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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Laboratory for Nuclear Science Technical Report

MEASUREMENT OF THE PROCESS

$$\underline{K^- + P \rightarrow \bar{K}^0 + N}$$

at 8 GeV/c

by

ANDREW BUFFINGTON

DECEMBER 1966

Report No. MIT-2098-301

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MEASUREMENT OF THE PROCESS

AT 8 GEV/C.

by

ANDREW BUFFINGTON

Submitted to the Department of Physics on December 15, 1966, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

ABSTRACT

The MASCOT system has been used to measure kaon elastic charge exchange scattering at an incident momentum of 8 GeV/c with a liquid hydrogen target. The measured total cross-section is 71 ± 21 microbarns, based on analysis of a fifth of the data. An angular distribution of the process has also been measured. This paper contains the details of design and construction of the MASCOT system as well as its calibration and application to this particular reaction.

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TABLE OF CONTENTS

	<u>PAGE</u>
ABSTRACT	2
TABLE OF CONTENTS	3
TABLE OF APPENDICES	4
I. INTRODUCTION	5
II. DESIGN CRITERIA	7
III. DESCRIPTION OF THE EQUIPMENT	12
IV. THE BEAM TRANSPORT SYSTEM	23
V. THE ELECTRONICS	26
VI. THE 1966 RUN	29
A. TABLE I: PARAMETERS OF THE RUN	33
B. TABLE II: COMPOSITION OF THE PICTURES	34
VII. ANALYSIS OF THE DATA	35
A. TABLE III: RESULTS OF MEASUREMENT OF THE PICTURES	43
B. TABLE IV: CALCULATION OF CROSS-SECTION	56
VIII. CONCLUSION	58
LIST OF FIGURES	60
FOOTNOTES	105
ACKNOWLEDGEMENTS	107
APPENDICES	109
BIOGRAPHICAL NOTE	132

TABLE OF APPENDICES

	<u>PAGE</u>
APPENDIX A	THE TECHNICAL DETAILS OF ARGO MAGNET 109
APPENDIX B	CONICAL MIRROR SYSTEMS 111
APPENDIX C	OPTICAL CALIBRATION OF THE MASCOT SYSTEM . . . 114
APPENDIX D	HYDEL MACHINES AND ACCURACY OF MEASUREMENT . . 121
APPENDIX E	LISTS OF DRAWINGS 126
APPENDIX F	RESOLVING TIME MEASUREMENT 127
APPENDIX G	COMPOSITION OF THE PICTURES 129

I. INTRODUCTION

The MASCOT system¹ was conceived in the summer and fall of 1962 as a device to measure final states induced by gamma-rays incident on various target materials at the Cambridge Electron Accelerator. It was to operate in an energy range for which the final states contain one or more neutral V-particles, and was to cover a large solid angle. Inevitably, then, its design was flexible enough to permit measurement of analogous pion- or kaon-induced reactions.

The data to be presented here is part of the results from a run made with the equipment early this year in the $4\frac{1}{2}^\circ$ beam at the Brookhaven A.G.S. Negative pions and kaons in the incident beam at 8 GeV/c were separately triggered on.²⁴ Although the trigger conditions permitted observation of any kaon-induced reactions into neutrals which had at least a single V-particle in the final state, and any pion-induced reaction into neutrals which had at least two V-particles, the data presented in this thesis will be the results of observation and measurement of kaon elastic charge exchange:

The total cross-section and shape of the angular distribution of this reaction are of interest as a test of Regge-Pole and absorptive model theoretical calculations.²¹ $K^- + P$ charge exchange angular distributions of data taken at incident momenta from 5 to 12 GeV/c have been fit successfully with a Regge-Pole model.^{16,17,22} It would also be of interest to

observe if reaction (1) occurs appreciably with the kaon produced near 180° in the center of mass system. Backwards peaking has been observed in pion-proton elastic scattering^{19,20} and in certain inelastic reactions²³. If backwards peaking is caused largely by a baryon exchange mechanism, and if we consider that there are no baryons of positive strangeness yet observed which could provide the exchange for $K^- p$ charge exchange, we would then predict the absence of a backwards peak in K charge exchange.

Part II of this paper will describe more fully the design criteria for the equipment. Part III will describe the detailed nature of the construction, assembly, and performance of the equipment. Part IV will describe the beam transport system, Part V the electronics, Part VI will give a brief summary of the parameters of the run from which the data was taken, and Part VII will describe the data analysis techniques and the results. Part VIII is a brief summary and comparison with other experimental measurements of the charge exchange process. The various appendices will be referred to, as relevant, in the text. Appendix E is a complete listing of the drawings of the equipment of the MASCOT system.

II. DESIGN CRITERIA

The following considerations were important in fixing the design:

(1) Short Decay Lengths.

At the time of the MASCOT development the energy ranges of interest for V-particle reactions involved had K and Λ V-particles of energies from roughly $\frac{1}{2}$ to 3 Gev, and hence mean decay lengths of several centimeters.

(2) Small Cross-Sections.

Reactions involving V-particles with pions and kaons incident on protons are typically 10^{-3} of the total cross-section. Such rare reactions can be observed in quantity by examining a large number of reactions, as is done by bubble chamber groups. Another technique for observing these rare reactions involves using a selective trigger which prevents the recording of the event unless it has a good chance of being an interesting one. If one is observing interactions of negatively charged beam particles with protons, a trigger highly selective for neutral V-particles can be made by using a scintillator anti-coincidence system. To achieve reasonable detection efficiencies for the V-decays the target-scintillator complex for such a selective trigger has to be small, of the order of the mean decay lengths above.. A small target in turn demands a large solid angle array of detectors outside, so as to have a reasonably large number of events from complex final states without having unusually long experimental runs.

(3) Topology and Measurement Accuracy.

The sizes of the detectors outside the target were fixed both by the momentum accuracy we desired on the measurement of charged

secondaries, and by the condition that we wanted also large solid-angle detection of gamma-ray secondaries. The momentum analysis was important for the unambiguous identification of K^0 and Λ decays, and for the rejection of e^+e^- pairs, whose occurrence looked like V-decays in the chambers. The momentum analysis was also important for the determination of missing masses and other kinematical quantities for reactions containing measureable V-particles. The gamma-ray detection was intended as a further aid in classification of final states, as well as visual rejection against the e^+e^- pairs. Ultimately we hoped to measure the gamma-ray tracks and use the added information to analyze complicated reactions such as

which could not be unambiguously identified with measurement of just the V-particle products.

In choosing the size of the momentum analysis region, we considered that a typical experiment using this equipment would be a measurement of the "missing mass" in a reaction in which a beam particle of known momentum, interacting in hydrogen to produce a single K^0 or Λ^0 and unseen neutral other products, made a V-particle which was then measureable in the detectors. The missing mass M of the unseen products was given by:

$$M^2 = (E_{\text{total}} - E_{\text{observed K or } \Lambda})^2 - (\vec{P}_{\text{total}} - \vec{P}_{\text{observed}})^2 \quad (3)$$

While trying sets of typical numbers in this equation, we found for a beam momentum of about 4 Gev/c and reasonable angles of production that a 2% measurement accuracy on the momentum of the charged prongs of the K or Λ would in general lead to a resolution of about $\pm 50 \text{ Mev/c}^2$ on the determination of M. Since we were satisfied with resolution of this approximate amount, we used this 2% requirement to determine the size of the momentum analysis region. The large solid-angle requirement meant the momentum measurement, target, and other equipment would have to be entirely within a magnetic field, as no large-aperture magnets existed at that time which would cover a satisfactory fraction of the solid angle. For measuring the radius R of the curved trajectory of a particle with momentum P in a magnetic field,

$$\Delta P/P = \Delta \delta / \delta = 8 R \Delta \delta / \ell^2 \quad (4)$$

where δ is the sagitta of a length ℓ of the curved track, and $\Delta \delta$ is the accuracy with which this sagitta can be measured. For a 15 kilogauss magnetic field R is typically 2 meters; for bubble chambers and spark chambers $\Delta \delta$ is typically $\frac{1}{2} \times 10^{-3}$ meters. Our requirement of $\Delta P/P \approx 2\%$ then yielded an ℓ of about 2/3 meters. The equipment thus had to be at least this large, in order to accommodate the momentum accuracy requirement, and was slightly enlarged to include the lead-plate spark chambers we chose to use for our gamma-ray detectors.

(4) Further Trigger Selectivity.

In an attempt to provide an even more selective trigger than that of the scintillator anti-coincidence system, we included in the design a hodoscope which could put a demand for charged secondaries into the trigger condition.

A more detailed description of the equipment starts in the next section. The design was completed in the late spring of 1963, and in 1964 the equipment was assembled and tested at Brookhaven Laboratory. A preliminary run was made early in 1965 with an unseparated negative pion beam incident at 5.4 GeV/c. The main run, from which the data for this thesis has been taken, was made a year later in a physically unseparated negative beam at 8 GeV/c in which the kaon component was electronically separated by Čerenkov counter. The aim of this main run was the observation of the reaction

in order to study the mass spectrum of the $K^0\text{-}\bar{K}^0$ system. The amount of data of this type gathered, however, was a factor of nine below the expected amount. This disappointing outcome came from the combined effects of a factor of three error made in the original estimate of the number of events to be expected, from a cross-section half the size we originally assumed in the estimate calculation, and from a Λ detection efficiency $2/3$ lower than that assumed in the calculation. The lower Λ efficiency was caused by an unfavorable momentum distribution; the mean Λ momentum for this reaction was enough lower than our original estimate so that many more Λ 's decayed within the anti-coincidence scintillator.

The kaon elastic charge exchange reaction was selected as the simplest data first to extract from this run. The treatment of this reaction is the first result from either run.

III. DESCRIPTION OF THE EQUIPMENT

The magnet "Argo" was designed by D.D.Jacobus, M.S.Livingston, and T.Collins of C.E.A.. It is shown schematically in Figure 1. A detailed technical description of its properties is given in Appendix A. Its special features were a very uniform field intensity and a very little flux leakage outside of the steel flux return. These features were achieved by adopting a very simple pancake coil shape and by enclosing coils and magnetized volume entirely in a thick steel flux return. The number and sizes of access holes to the spark chamber were minimized. Many design details, particularly those having to do with the optics and electrical connections for the spark chamber system, were complicated profoundly by this limit on the access.

The race-track shape of the magnetized volume permitted a configuration of chambers and hodoscopes as illustrated in Figure 2. This arrangement of target and detectors featured longer momentum analysis length in the downstream direction, where the high-momentum harder-to-measure products most often go. The momentum analysis (and V-decay) region was between the anti-coincidence scintillator and the outermost set of spark chambers. This region had to be kept as free as possible of material in order to reduce multiple-scattering error in the momentum analysis and to reduce false triggers and backgrounds resulting from the pair production process. The resulting error in momentum analysis and its effect on measurement of kinematical and geometric quantities relevant to our experiment are discussed in Appendix D. The various trigger backgrounds are discussed in Appendix G.

The light from the cylindrical spark chambers was brought out through a hole in the pole piece of the magnet; the diameter of the hole was much smaller than that of the chambers. This was accomplished by a system of conical mirrors for each chamber arranged as in Figure 3. Appendix B discusses the relevant properties of conical mirror systems.

