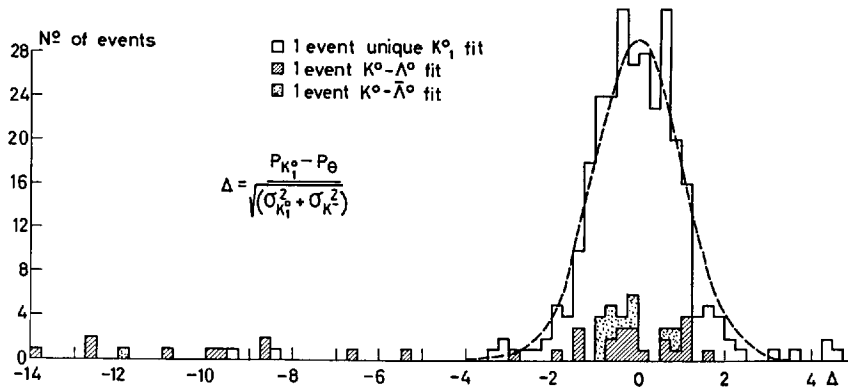
These accepted events still contain a number of ambiguous fits (23 K^0_1 or Λ^0 ; 14 K^0_1 or $\bar{\Lambda}^0$). The distribution of the decay angle in the c.m.s. of the assumed K^0_1 is, however, consistent with negligible contamination by Λ^0 's.

A run with the hydrogen target empty gave no events, putting an upper limit of 3% on the background due to interactions in the target walls, etc. From the measured resolving power of the Čerenkov counters, we expect that the background in the charge-exchange peak due to π^- and $\bar{p}$ interactions, the incident particle being misidentified as a K^- , is negligibly small. Experiments using the same set-up of trigger counters and π^- or $\bar{p}$ as incident particle have shown that a π^- background would be signalled by a large number of low-energy K^0 and a $\bar{p}$ background would be signalled by a large number of high-energy $\bar{\Lambda}$, neither of which is observed.

The background from other K^- interactions must be negligible as the particle or particles associated with a K^0_1 in the charge-exchange peak must have even strangeness, baryon number one and little energy. The last condition rules out Ξ^0 or a $\Lambda^0 K^0$ combination as these would decay before passing the anticoincidence shield.

After applying all corrections, the total cross section was determined as $70 \pm 10 \mu\text{barns}$. The main correction factors are as follows: a factor of 3* for the ratio $(K^0_1 + K^0_2)/(K^0_1 \rightarrow \pi^+ + \pi^-)$, 2.57 ± 0.03 for the probability of decaying inside the fiducial volume, 1.42 ± 0.06 for the loss of events due to chance anticoincidences. Other corrections were applied for losses due to inter-

* We have taken $\frac{2}{3}$ as the branching ratio $(K^0_1 \rightarrow \pi^+ + \pi^-)/$ all K^0_1 according to the $\Delta I = \frac{1}{2}$ rule and neglecting the small difference due to phase space. The corresponding experimental value is 0.694 ± 0.051 [2].

Fig. 1. Distribution of the parameter Δ .

actions of K^- and K^0 in the target and antineutrino shield, and also for loss of events due to bad measurements (these were consistent with being an unbiased sample of the events). The neutron detection efficiency of the anticoincidence counter was calculated by a Monte Carlo programme and was consistent with previous experiments [3].

The differential cross section is shown in fig. 2. The mean error on t is 0.005 at $t = -0.05$ increasing linearly with t to 0.04 at $t = -1.0$. The detection efficiency due to decay probability is effectively constant up to the highest momentum transfer observed $[-2.2 (\text{GeV}/c)^2]$ corresponding to a scattering angle of 170 mrad in the laboratory.

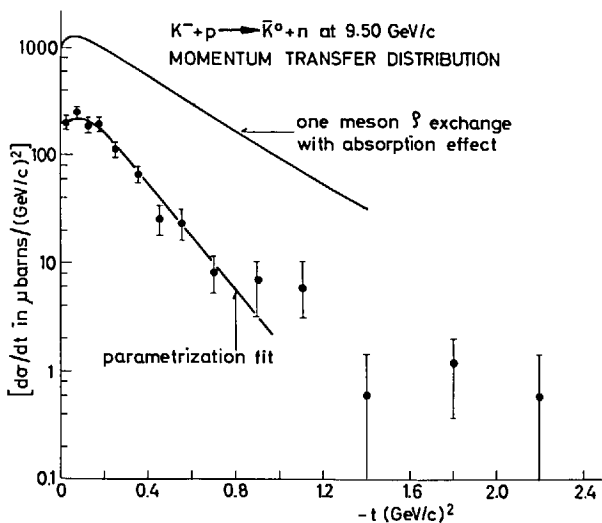
Fig. 2. Differential cross section of $K^- + p \rightarrow \bar{K}^0 + n$ at 9.50 GeV/c.

Table 1
 $\left(\frac{d\sigma}{dt}\right)_{t=0}$ in $\mu\text{barns}/(\text{GeV}/c)^2$ for $K^- + p \rightarrow \bar{K}^0 + n$
 at 9.50 GeV/c.

Optical theorem assuming a purely imaginary amplitude	185 ± 88
ρ Exchange	370 ± 176
$(\rho+R)$ Exchange	245 ± 50
Experimental value at $t = 0.05 (\text{GeV}/c)^2$	200 ± 30

At twice this momentum transfer, the detection efficiency has fallen by less than a factor of 2; the quoted value of the total cross section is thus reliable, provided there is no backward peaking. The shape of the differential cross section is clearly inconsistent with exponential behaviour at low t and similar to the one found for $\pi^- + p \rightarrow \pi^0 + n$ [4].

We have compared our $d\sigma/dt$ with different theoretical models. Table 1 shows the comparison at $t = 0$ with the optical theorem, using the experimental values of $\sigma_{\text{tot}}(K^-p)$ and $\sigma_{\text{tot}}(K^-n)$ obtained by Galbraith et al. [5]. It also shows a theoretical prediction made by a Regge pole model with the exchange of a ρ and $(\rho+R)$ [6]. Due to the large error in the difference between the experimental total cross sections, $[\sigma_{\text{tot}}(K^-p) - \sigma_{\text{tot}}(K^-n) = 1.90 \pm 0.45 \text{ mb}]$, it is not possible to draw any conclusion on the real part of the forward scattering amplitude and on the relative merit of ρ and $(\rho+R)$ exchange.

In fig. 2 is plotted the prediction of a modified one meson exchange model, including absorption effect [7], which is clearly inconsistent with the experimental data. In the same figure we plot the curve obtained by fitting helicity amplitudes [8]; setting

$$\frac{d\sigma}{dt} = \frac{\pi}{q^2} \left[\left(1 - \frac{t}{4M^2}\right) |G|^2 - \frac{t(t+4q^2)s}{4(4M^2-t^2)M^2} |H|^2 \right]$$

where we have assumed

$$|G|^2 = A e^{\alpha t}; \quad |H|^2 = B e^{\alpha t}$$

we fitted the following values:

$$A = 229 \frac{\mu\text{b}}{\text{ster}}; \quad B = 114 \frac{\mu\text{b}}{\text{ster}}; \quad \alpha = 7.4 (\text{GeV}/c)^{-2}.$$

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BRANCHING RATIOS OF K_2^0 DECAYS *

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The ratio of the transition rates for the reactions

$$K_2^0 \rightarrow \begin{matrix} \pi^+ \pi^- \pi^0 \\ \pi^\pm \mu^\mp \nu \\ \pi^\pm e^\mp \nu \end{matrix}$$

has been measured with a magnet cloud chamber, using a nearly monochromatic K_2^0 beam [1]. The knowledge of the K_2^0 incoming momentum allows, for each mass assignment, an overdetermined

kinematical fit with one degree of freedom.

A π^- beam of 1.063 ± 0.038 GeV/c momentum, produced at the CERN Proton Synchrotron, was focused on a 2-m long H_2 target. The π^- momentum has been estimated both by a floating wire measurement and by the magnetic curvature of pion tracks photographed during a preliminary run. Published values [2, 3] of the cross-sections for the reactions

$$\pi^- + p \rightarrow \begin{matrix} \Lambda^0 + K^0 \\ \Sigma^0 + K^0 \end{matrix}$$

enable us to calculate the momentum spectra of the K_2^0 's stemming from both these production

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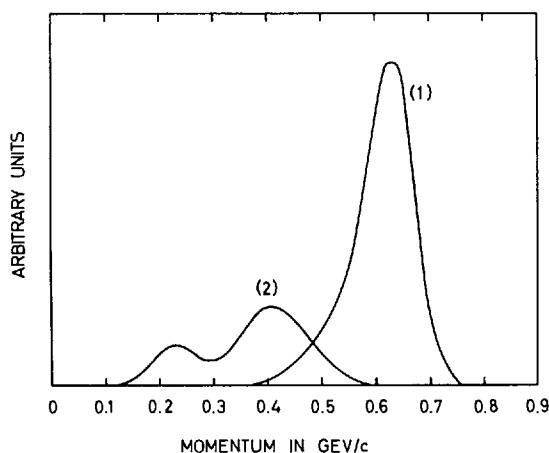