Also shown in Figure 3 is a symbolic representation of the rest of the optical system. It consists of two plane mirrors, a parabolic mirror, and an aperture which is placed in the hole in the second plane mirror, directly in front of the camera lens. This system selects light from sparks which is nearly parallel to the axis of the spark chambers.²

During assembly the pair of cones viewing each chamber was adjusted to be coaxial. The construction of the chamber was such that the axes of the two cones were parallel to better than a quarter of a milliradian (a level below which non-parallel axes made no measureable difference to the sparks being viewed through the system). The male conical mirror was then translated perpendicular to the optical axis until our conditions on concentricity were satisfied. To set these conditions of concentricity, we established a telescope looking along the optical axis from below the chamber. We then sighted on a radially scribed grid placed with its center on the optical axis above the spark chamber whose cones were being adjusted. Then the male cone was translated until complete symmetry was observed for the radial lines viewed through the conical mirrors. Since the original assembly of the equipment a more accurate optical technique has been developed, enabling us to measure the amount of unalignment for each set of conical mirrors. The results of the measurement, accurate to about .002 inches in the location of the male

cone axis relative to the female cone axis, have shown that our original alignment was good to within $\pm .010$ inches on all the upstream mirror pairs; but on the downstream mirror pair an error of $.090$ inches occurred. The poor alignment for this chamber was caused by difficulty in finding the correct location of the optical axis for the downstream chamber (because the chamber was half-cylindrical, we could not easily tell when we had achieved symmetry for our sighting on the radial pattern). We have taken the unalignment on the downstream mirror pair as well as a small unalignment on one of the upstream mirror pairs into account in the data analysis program.

The spark height information was provided by a fan-mirror array mounted above the chamber which provided a 60° stereo view.^{2,3} The choice of the number of mirrors and the 3° tilt angle resulted from the conditions that no reflected spark should be more than half obscured by the spark chamber electrode but that the accuracy of measurement of height should be sufficiently fine that the error in height measurement would not be the major contributor to errors in the measured kinematical quantities for our experiment. The tilt of the mirrors was chosen so we would be able to measure to 1% of the total height of the chamber, or about $\pm .4$ inches in the chamber, if we could measure a spark blob on the film to 10 microns. Actually the first condition (non-obscuring of the reflected image of the spark) was not met for the first few gaps of the innermost chamber, and we were forced to double in the data analysis program the error estimate for height measurement in that chamber.

The spark chambers were assembled on top of the conical mirror systems.⁴ The spark chambers had mating pieces machined to $.005$ inches tolerance, so each chamber was concentric to about that amount with its

female mirror cone. The chambers were assembled and checked to be coaxial to about $\pm .03$ inches. The distance between the upstream and downstream chamber centers also was known to the same accuracy. Later, in the calibration procedure, we took into account small amounts of parallel displacement of the chamber's axes from their theoretical locations. In our selection of the calibration parameters we insisted on agreement within these errors of the values of these directly measured quantities.

The glass and plastic supports under the chambers, as well as the glass bottom windows, were made or selected so no ray of light incident on them would deviate by more than $1/100$ of a degree from its unperturbed path because of local imperfections in the glass or plastic surfaces. In addition, the cones for each chamber were machined from special high-stability and fine grain stainless steel billets. After the cones were roughly machined, stress-relieved, and ground, they were plated with about $.015$ inches of hard chromium and were reground and polished. Polishing was continued until an inspection of the surface by eye showed that our criterion of $1/100$ of a degree was satisfied locally (i.e. that no local variations greater than $1/100$ of a degree extended beyond a region larger than about $1/32$ of an inch square). Gross variations in the conical shape, such as an elliptical distortion of the whole mirror, were checked to be below the $1/100$ of a degree tolerance figure. The downstream female cone was checked immediately before it was cut in half, but we had no direct way to verify its trueness after the cutting operation. However, we have encountered no difficulties in the calibration procedure which could be explained only by a gross distortion of this cone.

A test of the optics as a whole, provided by viewing distant objects through the cones, showed that most of the regions of the cone surfaces were much better than our $1/100$ of a degree figure. Furthermore, the measurement accuracy of sparks photographed through this system, as determined by the goodness of fit of our data to the kinematical and geometrical constraints can be understood adequately in terms of jitter and blob measurement accuracy. The accuracy of height measurement is the expected .4 inches/spark as determined from the distribution of deviations in height for the fit to the geometry of two intersecting helices for the V-decays of our data. Further discussion of measurement techniques and of accuracy is presented in Appendix D.

The external part of the optics had mirrors flat to six fringes of sodium light per inch tolerance. The somewhat poor quality of this optics necessitated a complicated calibration scheme which is discussed in Appendix C. Also described there is the calibration of the optics internal to the spark chamber box, and the measurement of the tilt angles of the tilted mirror arrays. Because of uncertainties in the measurement and interpretation of our calibration data, there is an estimated residual systematic error in measuring the planar location of a spark of .003 inches error in the quantity ($R\theta$) for those downstream portions of our detectors covered by pictures of non-interacting straight-throughs. This error grows to about .010 inches at wide angles in the detectors. The corresponding non-systematic error from measurement error and jitter is $\sim .03$ inches. The systematic errors are slowly varying and hence do not interfere with the goodness of fit of individual V's to our constraints.

Both the lead and thin-foil spark chambers were set into grooves in the plastic mounting plates at top and bottom. The edges of the spark chambers were insulated with mylar tape to inhibit edge-sparking. The power for generating the sparks was put through tabs into the top of the inner two chambers and into the sides of the other three. The inner two chambers and the 90° sector chamber downstream from these were constructed of hardened thin aluminum foil. The foil electrodes for the inner two chambers were .002 inches thick, while the third chamber's electrodes were .004 inches thick. The outer two chambers were constructed of lead, with thin aluminum and stainless steel sheets glued to opposite sides to yield rigid plates of $1/5$ radiation lengths thickness. The plates were made oversize in length, then rolled, and ends trimmed. After the plates were mounted in the grooves, they were cylinders true to about .005 inches in radius. Since large numbers of sparks had to be supported in the lead chambers, large tabs (2 inches wide at the narrowest point) were used to bring in the power; care was exercised to keep the inductance of the lead-ins low.

The lead chambers were re-made between our preliminary and final runs; the description given here is of the plates used in the final run. The earlier plates differed in the following respects:

- (1) Aluminum was used exclusively for the laminations.
- (2) The ends were trimmed prior to rolling.
- (3) The power was brought in by clamps about $\frac{1}{2}$ inches wide.
- (4) The downstream hole was in a different location.

The first three of these differences caused very poor performance in these chambers for the first run, because the resulting gap spacing

of the chambers was non-uniform to about .02 inches (out of a gap spacing of .2 inches) and because there was a poor connection scheme. Efficiencies as low as 50% were typical for these chambers when there were more than four tracks present. Gamma-ray showers were very hard to recognize because the efficiency became low deep in the chamber, after a shower had developed into several ionizing particles. Although the set of plates for the final run were much improved in performance, with efficiency of about 90% for four tracks in a single chamber being possible when the chambers were powered properly, these lead chambers were still a great weakness of the equipment.

The powering circuit was a standard spark gap and capacitor in series with the spark chamber plates. Because we desired to clean the spark gaps and re-adjust them during the experiment without suffering loss of running time, we enclosed the powering circuits in removable probes which plugged into gas-sealed sockets in the top of the spark chamber box. The gas pressure was separately and externally adjustable in each spark gap. We were able to adjust the performance of the lead chambers by this parameter; the great sensitivity of these chambers required us to check their operation and make adjustments if necessary every six hours or so during the run. Even with this care, we experienced considerable variation in the quality of the operation, particularly in the first quarter of the run when we were still inexperienced in making the adjustment. Some of the pictures were unrecognizable or unmeasurable because of poor chamber performance, and we have had to include a correction to take this into account in our efficiency calculations later.

Figure 4 is a photograph of the spark chamber mounted in the magnet, with its top cover, tilted mirror plates, and powering probes removed. Appendix F gives a description of the resolving-time measurements we made with the spark chamber. The fast electronics, and the criteria which had to be met by a triggering event before the chamber was sparked, is described in Part V.

The hydrogen target, whose final design and assembly was done by Charles Ward of this group, was similar to the units used by us for several past experiments.⁶ The cell region of the target is illustrated schematically in Figure 5. It consisted of a mylar tube about $2\frac{1}{4}$ inches in diameter and four inches in height with thin stainless steel caps glued on both ends. It was connected by long pipes to a reservoir above the magnet and was surrounded by several layers of radiation shielding and a vacuum jacket with thin windows to admit the beam. The insulation and shielding was sufficient that the one-liter reservoir lasted about four hours before requiring re-filling. The amount of scattering by the walls of the cell and vacuum jacket amounted to the equivalent of about one inch of hydrogen.

A cylindrical anti-coincidence scintillator encircled the active region of the hydrogen except for a beam hole upstream. The ends of the cylindrical scintillator were uncapped. A last beam counter was mounted in the upstream hole of the anti-coincidence scintillator and both of these scintillators were viewed from the top of the magnet by photomultipliers mounted at the end of long lucite light-pipes. A structure of steel bricks was built around these photomultipliers to shield them from the stray field of Argo. Increasing amounts of steel were added until the counting rates of the photomultipliers, reduced by the effect of the stray magnetic field,

had returned to within 10% of the rates with Argo turned down. The efficiency of the anti-coincidence scintillator with Argo at full current, deduced from a scan for straight-throughs on a group of several hundred pictures exposed with this counter in anti-coincidence, was found to be 99.998% for a single minimum-ionizing particle.

The hodoscope elements were vertical slabs with horizontal section as shown in Figure 2. The inner elements were $\frac{1}{2}$ inch thick, the outer elements were 1 inch thick. The outer array was included with the idea of using them for detecting gamma-ray showers in the formation of the trigger criterion. In the main run, however, they were used only for a run of several hundred pictures of

$$\pi^- + P \rightarrow \text{neutrals with at least one count in the outer array} \quad (6)$$

We made this run to investigate the possibility of using a reaction such as η -production for calibration purposes. A preliminary scan of this data showed such a heavy contamination of many-gamma final states that this attempt was discontinued. Thus our original idea of using these outer scintillators in a complex trigger condition is still untested.

The hodoscope elements and part of their light-pipes were mounted in light-tight boxes which permitted removal of the hodoscope system from engagement with the spark chamber assemblies without disassembly of either. Above the spark chamber box the light was transmitted through lucite rods to photomultipliers mounted above the pole-piece of Argo. These photomultipliers were shielded from Argo's stray field by coaxial mu-metal and soft iron cylinders. We used both RCA 6810 and Amperex 56AVP photomultipliers, and standard base circuits for each. The Amperex tubes, having

a lower noise level, were used on the downstream hodoscope members where there was the greatest counting rate.

The beam was deflected by Argo onto a downstream hodoscope member which served as a test location for setting the high voltage and discriminators for each photomultiplier used viewing the hodoscope members. We installed each photomultiplier in this location and adjusted its high voltage to give a mean pulse height from these beam-induced pulses of about $1\frac{1}{2}$ volts. Then the discriminator for the phototube was adjusted to pass all pulses greater than $1/3$ of this minimum ionizing pulse level. Discriminator curves indicated this procedure yielded efficiencies $\geq 98\%$ for each phototube in this location. Then the phototubes were moved to their proper locations in the hodoscope array, and the voltages were set at the indicated value for each. As a further check we placed a lead brick in front of Argo to scatter the beam particles into all of the hodoscope members and verified for each with an oscilloscope viewing the outputs that the mean pulse height was still close to the previous $1\frac{1}{2}$ volt level.

The spark chamber gas used was the commercially available "90-10" neon-helium mixture. For all our data-taking we added about .5% argon because we had found this made a slight improvement in the efficiency of the chambers in our preliminary run. The spark chamber was in an evacuable box and our gas system was closed to the outside. We found no beneficial effects from attempts to circulate and purify the gas with a calcium oven or with a liquid nitrogen trap; the data-taking of both the preliminary and final runs was made without any circulation or

purification. Nothing in our experience indicated that any of our spark chamber troubles were due to gas impurities.

Figure 6 is a photograph showing the arrangement of equipment on top of the magnet during the preliminary run. The photomultiplier shields and bases are clustered on the top pole-piece. The calcium oven and circulation system, later discarded, rise above the photomultiplier bases in the foreground and the hydrogen target reservoir vacuum jacket can be seen behind them. Around these and in the background is the framework for the hydrogen venting hood. At the left are the spark chamber trigger supplies and the hydrogen target vacuum pumping system. On the near side in the median plane are the movable plugs which allow the beam to be brought out of the magnet over a range of bending angles.

IV. THE BEAM TRANSPORT SYSTEM

The beam transport system for the final run is illustrated in Figure 7. It was designed to provide a well-focused, intense beam of kaons and pions at the target inside Argo. A central momentum of 8 GeV/c was chosen as an interesting energy region to study and a width of ± 50 MeV/c seemed to be a good compromise between error resulting from uncertainty in beam momentum and low flux from having defined momentum too sharply. The kaon component of the beam was tagged by the Čerenkov counter C, which was kindly loaned by Dr. T. Kycia of the Brookhaven staff. The momentum selection took place by means of two collimators and the bending magnet D2. The bending magnet D1 also provided rough momentum selection, and prevented high fluxes of undesirable particles from exposing the region of the Čerenkov counter and our front beam counters. The front four quadrupoles provided a parallel beam for the Čerenkov counter and the rear two quadrupoles re-focused the beam on our target in Argo. As much as possible the beam path was kept within vacuum pipe or helium bags to reduce the spreading of the beam from multiple scattering. The size of the last beam counter β_4 and of the hole in the veto counter V was $1 \frac{5}{8}$ inches in diameter.

The parameters of this beam layout were investigated on the LNS 7044 computer facility using the Brookhaven "Autobeam" program⁷ given us by Dr. Henry Ruderman of the Brookhaven staff. The beam study was made in two steps, namely, preparation of the parallel beam by varying the gradients of the first four quadrupoles and then having fixed these, maximization of the flux through our last beam counter

by varying the rear two quadrupoles. The currents in the two bending magnets were determined by the location of the AGS target and by the desired momentum. The program also solved for the correct collimator sizes at Coll 1 and Coll 2 in order to achieve our desired momentum width.⁸

We started with these computed values and varied individual currents of the quadrupoles to achieve the maximum number of tagged kaons through our last beam counter. The final currents we arrived at through this procedure were within 5% of the calculated values except Q_4 , for which the maximum of a plot of beam intensity vs. current came about 20% higher. The maximum for Q_4 , however, was very broad and we felt it was not worth the time to investigate further the cause of this discrepancy. The front two quadrupoles, for which the maximum in the curves of beam intensity vs. current were very sharp, were within 1% of the calculated values.

Because we were not the primary experiment at the A.G.S. during our run, we did not have control over the location of the G-10 target in the AGS machine. We had to compensate for lateral offset of the G-10 target by changing the setting of the D1 magnet. However, its setting for maximum kaon intensity was the calculated one at the "equilibrium" location of +.8 inches for which the beam was surveyed. We found we had acceptable fluxes over a wide range of target locations, and a study with 1/8 inch wide counters placed along the magnet chain showed that the mean of the momentum distribution shifted $\lesssim \frac{1}{2}\%$ over the full range of target locations we encountered.²⁴ About 90% of our data was taken at a single target location, +1.1 inches. However, almost all our target-empty runs were made at locations other than 1.1 inches. We have encountered

no differences between groups of data taken at different target locations. We believe that no bias in our results has been incurred because of this variation in the running conditions.

Figure 8 is a photograph showing the rear portion of the beam; the Čerenkov counter is in the foreground. This counter was a CO_2 type differential counter.^{9,10} The counter had a coincidence channel viewing a narrow circular slit on which the desired Čerenkov light was focused. An anticoincidence channel viewed the remaining light. A curve of the fraction of the beam at 8 GeV/c in coincidence with this counter as a function of CO_2 pressure is presented in Figure 9. It is clear from this figure that contamination of the kaon component of the beam, as tagged by this counter with its pressure set properly at the center of the kaon peak, was at a very low level, $\lesssim 3 \times 10^{-4}$. Although this system transported about 1.2×10^5 particles/AGS pulse into our spark chamber, only about half of these were useful because of the combined effects of ~10% inefficiency of our last beam counter β_4 , large spot size, and approximately 30% dead time in the anti-coincidence channels caused by the $\sim 10^6$ /sec noise rate in the photomultipliers viewing the anti-coincidence scintillator. About 2% of the beam was kaons.

V. ELECTRONICS

The trigger electronics is illustrated in Figure 10. Most of the circuits used were standard, commercially available electronics.¹³ Except for the circuits used for recording on the film which scintillators took part in the trigger, nothing was developed especially for this experiment. The design for the counting circuit or "limiter-adder", used after the hodoscope member discriminators, was kindly provided by Dr. T. Romanowski of Argonne National Laboratory. This circuit accepted the standardized outputs from the discriminators for the hodoscope members and gave an output proportional in height of voltage to the number of incident pulses within a 30ns time gate. (The limiters and discriminators for the hodoscopes are not shown in Figure 10.)

The electronics performs the following functions:

- (1) Discrimination against small pulses in photomultiplier outputs.
- (2) Standardization of all pulses meeting condition (1).
- (3) Formation of the condition $(BT) \equiv (\beta_1 + \beta_2 + \beta_3 + \beta_4 - V)$ which indicates incidence of a good beam particle and is monitored by the scaler indicated "BT" (for "Beam Telescope"). The β 's and V are the counters illustrated on Figure 7.
- (4) Formation of the conditions $(BT\pi) \equiv (BT-C)$ and $(BTK) \equiv (BT+C-\bar{C})$ where C indicates the positive coincidence channel of the Čerenkov counter and $\bar{C}$ indicates the anticoincidence channel.
- (5) Formation of the conditions $(BT\pi-A)$ and $(BTK-A)$ which indicate that a good tagged beam particle was incident and that it failed to count in any of the three photomultipliers watching the anti-coin-

cidence scintillator A around the hydrogen target.

(6) Formation of the count ($\geq N$) occurring simultaneously with the conditions (3) through (5) above. This count of the inner hodoscope is selected by a discriminator viewing the output of the limiter-adder counting circuit. A study of the discriminator curves of the counting circuits showed that the contamination of the ($\geq N$) output by ($N-1$) photomultiplier inputs was at a negligible (i.e. less than 10%) level. The flatness of the "steps" in the discriminator curves also indicated an efficiency for counting N inputs which was $>98\%$. This study was valid for values of N from 1 to 4. Although presumably the circuit would have functioned similarly for higher values of N , no measurements of comparable accuracy were made.

(7) Formation of the final trigger condition as a coincidence between the appropriate ($B\pi-A$) or ($BTK-A$) and ($\geq N$). The data for this thesis came from the pictures triggered with ($BTK-A \geq 2$). About 5/6 of the pictures came, however, from the other trigger with ($B\pi-A \geq 3$). Because the latter trigger was frequent we used a gate to keep it shut off until the last half of the beam spill. This favoring of K-induced events discouraged loss of many of these rare triggers because of having already met a pion-induced trigger earlier in the beam spill.

(8) Fanning out of the resulting trigger pulse to the spark chamber powering system and to the "slow logic" whose function was to flash the fiducial lights, advance the register, and wind the camera film.

The various ways in which Nature has been seen to meet these trigger conditions, or in which the equipment failed to impose them, are discussed in Appendix G. We found that about $1/3$ of the K-induced pictures were topologically legitimate triggers with a single V-particle showing in the chambers. However, only about 5% of the pion triggers showed the two V-decays which we hoped to demand by our count of $N \geq 3$ condition in the inner hodoscope for reactions with the pion beam component.

VI. THE 1966 RUN

When the equipment was first operated in the beam, the efficiencies of the two downstream chambers were unusably poor. This inefficiency seemed to be associated with poor connections in the lead-ins to those chambers, and with spurious discharge near the lead-in sockets. The connections were tightened, and appropriate additional insulation eliminated the spurious discharges. These improvements eliminated the obvious sources of trouble in these chambers, but the chambers remained sensitive throughout the run to the sparking voltages and to the nitrogen gas pressures in the spark gaps. If the voltage on one of these chambers dropped by more than about 3% of the optimum operating value, or if the pressure in one of the spark gaps shifted by more than about 2 PSI, the efficiency of the chamber was observed to drop from the ~90% efficiency normally achieved to below 40%. Although we spent considerable time investigating this effect, we were never able to learn much more about it, and finally were satisfied with checking the operation of the chamber every six hours or so during the run, and re-adjusting the pressures and voltages as it seemed necessary.

Another difficulty with the spark chambers gradually developed during the run. The repeated sparking in the incident beam region of the thin cylindrical chambers upstream of the hydrogen target caused increasing distortion of the electrode structure, giving dents and bumps ultimately of the order of a third of a gap width. This distortion of the spark chamber plates in turn caused decreasing efficiency in the recording of the beam sparks. By the end of the run, the efficiency of the spark chambers in the beam region had dropped to about 40%. Because we felt 40% efficiency

in tracking the beam was still adequate for good data analysis, and because there seemed to be no simple remedy for this problem, we continued to take data under these conditions.

Except for the difficulties mentioned above with the spark chamber, and infrequent failures in the electronic components of the triggering and spark chamber powering system, we experienced no major difficulties in the data-taking part of the experiment. After the run was completed, we discovered that one of the 35 mirrors of the tilted-mirror array for the downstream lead chamber had fallen off, probably early in the run. The loss of the height information for events taking place under this mirror is not a serious detriment to the measurements of the experiment. Subsequent analysis of the data showed we had achieved adequate efficiency for the spark chamber operation for the bulk of the data, after we had gained experience with the first week or so of running. The subsequent analysis also showed that the spark chamber would not support two nearby (within about .1 inches of each other) tracks efficiently, and would give a single blobby track or alternate sparks from each. We believe this performance was adequate for our data analysis and might have been improved only by extensive redesign of the equipment to provide more power to the chambers.

During the experiment we found it was important to keep the incident beam intensity below about 1.2×10^5 particles/AGS beam pulse. Even at this level of beam intensity about $\frac{1}{4}$ of the pictures had one or more extra tracks ("straight-throughs") showing along with the triggering event. In general these straight-throughs could be identified as not being associated with the triggering event, but about $\frac{1}{4}$ of the pictures with

straight-throughs were rendered unmeasurable because the extra track interfered with the identification or measurement of the incident beam. In about a tenth of the pictures with V-decays and straight-throughs the V-decay itself was unmeasurable because of the interference of the extra track. A correction in the cross-section calculation of the next section accounts for this loss of data.

The anti-coincidence circuit dead-time was determined during the run by placing 30 feet of cable in the input to the anti-coincidence dead time generator and seeing what fraction of the beam was nonetheless vetoed by pulses from the dead time generator. This extra delay caused the anti pulses to arrive too late to provide the normal anti-coincidence for straight-through beam particles. Since this operation could not be carried out while data-taking was in progress, we installed a monitor which recorded the fraction of the beam which was vetoed by the output of the dead time generator delayed by 30 feet of cable. This monitor, however, did not measure the dead time directly because the output pulse shape was altered by its passage through the delay cable. Moreover, since only the early rolls of film have been analyzed at this time and since the monitor was not operating correctly until about a quarter of the way through the run, the monitor was not useful for determining the dead time for the target-full portion of the data presented in this thesis. There is an estimated uncertainty of about .05 in the determination of the dead time for the target-full portion of our data, because we had only infrequent measurements of this quantity. Because we achieved proper operation for the monitor for most of the data yet to be analyzed, we do not feel that uncertainty in the dead-time measurement is a basic limit-

ation in our normalization. A typical correction to the measured value of (BTK) due to the dead time effect was 0.7 during the target-full data-taking, and 0.8 during the lower intensity target-empty data-taking.

Table I gives a summary of the running parameters for this experiment. The composition of a sample of about 250 of the kaon-induced pictures is given in Table II. As can be seen from the table, about $1/3$ of the pictures taken when the target was full were the V-decays we had expected to trigger the equipment when we designed it. About $2/3$ of these V-decays were analyzable; the other third, although meeting the electronic conditions of the trigger, were useless because the V decayed too far out from the target for complete momentum analysis. Appendix G provides a more detailed explanation of the other categories.