Fig. 1. Calculated momentum spectra of the K_2^0 's decaying inside the chamber:

- i) assuming $\Lambda^0 K^0$ associated production;
- ii) assuming $\Sigma^0 K^0$ associated production; the peak at 0.230 GeV/c is due to K_2^0 's going backwards in the centre of mass; evidence for this peak has been found in the data and the standard error on the Gaussian approximation of the peak at 0.405 GeV/c has been increased to take this into account.

processes and decaying inside the chamber (see fig. 1).

A sweeping magnet, a 10-cm thick Pb gamma absorber, a second sweeping magnet, and the magnet cloud chamber were placed successively along the beam, downstream of the H_2 target. The cloud chamber, which was 7 m distant from the target, has a $40 \times 60 \times 170 \text{ cm}^3$ illuminated volume, and was filled with a mixture of 80% He, 20% A, and alcohol vapour at a total pressure of 820 mm Hg. It was provided with a 26 cm diameter entrance window of mylar, 0.5 mm thick. The 2 MW magnet produces a 10.7 kG field with 3% variation over the illuminated volume.

In six weeks of effective running time, 10 000 useful pictures were taken at the rate of one picture every 4 minutes. The scanning was done on three stereoscopic views, by a physicist and a scanner working together. Low-energy electron pairs (both tracks less than 50 MeV/c) were rejected on the scanning table; 1063 V^0 -type events were found, of which 9 have at least one track ionizing like a proton and cannot be K_2^0 decays. The number of K_2^0 candidates accepted for measuring was 1054.

The measurements were made on a IEP-type projector, and the geometrical reconstruction calculated with the CERN THRESH standard programme. For one of the following reasons, 257 events failed in this reconstruction: track very

short, track distorted, very high dip, or hidden apex. Of these 257 events, 141 have very small opening angles, and since, as we shall see below, the electron pair background is important, these presumably were high-energy electron pairs; the remaining 116 events probably represent K_2^0 decays; the effect of discarding them will be discussed later in this letter.

The 797 well-measured events were analysed with the standard CERN GRIND programme. Three hundred and nine high-energy electron pairs were recognized by their very small opening angle and eliminated from the sample. Fig. 2 shows that the electron pairs are well separated, and that the correction to be introduced for small-angle K_2^0 decays mistaken for electron pairs is negligible.

For the analysis of the 488 remaining events, the K_2^0 momentum spectra of fig. 1 were approximated by two distributions Gaussian in the reciprocal momentum, the one centred at $(0.630 \text{ GeV/c})^{-1}$ with a standard deviation of $(0.048 \text{ GeV/c})^{-1}$, the other at $(0.405 \text{ GeV/c})^{-1}$ with a standard deviation of $(0.095 \text{ GeV/c})^{-1}$. Combining these two K_2^0 incoming momenta with the five decay modes cited above, one obtains 10 decay schemes. Accordingly, 10 kinematical fits were attempted for each event.

It turned out that 48 events fit none of the 10 possible decay schemes (this point also will be discussed later), and that most of the 440 others fit several schemes with comparably good χ^2 values, so that identification of individual events

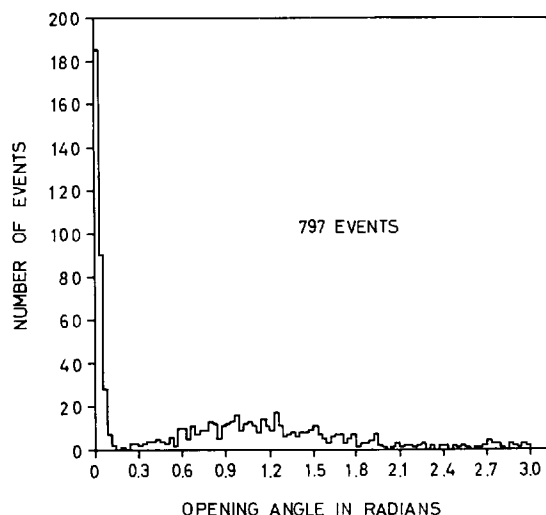


Fig. 2. Distribution of opening angles for all 797 well-measured events.