TABLE IPARAMETERS OF THE RUN

Dates of the data-taking:	January through mid-March, 1965
Type of target:	Liquid hydrogen, mylar walls
Type of beam: ²⁴	8 Gev/c negatives, kaons electronically tagged
Momentum spread of beam:	± 50 Mev/c (estimated)
Total number of kaons through target:	4×10^8 (approximate)
Total number of kaon-induced photographs:	47949 (4074 with target empty)

TABLE IICOMPOSITION OF THE KAON-INDUCED PICTURES, TARGET FULL

(based on examination of 250 frames from roll 9a)

1. Analyzable V-decay in the chambers	.22
2. Incomplete, non-analyzable V-decay in the chambers	.14
3. Incident beam, various numbers of gamma rays showing in the lead chambers, but no V-decay	.31
4. Event with charged prong coming from target through beam hole or out the open top or bottom ends of anti-scintillator	.05
5. Events containing a straight-through which ruins measurement or interpretation of event	.04
6. Event with off-axis tracks coming from upstream of the target	.15
7. Blank pictures	.06
8. Miscellaneous (processes each less than 2%)	.03

VII. ANALYSIS OF THE DATA

The data analysis¹¹ performed the following tasks:

- (A) Selection of "interesting" events from the raw data and specification of an interpretation for these events.
- (B) Measurement, reconstruction, and fitting of these events to K and Λ hypotheses.
- (C) Rejection of events:
 - (1) Not fitting K hypothesis.
 - (2) Not consistent with the charge exchange hypothesis.
 - (3) Having gamma-rays or associated extra tracks showing in the photographs.¹²
- (D) Subtraction of background events, corrections for efficiency, and determination of the correct normalization for this sample of charge exchange events.
- (E) Calculation of the best value for total cross-section, and determination of the shape of the angular distribution.

The first step of the analysis of these pictures, then, was the selection of candidates for measurement. Our scanning staff, typically one or two girls at any one time working on this data, selected each picture which had the topology of an incident beam disappearing into the hydrogen target and the subsequent appearance of one and only one two-prong decay which was measureable on the other side of the target. By "measureable" we meant a V-decay which each prong visible in at least three spark chambers. An interpretation was then spelled out for each event specifying which tracks made up the prongs of the V; the slope of

the tracks within each chamber and the rough height estimated from the stereo view were frequently a good guide in determining the interpretation. About $3/4$ of the time they specified it uniquely. Because of occasional poor chamber performance or difficult topologies, some events were questionable as to interpretation or as to inclusion as a measureable event. About $3/4$ of these questionable events were examined by the author in the company of Miss Eva Bonis, the supervisor of the scanners; the remainder were examined by her alone. All questionable events were measured if any reasonable interpretation seemed possible.

To check the efficiency of the scanning process, the author re-scanned a sample of film containing about 400 V-decay events which had been scanned only once. This re-scan added only five events. Thus the estimate of the efficiency of a single scan is about 99%. Because about 80% of our data has been scanned twice, no correction for scanning efficiency has been included in the normalization calculations.

After a picture was selected as a candidate and its interpretation was specified, it was measured on our Hydel encoding machines. The punched-card output of this measurement formed the input data for our program which, in the L.N.S. 7044 computer, reconstructed the individual sparks into coordinates (R, θ, Z) in "real" space (i.e., into polar coordinates in one-to-one correspondance with our detectors). The n sparks within a single chamber's track segment were least-squares fitted to a straight line and the (R, θ, Z) of that line at the mean radius formed the coordinates of the track in that chamber used for the subsequent analysis. The program also calculated the estimated errors in θ and Z for each track segment.

The error in θ in radians was taken to be the observed error for the chamber divided by $(\sqrt{n} R)$ unless the individual deviation per spark for that segment was greater than .042 inches. In this case the deviation itself divided by R was used. A similar condition was used to determine the error in Z . Appendix D elaborates on the measurement techniques, the selection of these error functions, and the resolution of the equipment.

Several geometric conditions were enforced in this program to eliminate events with gross mis-measurements. The heights of the beam sparks were restricted, sparks were not allowed outside of the chamber limits, the Z -error estimate had to be less than two inches for every segment, and events were not allowed for which the same spark had accidentally been encoded twice. Events failing at this stage of the analysis were remeasured and re-analyzed; finally all of the candidates selected for measurement were successfully reconstructed.

The reconstructed sparks were then analyzed by our V-fitting program. This program first rejected events in which the two prongs of the V-decay curved in the same direction, or missed intersecting in the horizontal projection by more than 0.05 inches. It also rejected events in which the second segment for either prong was more than one inch in height away from the appropriate helix connecting the coordinates of the first and third segments for that prong. For events meeting the above geometric requirements, a least-squares fit in height to two intersecting helices was formed. Occasionally each of the two possible planar vertex locations (given by the two intersection points of the circular tracks of the two decay products) was within the allowed region of the chamber. In

this case the least-squares fit to two intersecting helices was performed for each case, and the vertex location was chosen as correct which gave the smaller standard deviation to the fit. We rejected any event for which the standard deviation was greater than .5 inches. These geometric conditions were imposed as an aid in identifying misinterpreted or mis-measured events, and, as will be seen, did not seriously bias the recognition or correct analysis of the measured events.

An event meeting the geometrical requirements was then tested to see if it might be consistent with a decay of a known V-particle. The radius of curvature, dip angles, and momentum for each prong was calculated, as was the opening angle for the V-decay. Finally the mass of the parent "V-particle" for each of the hypotheses, K, Λ , and electron-positron pair was taken from the expression:

$$\text{Hypothetical Mass} = \sqrt{(M_+^2 + M_-^2 + 2(E_+E_- - P_+P_- \cos \theta_{\text{opening}}))} \quad (7)$$

Here P_+ and P_- signify the magnitude of the calculated momentum of the positive and negative charged particles, M_+ and M_- signify the decay product masses appropriate to the decay process being hypothesized, and E_+ and E_- signify the energies of the decay products. If the decay being considered was actually a K (or Λ) decay, we would expect the hypothetical K (or Λ) mass to be quite close to the known mass of K (or Λ). If it really was an electron-positron pair, the "pair mass" (with M_+ and M_- set to zero) should be quite small.

Analysis of the events continued with the calculation of the derivatives of the hypothetical V-masses with respect to the individual spark locations. This was done by increasing each spark coordinate by its estimated error and calculating the resultant change in the V-mass. These derivatives were used to estimate the number of standard deviations by which the hypothetical mass seemed to deviate from the "correct" mass, normalized to the error estimates from the reconstruction program. If this estimate of the deviation was less than the arbitrary figure of five standard deviations for any of the three hypotheses, the analysis of the event proceeded; otherwise the event was rejected. If an event satisfied this selection criterion for both K and Λ hypotheses, then each case was retained as a separate event unless one estimate was three standard deviations better than the other. Events not close to either K or Λ hypotheses but with a pair mass less than $50 \text{ Mev}/c^2$ were immediately classified as unambiguous pairs and were not analyzed further. Events with a pair mass greater than $50 \text{ Mev}/c^2$, but within five standard deviations of $50 \text{ Mev}/c^2$, and not within five standard deviations of either of the other two hypotheses, were also classified as unambiguous pairs. If an event satisfied the selection criterion for either K or Λ and the pair hypothesis, then the pair hypothesis was suppressed. Later we use a showering criterion in the picture to check the data for contamination from real pairs which happen also to fit K hypotheses.

Events meeting all the conditions of analysis up to this point were then forced to satisfy two constraints:

(C1) That the hypothetical mass and correct K, Λ , or pair mass co-

incide. (We used a "correct pair mass" of 50 Mev/c²)

(C2) That the beam and fitted V intersect at a single point.

The I coordinates x_i of the sparks were altered by amounts Δx_i

given by solving simultaneously the (I+2) equations:

$$\left. \begin{aligned} \Delta x_i &= \sum_{j=1}^2 a_j \frac{\partial C_j}{\partial x_i} \\ \text{and } \Delta C_j &= \sum_{i=1}^I \sum_{k=1}^2 a_k \frac{\partial C_j}{\partial x_i} \frac{\partial C_k}{\partial x_i} \end{aligned} \right\} \quad (8)$$

where ΔC_i denotes the amount by which the constraints were not satisfied. Because of non-linear variation of the constraint functions with the coordinates x_i, perfect satisfaction of the constraints was not usually achieved with a single calculation, and the constraints had to be satisfied in an iterative manner. The above equations minimized the value of $\delta\chi$ for each iteration,

$$\delta\chi = \sqrt{\sum_i \Delta x_i^2} \quad (9)$$

which, with each Δx_i appropriately normalized, represented the number of standard deviations of change introduced in that iteration. Iteration was ceased after a value of $\delta\chi$ less than .01 occurred. Then the total number of standard deviations,

$$\chi = \sqrt{\sum_i (x_{\text{initial}} - x_{\text{final}})_i^2} \quad (10)$$

was calculated and was a measure of the goodness of fit of the event.

All events with a χ greater than 4 were re-examined and were re-measured

if another interpretation or a more accurate assignment of sparks seemed possible.

This analysis sequence was tested with computer-generated Monte-Carlo events which (1) were made to correspond to the geometry of our detector, (2) were distributed in momentum and angle similarly to the data, and (3) were randomly jittered with the same average errors as those observed for the data in each chamber. It was found with these errors that a total of about 4% of the events failed to meet our geometrical conditions of analysis, apparently independent of the identity of the particle used in generating the events (K or Λ) and only weakly dependant on the V-particle momentum from 2 to 8 Gev/c. A study of failing events indicated that the failures were not the result of any peculiar geometry or topology for a V-decay, but merely an unfortunate combination of errors for that particular event which put its coordinates outside of the allowable range of values.

If a data event failed to meet all of the geometrical conditions imposed in the analysis, or was not close to any of the kinematic hypotheses, the photograph was re-examined by the author or one of the scanners. About 10% of the failed pictures seemed to be interpreted correctly, but the measurement did not follow carefully the spelled-out interpretation. Another measurement of the event, with special care being taken about the segments which seemed to be the cause of the failure, usually resulted in a good fit. This procedure should have recovered any data events which failed due to an unfortunate combination of errors in measurement. For this reason, no correction has been considered for the efficiency of the analysis program in the normalization.

We found about $1/4$ of the pictures did not have a unique interpretation specified by the slope or height information within a chamber. It followed that many of the data events which had failed on a first measurement could be re-interpreted with a different grouping of tracks and that a measurement with this new grouping could be successfully analyzed. To study how an event might fit a wrong interpretation fortuitously, we generated a set of Monte-Carlo events distributed in the chambers corresponding to forward-angle elastic charge exchange events. We then interchanged the various segments of these computer generated events to produce "misinterpreted" events. We found only one or two percent of the events with segments so interchanged would meet the analysis conditions and give a good fit, unless the interchanged segments were within about .05 inches of each other. Since the resulting physics of these interchanged events with close segments was essentially the same in such quantities as the calculated momentum or angle of production of the V , and since the spark chamber rarely would support two distinct tracks this close (see discussion, page 30), we felt justified in concluding that an event was correctly interpreted if it could be made to fit in the analysis program, and was probably incorrectly interpreted or poorly measured if it did not.

Table III shows the results of the data analysis for the portion of target full and target empty runs which have been analyzed up to this time. Figures 11a through d show the distribution of χ for the unambiguous K 's and Λ 's for target-full and target-empty data. The solid curve in Figure 11a is the expected shape of a χ distribution for a two-constraint fit. As

TABLE IIIRESULTS OF MEASUREMENT AND ANALYSIS OF THE PICTURES

	Target Full Runs	Target Empty
Percent of total data scanned:	21.3	42.9
Number of pictures scanned:	9360	1746
Number of pictures selected as candidates for measurement:	1559	272
Number of pictures,		
Fit to Unambiguous K:	802	161
Fit to Unambiguous Λ :	143	25
Fit to Both K and Λ :	299	33
Fit to Unambiguous Pair:	89	10
Failures, all types:	226	43
Breakdown of failures,		
Judged to be "not measureable":	170	34
Residual number of failures:	56	9
Fit to elastic charge exchange hypothesis:	269	43

can be seen, the distribution in χ for our data is a good fit to the expected shape, except for the $\sim 5\%$ of the events above $\chi = 3$. The agreement of our experimental χ distribution with the expected shape indicates that our estimates of errors for the coordinates seem to be in good agreement with the actual errors observed in fitting to the constraints.

Because we were liberal in selecting events for measurement, including all data which seemed to have a possible interpretation, we expected a residue of events which could not be made to fit. The bulk of this residue would be events in which both prongs of the V-decay did not pass through the requisite three chambers, but in which one prong went out the downstream hole or missed the downstream chamber altogether; however, perhaps a nearby extra track (usually associated with a gamma-ray shower, but occasionally a prong from a late-decaying other V-particle or a neutron star reaction in the lead chamber) was mis-interpreted as the desired missing segment to make up a complete "measureable" V-decay. Also several percent of the data would be expected to be failures or poor fits because a legitimate V-decay may have undergone interaction or decay of one of the daughter prongs before momentum analysis was complete. Other false "V-decays" would be un-analyzable three-body K_2^0 decays within the volume of the detector, neutron stars in the material of the spark chamber plates, or a beam particle which managed to slip through the anti-coincidence scintillator and then interacted in the material of the spark chamber plates.

All failing events were examined by the author and by Miss Bonis;

we would not give up an event as a failure unless all reasonable interpretations had been considered without success. We then classified those failures as "not measureable" which had a prong close to the edges or hole in the downstream chamber and therefore might have been an incomplete V-decay event. Table III shows that most of the failures were of this type. The residual failures, events which simply would not fit, but seemed to be measureable according to our original criterion, are only a small percent of the total data and thus can be adequately explained by the other mechanisms mentioned above.

Assuming at this point that all of the observed decays which were measureable were correctly interpreted and measured, and that these measurements were correctly analyzed to identify the decays as K's or Λ 's, we proceeded to investigate which of the K events could be due to the elastic charge exchange process, equation (1). To accomplish this we re-analyzed the kaon events in the data imposing a third constraint that the "missing mass", or combined mass of all the products in the final state except the measured kaon, be a neutron mass. The missing mass is given by the equation:

$$\text{Missing mass} = \sqrt{(E_{\text{tot}} - E_k)^2 - (\vec{P}_{\text{tot}} - \vec{P}_k)^2} \quad (11)$$

where E_{tot} and P_{tot} are the energy and momentum of the initial state.

All events were fitted which had an original estimate for the χ of fitting all three constraints that was less than 10. The last entry in Table III presents the results of this fit. About a quarter of the events fitting the kaon hypothesis were consistent with the charge exchange hypothesis.

In our iteration procedure we neglected the momentum spread of the beam by merely imposing the mean momentum of the beam. To investigate the importance of this neglect, we analyzed a sample of Monte-Carlo generated events which were not jittered by our sources of errors and were generated at an "incident momentum" input parameter of 8.0 GeV/c. The analysis program was altered to calculate missing masses on the basis of an incident momentum of 8.1 GeV/c, and the resulting analysis was compared with results of analysis at 8.0 GeV/c. It was found that the χ of a fit to an event was worse by about .2, but that the cosine of the production angle of the kaon changed by only .001 on the average. We then concluded that we were not incurring a loss of events or a significant alteration of the physics by having neglected the spread of beam momentum.

In our iteration procedure, we also neglected any vertical divergence of the beam. To investigate the importance of this, the Monte-Carlo events were altered so the beam was at an angle of 20 milliradians. Comparable results to those for the case in the preceding paragraph were observed.

To be sure no charge exchange events were missed because a beam was poorly measured in the horizontal plane, all events with the beam's horizontal angle further away than 20 milliradians from the mean angle of the beam were examined and remeasured to eliminate the error. The actual angular divergence of the beam was measured to be about ± 6 milliradians.

The photographs for all events fitting the elastic charge exchange hypothesis were then examined for tracks additional to those of the V, particularly in the lead chambers. The purpose of this examination was the

elimination of background events like

$$K^- + P \rightarrow K^0 + N^* ; \quad N^* \rightarrow N + \pi^0 ; \quad \pi^0 \rightarrow 2\gamma \quad (12)$$

which might be kinematically indistinguishable from the charge exchange process, but which might be identified by the extra tracks induced in the lead chambers by the showering of the gamma-rays from the pion-decay. We used a criterion for a "track" of at least four sparks in a localized region of the chamber which seemed to point roughly back towards the hydrogen target and which had the proper alternating ExB drift for our chamber in at least the first few gaps of the track. About 90% of our V-containing pictures had at least one of these extra tracks; about 80% of them had several such tracks. Most of these tracks had more than the minimum four sparks, and most started in the lead chambers after missing the first few gaps. Most of the tracks were characteristically similar to the lead-chamber portion of our unambiguous electron-positron "decays", showing

- (1) variation in intensity from gap to gap of the sparks,
- (2) disappearance of the regular ExB drift spacing after about 6 gaps,
- (3) either multiple sparks in gaps deep in the track or the track dying out either abruptly or with a gradual diminishing in intensity of the sparks deep in the chamber. We found that 75% of our unambiguous pairs exhibited this behavior in both prongs in the lead chambers. Such performance would be expected for a pair because of the showering process initiated in the lead chamber by the electron and positron. It seems reasonable to associate the extra tracks in our lead chambers with showers induced by

gamma-rays produced through the same reaction which produced the observed V-particle.

We then felt justified in rejecting for elastic charge exchange any event which contained any of these extra tracks in the lead chambers. We also rejected two events which had an extra track in the thin foil chambers and two events which had an extra track in the lead chambers which, however, did not have any of the showering properties expected from our gamma-rays, but instead penetrated through all gaps of the lead chamber as a clear, regular track. These four events were different from our many events in which a straight-through beam particle showed or in which a cosmic ray or stray particle from the accelerator happened to pass through the detectors during the resolving time: the extra tracks seemed to have the same ExB drift as the segments of the measured V and there seemed to be no reasonable way to explain their presence except as having come from the hydrogen target.

Figures 12a through 12c present the target-full K events for the three categories,

- (1) "good" charge-exchange events with no extra tracks,
- (2) "doubtful" charge-exchange events in which chamber performance was inferior and it was difficult to determine whether gamma-rays were present or not, and
- (3) "rejected" events in which extra tracks were present.

The quantity plotted is the number of events for each category above versus the goodness of fit χ of the event. The six shaded events are ones in which the initial mass for the kaon is unusually large, but a somewhat poor fit to

the kaon mass is still possible because of large error estimates in the event. It is probable the fit of some of these events will be improved when they are remeasured; others may remain poor fits because of poor chamber performance or some other process which might interfere with accurate measurement of the event. In all of these shaded events, however, the major contribution to χ comes from the kaon mass constraint rather than the missing mass constraint.

The smooth curve in Figure 12a is the expected shape of the χ distribution for pure elastic charge exchange events. It seems that the "doubtful" events should be added to the "good" events because their distributions in χ are very similar, and because most of these doubtful events were from the early part of the data run, when the spark chamber had a tendency to spark twice, putting many spurious sparks on the film which then could conceal a small track with only a few sparks, or when the downstream chamber had an occasional tendency to operate inefficiently. As was said above, however, most extra tracks have a well-defined appearance with more than the minimum number of sparks to qualify for a "track". The doubtful pictures were classified that way because we might have been unable to see a track which had near the minimum number of sparks.

Figure 12a, however, is not pure charge-exchange events, even after the rejection of the pictures with extra tracks, because some gamma-rays might have escaped undetected. To investigate what fraction of events might have such undetected gamma rays we made a Monte-Carlo program which calculated this quantity for the geometry of our detectors with the reaction

The distribution in four-momentum transfer for this reaction was taken from the results of another group¹⁶ for the K charge exchange reaction. The decays of N^* and of π^0 were taken to be isotropic in their respective center-of-mass systems. We found with this program that the fraction of K^0N^* events with no gamma rays detected in our lead chambers varied from 22%, if no condition on gamma-ray energies was included, to 26%, if we required that all "detectable" gamma-rays had to have energy greater than 100 Mev. For our thickness of lead plates, we would expect gamma-rays to begin to meet our four-spark criterion when their energy was about 50 Mev. Since the geometry of the detectors seemed to be the dominant factor in determining the fraction of events with no gamma rays detected we did not study the cut-off energy problem further, and felt that 25% would be a representative value to use.

We desired to subtract the events contaminating Figures 12a plus 12b and get a corrected curve for χ . If all the events in Figure 12c were the K^0N^* process we calculated with the Monte-Carlo program, then the corrected curve for χ would be the events of 12a plus those of 12b minus one-third of those of 12c. The results of this operation are presented in Figure 12d. We can see that the fit to the expected shape (smooth curve in Figures 12a and 12d) for a three-constraint fit is quite good now, in spite of the crude assumption we made about the dynamics of the background processes. In fact, a study of Monte-Carlo generated $K^0N^*_{1238}$ events fit in analysis to the elastic charge exchange hypothesis showed a χ distribution which was similar in shape to the expected curve for true K^0N events, but with its maximum higher at 2.0, instead of 1.4. Thus only about a third or less of

the events on Figure 12c could actually have been $K^0 N^*_{1238}$ events.

The success of the subtraction process suggests, however, that the dynamics of the other backgrounds as to gamma-ray distributions must be similar to the $K^0 N^*$ process we calculated.

Figures 13 a through c present the results of a similar analysis for the target-empty events. Despite a tendency of the target-empty events to peak somewhat higher in the distribution of χ than the target-full events, the two histograms, 12d and 13 c, are essentially the same within our meager statistics.

We were interested in the possibility that the events fitting our charge-exchange constraints might not all be true kaon decays, but possibly contain some electron-positron pairs which happened to fit adequately the kaon kinematics. To check on this we examined all the events fitting the charge exchange hypothesis, without or with gamma-ray tracks, to see if any of the events exhibited showering characteristics in the prongs of the V-decay. As was mentioned before, we would expect $3/4$ of whatever pairs might be contaminating our data to satisfy in both prongs all three of the showering characteristics listed on page 47. Of the 342 events examined, five were observed to have the requisite showering characteristics in both prongs, 291 were observed not to have them, and 46, for various reasons, were uncertain. The five events observed to have the showering characteristics all had "pair masses" greater than $200 \text{ Mev}/c^2$, whereas of our unambiguous pairs, 85% had "pair masses" less than $50 \text{ Mev}/c^2$, and $30 \text{ Mev}/c^2$ was the median value. Thus we feel there is no significant contamination of our data from electron-positron pairs.

Another possibility of contamination was that high-momentum lambdas might also fit the kaon and the charge-exchange hypotheses. To investigate this possibility we generated several hundred Monte-Carlo lambda events with a missing mass of $850 \text{ Mev}/c^2$, a value chosen which best matched the laboratory kinematics of lambda production and elastic kaon charge exchange. About 85% of these events fitted the charge-exchange hypothesis when analyzed by our V-fitting program. We found that all of the false "kaons" generated and analyzed in this manner had a cosine greater than 0.7 of the decay angle of the positive prong in the center-of-mass system of the kaon. A study of the decay cosine distribution for Monte-Carlo generated true charge exchange events with a production distribution scaled in energy to that measured by P. Astbury et.al.¹⁶ showed a ratio of $1.1 \pm .15$ for the number of events with decay cosine angle between +.7 and +1.0 to the number between -1.0 and -0.7. The analogous events for the target full data gave the ratio 25/25 and for the target empty data 6/6 for the portions of each with no extra tracks showing. Although statistical fluctuations in these quantities might allow several lambdas to be in our data in spite of the negative result of this analysis, it seems there is no significant contamination of our data from lambdas which fortuitously fit the charge-exchange hypothesis.