was often not possible. We therefore generated 5000 Monte Carlo events according to phase space and to the K_2^0 calculated spectra, and analysed them in exactly the same way as the experimental ones; very often a $\pi e \nu$ mass assignment could easily be made to fit a $\pi \mu \nu$ generated decay configuration, whereas the reverse was not generally possible. We therefore determined an *arbitrary* procedure of separation, a set of tests based on the values of the χ^2 associated probabilities of the 10 attempted fits, which *empirically* gives good results for the Monte Carlo events. For instance, in one test, any event which fits either or both of the $\pi^+ \pi^- \pi^0$ decay schemes (with higher or lower K_2^0 momentum assignment) is ascribed to the best of these two fits, regardless of the probability with which the event may fit any leptonic decay. The Monte Carlo events were then used to determine with which probabilities an event generated according to any decay scheme will be correctly classified by this procedure in the mode to which it belongs, or mis-classified in each of the other modes. The same classification probabilities were assumed to be valid also for the experimental events and used to make a maximum likelihood estimate of the best values of the three parameters: % of $\pi^+ \pi^- \pi^0$ decays, % of $\pi^\pm \mu^\mp \nu$ decays, % of events produced in association with Λ^0 . Because no charge asymmetry was observed in the geometrical parameters of our data, no attempt was made to estimate separate branching ratios for $\pi^+ \mu^- \nu$ and $\pi^- \mu^+ \nu$, or for $\pi^+ e^- \nu$ and $\pi^- e^+ \nu$. The effect of form factors was taken into account by giving different weights to Monte Carlo events generated in different points on the Dalitz plot, thus modifying the classification probabilities; for this we used formulae of Pais and Treiman[4], V-A matrix elements, and a form factor ratio of 0.1 for the leptonic decays, and an energy distribution parameter $\alpha = -7.3$ for the $\pi^+ \pi^- \pi^0$ decays [5, 6]. The results, which were not sensitive to the use of these matrix elements rather than pure phase space, were:

$$\Gamma(\pi^+ \pi^- \pi^0)/\Gamma \text{ (all charged modes)} = 0.15 \begin{matrix} + 0.03 \\ - 0.04 \end{matrix}$$

$$\Gamma(\pi^\pm \mu^\mp \nu)/\Gamma \text{ (all charged modes)} = 0.39 \begin{matrix} + 0.08 \\ - 0.10 \end{matrix}$$

$$\Gamma(\pi^\pm e^\mp \nu)/\Gamma \text{ (all charged modes)} = 0.46 \begin{matrix} + 0.08 \\ - 0.10 \end{matrix}$$

$$\text{Percentage associated with } \Lambda^0 \sim 67\%.$$

These results agree with previously reported values [5-8]. The errors quoted here are compounded of the sampling errors and of the possible errors introduced by discarding a certain number of K_2^0 decays from the sample, as discussed

below; the percentage of Λ^0 associated K_2^0 decays obtained by this estimate agrees with the a priori value obtained in the K_2^0 spectra calculations.

The 48 well-measured events which could not be made to fit any of the 10 K_2^0 schemes were analysed again, without putting any constraint on the incoming K_2^0 momentum; 21 events gave K_2^0 fits, most of them with low K_2^0 momentum (3 $K_{\pi 3}$ decays, 1 $K_{\mu 3}$ decay, 8 $K_{e 3}$ decays, 9 decays fitting several leptonic modes). Another 8 of these events were compatible with various background modes, and 19 events remained unexplained.

The 116 events whose geometrical reconstruction did not converge in THRESH were discarded from the sample. THRESH did, however, find first approximations for the geometrical parameters of all but four of these events. A two-dimensional scatter diagram of the transverse momenta of the charged secondaries for these 112 decays was made; 14 very badly distorted events, whose estimated transverse momenta are patently greater than the maximum values kinematically possible in $K_{e 3}$ decay, were neglected, and the distribution of the residual 98 was compared with the corresponding scatter diagram for the 440 accepted K_2^0 decays. This comparison seems to indicate a slight lack of events with low transverse momenta (presumably $K_{\pi 3}$ decays) among the rejected events.

The fact that the different decay modes may not be present in the same proportions within the samples of accepted and rejected events introduces an error which was taken into account by estimating maximum and minimum values for the numbers of events of each mode within the discarded events; the effect this would have had on the branching ratio estimates, had all events been accepted, could then be estimated. These new errors were found to be of the same order of magnitude as the sampling errors, and both were added quadratically to obtain the errors quoted in the results.

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