Figures 14a through 14f present the angular distributions of events on Figures 12 and 13 with χ less than 3.5. Figures 14c and 14f are the subtracted angular distributions which we feel best represent the "true" charge exchange angular distributions for target-full and target-empty data, and were formed by a subtraction identical to that used for Figures

12d and 13c. The statistics of the target-empty data are too scanty to be sure there is a shape to the angular distribution for events in the mylar walls of the hydrogen target different from the shape for the hydrogen itself, but the target-empty distribution shows less of a forward peak than the target-full distribution.

The Monte-Carlo program was used to determine the efficiency of the MASCOT system as a function of production angle of the neutral kaon. The program generated events at a fixed production angle, and appropriately varied the production point within the hydrogen target, the phi-angle of the production, and decay distance of the kaon, and the two internal decay parameters of the kaon. The program calculated what fraction of the events at that production angle would fail to decay between the anti-coincidence scintillator and the middle momentum analysis chamber (beyond which complete momentum analysis was not possible). The program also rejected events in which the event was incomplete because a prong of the V went out the downstream hole and hence did not provide the necessary third segment to make up a "measureable" V. Finally the program rejected events which did not satisfy the necessary hodoscope count by having the two prongs of the V travel through distinct members of the hodoscope array.

The result of this efficiency calculation is presented in Figure 15a. Each dot represents a Monte-Carlo program run of 10^4 events. Thus the statistical uncertainty in this curve is much less than the statistical uncertainty in the data itself. We investigated the sensitivity of this program to the parameters important to this calculation, the size and

location of the downstream hole and the position of the edges of the hodoscope scintillators. This was done by altering the parameters representing each of these quantities one at a time by its estimated uncertainty. The values for the hole diameter and location, although roughly known from the mechanical assembly, were taken from a plot of the locations of all the sparks in the downstream chamber, in which the hole showed as a well-defined region in which no sparks were observed. The errors in these parameters were estimated to be about .2 inches; also the error in the location of the edge of the hodoscope scintillators was estimated to be about .2 inches from the mechanical assembly. Each of these changes in parameters altered the net efficiency by less than .005. Another error of .005 would occur because of uncertainty of the order of half a spark chamber gap thickness (or $\sim .1$ inches) about the length of the possible analyzable V-decay drift distance between anti-scintillator and last allowable spark chamber gap. We feel that a total figure of .007 is a fair estimate of the uncertainty in the efficiency calculation due to possible errors in determining the input parameters.

The Monte-Carlo program also took into account the possibilities of prongs of the V going out the top, bottom, or side slot of the detectors, or passing through the downstream thin foil chamber, but then curving out the side without registering in the downstream lead chamber. None of these possibilities occurred, however, unless the elastic charge exchange production angle was taken to be greater than 60° in the center-of-mass system. No significant elastic charge exchange production was observed at production angles greater than about 25° in this representation.

Figures 15b and 15c present the angular distributions of the data of Figures 14c and 14f, in which the numbers in each bin have been divided by the appropriate geometric efficiency taken from Figure 15a, but the resulting numbers again have been divided by 10 to preserve the statistical scale. Table IV presents the details of the normalization calculation. Figure 16 is a plot showing the result together with the measurements of total cross-section at other incident momenta that have been published to this time.^{16,17} Figure 17 is our angular distribution of Figure 15b, correctly normalized and with Figure 15c also normalized and subtracted away, replotted as $d\sigma/dt$, where t is defined as the four-momentum transferred from the incident kaon to the nucleon, and is given to a good approximation by the relation

$$t \approx 2 (\cos \theta_{kcm} - 1) \times P_{kcm}^2 \quad (14)$$

where θ_{kcm} is the production angle in the center-of-mass representation and P_{kcm} is the magnitude of the three-momentum of the kaon in this same representation.

In the normalization calculation we estimated the loss of data from interference of straight-throughs or chamber performance by a scan of several hundred events in each of target-full and target-empty data. Because most of the target-empty data was taken at lower instantaneous intensities of the beam the fraction of pictures containing straight-throughs was less than for the target-full data, about 20%.

We have neglected the possibility of bubbles in our hydrogen target diminishing the effective density (taken to be .07 g/cc) of the hydrogen.

TABLE IV

CALCULATION OF CROSS-SECTION FOR THE CHARGE EXCHANGE PROCESS

	Target Full	Target Empty
Incident particles recorded (BTK):	76.67×10^6	46.48×10^6
Inc. particles, including estimates of some accidentally lost readings:	85.7×10^6	46.48×10^6
Average dead-time loss factor:	$.70 \pm .05$	$.82 \pm .01$
Hence, inc. particles, corrected for dead-time loss ($\times 10^6$):	(60.0 ± 4.3)	(38.1 ± 0.4)
Observed number of events fitting charge-exchange hypothesis with $X < 3.5$ and no gamma-rays:	54 ± 7.5	16 ± 4
Above, corrected for geometric efficiency:	494 ± 65	131 ± 33
Above, further corrected for loss of data from straight-throughs or poor chamber performance:	544 ± 71	144 ± 36
Target-empty data further corrected to correspond to incident flux of target-full data:	227 ± 54	
Hence, number of events in H_2 :	317 ± 95	
Above, further corrected for branching ($K^0 \rightarrow \pi^+ \pi^-$ / all modes) = $1/3$:	951 ± 285	
Above, further corrected for hodoscope efficiency (.98/element):	990 ± 296	(see footnote #14)
Number of events expected for our effective flux incident and a cross-section of 1 microbarn:	$14 \pm .5$	
Hence, our measured cross-section of the elastic charge-exchange process at 8 GeV/c incident	71 ± 21 microbarns	

This is a policy similar to that followed with previous experiments and comparable hydrogen targets in this group.¹⁵ The thickness of the target was taken to be 5.5 centimeters. This figure is the 2.2 inch diameter of the cylindrical target with the observed spatial distribution of the beam folded in. This in turn yielded a thickness of 2.34×10^{23} atoms/cm² of the hydrogen in the target.

We have also neglected the effect on our normalization of an estimated .003 of the incident beam counts in (BTK) which were kaons decaying into muons before reaching the hydrogen, but with the muon still registering in the last beam counter.

VIII. CONCLUSION

We have measured an angular distribution and total cross-section for the kaon induced elastic charge exchange process. When the remainder of the data we have gathered is analyzed, we shall have a measurement of comparable statistical quality to the measurements of the other group which has published observations for this reaction at comparable incident momenta^{16,17}. Our preliminary values, based on analysis of about a fifth part of the data, indicate agreement within statistics about the shape of the angular distribution, and a value for cross-section which is in reasonable agreement, between our measurements and theirs. Our statistics are too poor to shed any new light on the relation between the charge exchange process and the theoretical calculations.

Our geometrical efficiency, whose forward-angle behavior was plotted in Figure 15a, rises to a maximum of about 26% at laboratory angles of 20° , corresponding to a momentum transfer of $t = -5 \text{ (Gev/c)}^2$. For larger values of momentum transfer, the outgoing kaon has a shorter mean decay length, and as a result more decays occur within the anti-coincidence scintillator. The efficiency drops, for this reason, passing through 10% at about -8 (Gev/c)^2 with a kaon at 30° in the detectors, and reaching a value of about 2% for large angles up to 90° in the detector and with values of t near the largest possible momentum transfer. Because the rear members of the hodoscope were not in operation during this experimental run (we had found during our test run that off-axis false triggers frequently utilized these counters to make up the trigger conditions) the efficiency rapidly drops for kaon lab angles greater than 90° , going from 2% at $\cos \theta_{\text{cm}} = -.85$ to $\frac{1}{2}\%$ at $\cos \theta_{\text{cm}} = -.90$ and finally to zero for $\cos \theta_{\text{cm}}$ less than about $-.93$. The equipment of the other group^{16,18} becomes very inefficient for detection of kaons at angles

greater than about 30° in the detectors.

We observed no events fitting charge exchange kinematics and without gamma ray tracks with momentum transfers greater than $-t = 2.5 \text{ (Gev/c)}^2$. This enables us to put upper limits on the differential cross-section of $d\sigma/dt < \sim .2 \text{ } \mu\text{barns}/(\text{Gev/c})^2$ for $-t$ between 2.5 and 8 $(\text{Gev/c})^2$ and also $d\sigma/dt < \sim 1 \text{ } \mu\text{barns}/(\text{Gev/c})^2$ for $-t$ between 8 and 13 $(\text{Gev/c})^2$, a previously uninvestigated region.

Our rapidly diminishing efficiency for very wide angle kaons beyond 90° in the detectors prevents us from determining much about a possible backward peak. If such a peak had the same general shape as the forward peak we would expect to detect only a few percent of the events which came in the tail of the peak. Even in the tail of the peak where we have nonzero detection efficiency, the efficiency is reduced by about a factor of five. Assuming a possible backward peak had 2% of its events with $\cos \theta_{\text{cm}}$ greater than $-.9$ and that our average efficiency for detecting these events was 1%, our seeing no events in this region sets an upper limit on the cross-section of a possible backward peak of 700 μbarns . Thus it appears that unless a possible backward peak is very broad we had no hope of seeing it with the equipment operated in the manner that it was during our run. The backward peaks in pion elastic scattering at comparable incident momenta are very small, contributing only a few μbarns to the total cross-section.

LIST OF FIGURES

<u>Figure</u>	<u>Title</u>	<u>PAGE</u>
1.	Mascot Magnet "Argo"	61
2.	Mascot System Spark Chamber - "Medea"	63
3.	Mascot System Schematic Diagram of the Optics	65
4.	Photograph of Spark Chamber mounted in Magnet	67
5.	Mascot System Hydrogen Target - "Jason"	69
6.	Photograph of Argo set up during test run	71
7.	Beam Transport System for Second Run at BNL	73
8.	Photograph of a Portion of Beam Layout for Second Run	75
9.	Čerenkov Counter Pressure Curve	77
10.	Mascot System Fast Trigger Logic	79
11.	A Plot of the Fit Parameter χ for Data (2 constraints)	81
12.	A Plot of the Fit Parameter χ for Data (3 constraints)	83
13.	A Plot of the Fit Parameter χ for Data (3 constraints)	85
14.	A Plot of the Angular Distribution	87
15.	Calculated Efficiency and Corrected Angular Distribution	89
16.	A Plot of Total Cross-Section	91
17.	A Plot of $d\sigma/dt$	93
18.	Temperature Rise in the Argo Magnet	95
19.	Field Strength vs. Current in the Argo Magnet	97
20.	Resolution of $\cos \theta_{cm}$ for K charge exchange	99
21.	Plots of First K Mass, Monte-Carlo and Data	101
22.	A plot of the Delay for 50% efficiency vs clearing	103

Figure 1.

Schematic Illustration of MASCOT magnet.

MASCOT MAGNET "ARGO"

Figure 2.

Schematic Illustration and Specifications of MASCOT
Spark Chamber System.

Specifications:

Thin Foils : 6 Gaps Foils .002 Al Each

Lead Plates : 14 Gaps Plates $\sim .3$ rad. Length Each

Angular Coverage : (1) All Charged Particles $\sim 3.8 \pi$ ster.

(2) Momentum Analysis $\sim 2.5 \pi$ ster.

(3) Photons $\sim 2.0 \pi$ ster.

Hydrogen Target : ~ 2 " thick ; inserted and filled from above

Height of Chamber : 40 inches

Expected Resolution :

$$\text{Downstream : } \frac{\Delta P}{P} \approx 3\% \quad P \approx 3 \text{ GeV/c}$$

$$\text{Upstream : } \frac{\Delta P}{P} \approx 5\% \quad P \approx 1 \text{ GeV/c}$$

$$\text{Error in Height : } \Delta h = .4 \text{ inch}$$

MASCOT SYSTEM
SPARK CHAMBER - "MEDEA"

Figure 3.

Schematic Diagram of the MASCOT system Optics.

**SCHEMATIC DIAGRAM OF THE OPTICS
FOR THE MASCOT SYSTEM**

FIGURE 3

Figure 4.

Photograph of MASCOT Spark Chamber mounted in Magnet.

Pole-piece, top cover, hodoscopes, tilted mirror arrays, and high voltage probes have been removed.

Figure 5.

Schematic Diagram of Hydrogen Target Cell Region.

MASCOT SYSTEM HYDROGEN TARGET
" JASON "

Figure 6.

Photograph of Argo Magnet set-up during Test Run.

Figure 7.

Beam Transport System for Second MASCOT Run at Brookhaven.

BEAM TRANSPORT SYSTEM FOR SECOND MASCOT RUN AT BROOKHAVEN

Figure 8.

Photograph of Rear Portion of Beam Setup for Second Run at Brookhaven.

Cerenkov counter and first beam counter can be seen in foreground. Photograph was taken from the top of the second bending magnet D2. The last two quadrupoles, as well as an unused third one, are further downstream. In the background is Argo with its hydrogen venting hood installed on top.

Figure 9.

Čerenkov Counter Pressure Curve

A PLOT OF THE FRACTIONAL COUNTING IN THE CERENKOV COUNTER AS A FUNCTION OF CERENKOV COUNTER GAS PRESSURE FOR 8 Gev /c K⁻ INC.

Figure 10.

Schematic Diagram for Mascot System Fast Electronics Logic.

MASCOT SYSTEM FAST TRIGGER LOGIC

Figure 11.

A plot of the fit of the Data to two constraints.

The constraints are that the V-mass be correct and that the fitted V intersect the beam.

Both target-full and target-empty unambiguous events are presented.

A PLOT OF THE FIT PARAMETER X FOR DATA
(2 CONSTRAINTS)

Figure 12.

A plot of the Fit of the Data to Three Constraints.

The three constraints are that the V-mass be that of a kaon, that the fitted V intersect the beam, and that the missing mass be that of a neutron.

- (a) Fit of the data with no gamma-ray tracks.
- (b) Fit of the data with probably no gamma-ray tracks.
- (c) Fit of the data with gamma-ray tracks.
- (d) Fit of the data with no gamma-ray tracks after the subtraction procedure described in the text.

Target-Full data is presented here.

A PLOT OF THE FIT X FOR DATA (3 CONSTRAINTS)

Figure 13.

A plot of the Fit of the Data to Three Constraints.

Plots are analogous to Figure 12 , but for target-empty data.

A PLOT OF THE FIT X (3 CONSTRAINTS)

Figure 14.

A Plot of the Angular Distributions of Various Subsets of the Data.

Figure 15.

Results of Efficiency Calculation and Corrected Angular
Distributions for target-full and target-empty data.

Figure 16.

A Plot of Total Cross-section for the Kaon Elastic Charge-Exchange Process as a Function of Incident Momentum

ELASTIC CHARGE EXCHANGE TOTAL CROSS-SECTIONS
AS A FUNCTION OF INCIDENT MOMENTUM

μ barns cross-section

$\circ$ P. Astbury et al.^{16,17}
 $\triangle$ This experiment

Lab Inc. Momentum of K^- , GeV/c

13 22

200

100

5

7

9

11

13 22

Figure 17.

A Plot of $d\sigma/dt$.

Figure 18.

Temperature Rise in the Cooling Water of the Argo Magnet
as a function of current through the coils.

A PLOT OF TEMPERATURE RISE IN THE
ARGO MAGNET AS A FUNCTION OF
EXCITATION CURRENT

Figure 19.

Field Strength as a Function of Excitation Current in the
Argo Magnet.

FIELD STRENGTH OF ARGO AS A
FUNCTION OF EXCITATION CURRENT

Figure 20.

Resolution of $\cos \theta_{\text{cm}}$, the production angle of the charge-exchange kaon, as set by the errors of the MASCOT system and determined by the Monte-Carlo program.

Figure 21.

A Comparison of First Kaon Mass for Jittered Monte-Carlo events and the data.

Figure 22.

A Plot of the Delay for 50% Efficiency versus Clearing Voltage on the MASCOT spark chamber and at various magnetic field intensities.

FOOTNOTES

1. For earlier references to the MASCOT system, see MIT-LNS progress reports starting May, 1963.
- 2,3. Such viewing techniques are common in spark chamber work; see, for example, "Cylindrical Spark Chamber", M.A.Wahlig et.al., RSI 33, 539 or "High-Z Cylindrical Spark Chamber Study of the Reaction $\pi^- + p \rightarrow \pi^- + p + \pi^0$ " P.M.Mockett, Ph.D. Thesis, May, 1965, M.I.T. (unpublished)
4. The conical mirrors were machined and finished at the Taft-Peirce Manufacturing Company, Woonsocket, R.I.
5. For previous work of this type see reference 3. above.
6. For a description of an experiment using a target similar to ours in construction, see M.Wahlig et.al. , Phys. Rev. Lett. 13, 103.
7. For a description of this program, as well as the location of the magnets through D1 for our beam, see BNL Internal Report #9213, "Design of a Medium-Energy Pion Beam for the AGS." by L.Read et.al..
8. The intensity of the beam depended on the number of circulating protons that were allowed to spill on our G-10 target. When the intensity of our beam was too great for the clean operation of our spark chambers we reduced our effective beam intensity by stopping down the apertures of Coll 1 and Coll 2 with shims. About 90% of the data was taken with the vertical opening of both collimators at two inches, and the horizontal opening $1\frac{1}{2}$ inches on the front collimator and one inch on the rear collimator.
- 9,10. For a description of this counter see T.Kycia and E. Jenkins, "A High Resolution Differential Cerenkov Counter", Brookhaven Internal Memorandum (unpublished) or W.F.Baker et.al., Phys.Rev. 129,2285.
11. For a review of data analysis techniques see, for example, Section XIV "High Energy & Nuclear Physics Data Handbook", edited by W. Galbraith and W.S.C.Williams (Rutherford High Energy Laboratory, Chilton, England (1963)).
12. No attempt to count or measure these extra tracks, associated with gamma-ray induced showers in the lead, is reported in this thesis. However, work is in progress at this time to make use of this extra information, further to specify the possible two-body final states showing a single V-particle. When the data is ready for final publication, we hope to include in the analysis the results of this extra information, measuring and analyzing the gamma-ray tracks.

13. See, for example, "Nanosecond Counter Circuit Manual", R. Sugarman et al., BNL Report #711 (T-248).
14. A check of the efficiency was not made at the end of the experiment, but a plot of the locations of sparks in the downstream chamber, for the target-full data early in the run and for the target-empty data late in the run, showed no difference in the distribution of sparks behind each hodoscope member. We would have been able to see, with our statistics, a change of one hodoscope member relative to its neighbors of 10% or more. Complete analysis of the data will greatly improve the statistics of this technique and greatly reduce the uncertainty about possible changing efficiency of the hodoscope members in the course of the experiment.
15. M.A.Wahlig, in a private communication.
16. P. Astbury et al., "The Charge Exchange $K^-P \rightarrow \bar{K}^0N$ at 9.5 Gev/c", Phys. Letters 16, 328.
17. P. Astbury et al., " K^-P Charge Exchange at 5, 7, and 12 Gev/c", Phys. Letters 23, 396.
18. A. Michelini, in a private communication.
19. H. Brody et al., "Measurement of πp Backward Scattering at 4 to 8 Gev/c", Phys. Rev. Letters 16, 828.
20. W.R.Frisken et al., Phys. Rev. Letters 15, 313.
21. For a review of these calculations and their application to charge exchange and other two-body reactions, see D.S.O.Morrison, "Review of the Inelastic Two-body Reactions", CERN Report PS/5579/mk (1966).
22. R.J.N.Phillips and W.Rarita, Phys. Rev. 138B, 723.
23. See ref. 21 above, page 12 and following, and references therein, for a review of backward peaking reactions and single particle exchange mechanisms.
24. A discrepancy between the pion-induced two-V data and the 8 Gev/c beam momentum value has arisen since this thesis was submitted. About 200 events of the type $\pi^- + P \rightarrow K_1^0 + K_1^0 + \text{neutrals}$ were analyzed. A plot of the mass spectrum of the neutrals showed a large peak centered at about 1150 Mev/c², containing about a third of the events, with a width of about ± 200 Mev/c². Scanning the events for gamma-ray tracks revealed that almost all of the events in the peak were without gamma-ray tracks showing in the chambers.

If the peak were due to production of two kaons and an associated resonance such as N_{1238}^* , which would have gamma-rays as its final decay products, a large fraction (estimated from Monte-Carlo studies to be about 2/3) of the events in this peak should show at least one gamma ray. It seems highly improbable the events in this peak are any reaction but $\pi^- + p \rightarrow K_1^0 + K_1^0 + \text{neutron}$. A comparable sample of Monte-Carlo generated events with this reaction were analyzed with our program sequence. They yielded a missing-mass peak which was centered correctly on the neutron mass and with the same $\pm 200 \text{ Mev}/c^2$ width as the curve from our data. We made a study with these events with each of the major calibration parameters altered by several times the uncertainty allowed by our calibration procedure. In no case was the missing mass peak moved by more than a few Mev/c^2 . Thus we concluded that the calibration uncertainties could not make such a shift in the mass curve. The value of Argo's magnetic field, measured with our Hall probe and cross-checked by the mass distribution of the observed V-particles in our data to about 1%, also could not be varied enough to correct the shift in the neutron mass peak. Thus it seems the only explanation of the shift is our having used the wrong value of the beam momentum in calculating the missing mass. The peak would be centered correctly if the incident momentum were $7.8 \text{ Gev}/c$ instead of the $8.0 \text{ Gev}/c$ we formerly used.

The momentum of the beam was set by the known properties of the BNL bending magnet D2 and by the geometry of the beam. Each of the components of the beam system (magnet coils, power supply shunt, reference potentiometer, and beam survey) were checked and were found not to be defective. The desired change in momentum is about 5 times that we could justify within the measurements we made with the $1/8$ inch wide counters placed along the beam path. At this time we do not understand this discrepancy; the narrowness of the shifted missing mass peak suggests that something was indeed wrong in the original beam setup and that the beam momentum really was $7.8 \text{ Gev}/c$.

For the charge exchange data presented in this thesis, the error in determining the missing mass is enough greater than the two-V data, and the statistics sufficiently poor, that no great change would be noticed, either in the X curves or in the angular distribution, if we used the new value of beam momentum in analyzing the events.

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The long program of design, development, test, and experimenting with the MASCOT system would have been fruitless without the continuing help and support of many people. The original concept of the MASCOT system and many of the detailed techniques used in realizing it were due to Prof. David Frisch. I have benefitted greatly from his council and from the independence allowed me in this work. His interest and enthusiasm throughout the whole program was what made final results possible.

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Charles Ward designed, constructed, and tested the mechanics of the hydrogen target and set up much of the trigger electronics; he was in constant attendance during both experimental runs. We shared the burdens of the calibration procedure, part of the de-bugging of the analysis program, and that part of the computer programming which was intimately bound up with calibrations. Many fruitful ideas grew from our discussions together.

Many thanks are due to the members of the M.I.T. spark chamber group, particularly John Liu, Richard Stimets, Lyman Stinson, and Lauren Sompayrac, whose support during the setup and running of the experiment was indispensable. Ed Drucek, our technician at Brookhaven, deserves especially to be recognized, because of his enthusiastic support and long hours of work during the preparation and running of the experiment.

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APPENDIX A TECHNICAL DETAILS OF ARGO MAGNET

The Argo magnet was designed by Drs. M.S.Livingston and D.D.Jacobus of the Cambridge Electron Accelerator. The major design work extended from September 1962 to February 1963. The lowest bid for construction of both the steel frames and excitation coils was put in by the Westinghouse Electric Corporation. Construction started at their Large Rotating Apparatus Division in East Pittsburgh, Pennsylvania, in April of 1963 and was complete when the last set of coils was shipped in September 1964. The pieces were assembled and tested at Brookhaven National Laboratory.

The magnet assembled weighs 140 tons. It is possible to remove the pole-pieces and to remove the equipment within the magnetized volume without disassembly of the magnet proper. The magnet can be moved horizontally over distances of several feet by a simple hydraulic jack system which attaches to the floor pad. Mechanical jacks in each of its three feet can raise it one inch. For a move of greater distance than these, the magnet can easily be disassembled into four pieces with the disconnection of only a few of the electrical and water connections being required. The weight of each piece when disassembled is less than forty tons.

The excitation of the magnet is provided by twenty-two pancake coils mounted entirely within the flux return provided by the steel frames. Each of these pancake coils consists of 56 turns of copper conductor each with a cross-sectional area of approximately half of a square inch. A cooling water path of diameter approximately .3 inches is provided within the conductor. Each pancake coil is arranged with four parallel water circuits.

All of the water circuits are connected in parallel across the cooling water supply. With a pressure drop of approximately 130 PSI the flow through the coils is 130 gallons/minute. Figure 18 shows the experimental temperature rise of the water for various currents through the coils.

The field intensity as a function of magnet current was measured at the hydrogen target position with a Hall probe. The result is presented in Figure 19. At maximum current, we used the probe to check on field inhomogeneities in the accessible regions of the chamber, along the length of the hydrogen target socket, and in the region inside the downstream chamber. We found the field to be constant to within one percent in the regions of momentum measurement, with the worst place being directly over the downstream optics hole. Because the apparent curvature of a track is the result of the magnetic field value integrated along the track, we felt that the measured value of the curvature would be more accurate than this 1% figure, and because this was well below the other errors in most of our measurements, we made no attempt in our study of the magnet further to investigate field inhomogeneities.

A rough cross-check of the average magnetic field intensity was provided by the distribution of raw kaon masses from the charge exchange data. The distribution of kaon mass before iteration of the data is presented in Figure 21b; the analogous curve for Monte-Carlo generated events is presented in Figure 21a. These curves agree within statistics. An error in assignment of the magnetic field intensity value of 1% would shift the mass curve of the data by $2\frac{1}{2}$ Mev. Thus the agreement of data and Monte Carlo curves checks the magnetic field by about 4%.

APPENDIX B CONICAL MIRROR SYSTEMS

It was our aim, in the design of the MASCOT system, to view our cylindrical spark chambers through holes considerably smaller than the chambers themselves. This task was accomplished by placing concentric and coaxial male and female conical mirrors of 90° central angle beneath the spark chambers as illustrated in Figure 3. Such an array of optical surfaces has some interesting properties. If an object is viewed by eye or camera through the conical array, considerable astigmatism is observed. The rays from a point source no longer diverge at the same rate in all directions after they have passed through the conical array.

This astigmatism takes a fairly simple form if the observer is close to the axis of the cones and far away. Consider that such an observer views in the male cone a point source a distance D behind the female cone. Let the radii of the male and female cones be r and R respectively. Then simple ray tracing yields the result

$$\left. \begin{aligned} D_p &= D + (R-r) \\ D_t &= D(r/R)^2 + (R-r) r/R \end{aligned} \right\} \quad (B-1)$$

where D_p is the distance behind the male cone surface of the virtual point source as deduced from those rays in the plane containing the point source and the axis of the cones, and D_t is the analogous distance deduced from rays in a plane at right angles to the first. D_p , of course, is just the actual geometric distance to the object; this results

from the fact that the conical mirrors seem to be merely two parallel straight reflecting surfaces in the plane for which D_ρ was calculated. D_t is always less than D_ρ ; the apparent depth of an object along the axis of the cones is decreased by $(r/R)^2$.

For our experiment the lens to film distance of the camera was set to focus the D_t component of the light from sparks. This meant that a single spark would appear as a narrow radial line with poorly defined ends. Although poor focus of an optical system is usually a serious defect, in this case our poor radial focus was not, because most of our tracks were incident nearly radially on the chambers, and the sparks themselves were radial, so only the angle of the spark required accurate measurement.

If our cones were not properly aligned, or if the camera was not viewing perfectly parallel to the axis of the cones, an error would occur in the angular and height measurement of a spark. Further, if the position of the axis of the cones was poorly known, an additional error would occur. The functional forms of these errors, easily derived by ray tracing, are given in equations (B-2) to (B-4). The measured coordinate θ of a spark which occurred at radius R over the female cone and height Z above it is considered to have an error $\Delta\theta$:

- (1) Cone unalignment of distance a in direction θ_1

$$\Delta\theta = a \sin(\theta - \theta_1) (1 - Z/R)/R \quad (B-2)$$

(2) Non-Axial Viewing at an angle α to the axis of the cones, in a direction θ_2 ,

$$\Delta\theta = \alpha \sin(\theta - \theta_2) Zr/R \quad (B-3)$$

(3) Error in locating the axis of the cones by an amount b in a direction θ_3 ,

$$\Delta\theta = b \sin(\theta - \theta_3) (1/r - 1/R) \quad (B-4)$$

These formulae would be expected to be correct unless the amount of unalignment in one of the cases was large enough that direct viewing of the sparks was obstructed by the spark chamber plate structure. In fact, the amounts of unalignment were small. An important feature of these formulae is that the θ -dependance of all the corrections is sinusoidal. This means that for constant radius and height, the corrections all add to give a simple sinusoidal total correction, and that we could not deduce which of the three mechanisms was the cause of whatever distortion we were correcting for unless we investigated its behavior as a function of radius or height. Note also that the third mechanism is independant of height. This similarity of the various corrections in the θ -dependance is utilized in the calibration techniques described in the next appendix.

APPENDIX C OPTICAL CALIBRATION OF THE MASCOT SYSTEM

This Appendix will be devoted to a description of the calibration of the optics for the MASCOT system. The optical calibrations provide the reconstruction program with the parameters necessary to achieve a correct relation between the actual locations of the sparks in the chambers and their apparent locations as recorded on the film at the camera. These calibrations took place as a series of three steps:

- (1) Calibration of the external optics: obtaining the mapping and its height-dependance for relating an image on the film plane to the corresponding location within the magnetized volume of Argo.
- (2) Determination of the alignment parameters of the optical elements within the spark chamber and the alignment of the spark chamber box in the field of view calibrated in (1) above.
- (3) Calibration of the tilted-mirror stereo system.

Parts (1), (2), and the cross-checks on part (3) were joint work with Charles Ward.

In order to accomplish the first step of these, the spark chamber was withdrawn from its cavity in the magnet. The external portion of the optics was left undisturbed beneath the magnet. A fiducial plate was prepared which was pierced with a square array of holes .040 inches in diameter spaced every half inch covering the field of view of the external optics. A diffusing screen and source of illumination were placed behind the plate and the resulting array of bright "dots" was photographed in the magnet cavity at five different heights above the face

of the bottom pole-piece. Each dot appeared on the film as a round black spot about 40 microns in diameter with an edge that was well-defined to about 5 microns. The distortion of the elements of the external optics caused a departure on the film of the dots from a square array. In lowest order these distortions would change the square array into a parallelogram array, as will be discussed below.

The pictures of the fiducial plate were measured on an Hydel encoding machine; a description of this machine and of the technique of measurement is contained in the next Appendix. The card output of this measurement for each height of the fiducial plate formed the data for a computer program which calculated the parameters of the parallelogram grid which satisfied the conditions of a least-squares fit to the array of points. We found that most of the distortion was of the linear form; only a small (approximately 10% of the total distortion) residue would have required higher-order terms to fit it. The distortion was primarily a stretching of the Y-direction relative to X of about 4%, or a distance of about 400 microns over the whole field of view. The parameters of this fit were seen to vary linearly as a function of the height of the plate, as required by straight-line propagation of the light in the empty magnet cavity. A table of residual deviations of the dots from this parallelogram fit was prepared for the set of measurements at each height of the fiducial plate and was smoothed by an averaging procedure to diminish the effect of measurement errors on the individual dots. The resulting smoothed tables showed deviations of the order of ten to twenty microns (up to forty at the edge) in a pattern which did not change

over the full range of heights by more than a few microns. The values for these residual deviations and for the parallelogram parameters were consistent with the quality of the optics used in the system. The distortion was caused mostly by non-flatness of the plane mirrors.

We incorporated the results of these measurements into our program which reconstructed sparks from the locations on the film to "locations" in real space. A point on the film was corrected both for the effect of the parallelogram distortion and by an interpolation with the four nearest values in the table of residual deviations. The parallelogram parameters depended on the height of a spark, as roughly determined by our stereo system, but the values in the table of residual deviations were taken to be height independent, because we had seen little variation in this table as a function of height. Reconstruction of the fiducial plate measurements with this full program of corrections reproduced the original spacing of the dots on the plate, except for the random measurement errors on each dot. The residual systematic error still remaining in this calibration, estimated to be at the .1% level, is due to the slow random variations in the scales of our Hydel machines which typically take place over a period of about two days. Presumably we could gain a little on these errors by remeasuring the fiducial plate pictures several times and averaging over the results to get a more representative value of the Hydel scales, but it is felt not to be worth the trouble.

The second part of the calibrations was not as straightforward as the first part. First we knew, from direct and optical measurements on the system, the amounts of cone unalignment for each of the chambers.

The coordinates of each spark (R, θ, Z) had their θ corrected for the effect of this cone unalignment by using the appropriate values of a and θ_1 for that chamber in equation (B-2). The Z of the spark was also corrected by a similar formula. Note that the Z of the equations in Appendix B is the height of the sparks above the female cone and not the usual height above mean beam height used in all our calculations elsewhere.

We then noted that the correction formulae, given in the previous Appendix for all three relevant unalignment mechanisms, all had similar (sinusoidal) θ -dependance. Further R (and hence the corresponding radius of the apparent spark location on the male cone r) did not vary much within a single chamber. We then felt that the remaining correction could be entirely of the form of equation (B-4) because all remaining corrections were known to be small and because we could depend on the fit to our calibration data to give us the correct reconstruction for sparks close to beam height. We chose the values of b and θ_3 separately for each of the four upstream chambers that would simultaneously satisfy the conditions of the following calibration data:

(a) Measurement and analysis of about 800 pictures of beam particles of known momentum passing through the detectors without reaction had to yield, on the average, the correct curvature of the tracks being analyzed regardless of which three chambers were being utilized in the analysis to measure the curvature. These pictures were groups of several hundred each with the Argo magnet at normal polarity, at reversed polarity, and off.

(b) Measurement and analysis of about 100 pictures of cosmic rays had, on the average, to yield straight tracks regardless of which three chambers were being utilized in the analysis to measure the curvature. The cosmic rays were fairly radial around the hydrogen target region and at about 90° to the beam direction.

(c) Measurement and analysis of a photograph of a lucite plate with radially scribed lines at known angular spacing, placed at the top of the chamber (with the stereo mirror arrays removed), had to reproduce the angular spacing for the lines.

Values of $\underline{b}$ and θ_3 were found for each chamber and the set of values satisfied all of these conditions within the expected errors for each group of calibration data. Furthermore, all the values of $\underline{b}$ were suitably small and did not contradict the original .03 inch limits of non-coaxiality for the mechanical elements which were set at the time of the original assembly of the chambers.

We then calculated the appropriate values of $\underline{b}$ and θ_3 for the downstream chamber using, however, different calibration information:

- (a) The downstream portions of (a) and (c) above.
- (b) Measurement and analysis of about 50 pictures of straight off-axis tracks passing through upstream and downstream detectors with the Argo magnet off.

Again, reasonable values of $\underline{b}$ and θ_3 were found which did not contradict our mechanical knowledge of the equipment. Some difficulty arose from condition (b) and the best we could achieve with the limited range of the two-parameter fit and the limits of the other calibration data and mechanical

restrictions was about two standard deviations off in straightness for these pictures. This error would correspond to about .01 inches of systematic errors at the extremes of the 90° sector chamber and the downstream lead chamber. Because the number of these off-axis straight tracks was few and the quality of the pictures from which they were measured was poor, and because we achieved good fits to the geometrical and kinematical constraints of the data with these calibrations, the cause of this discrepancy was not further investigated.

The measurement and calibration of the tilted-mirror stereo system was the third step in the calibration procedure. The mirror plate being measured was placed on a flat reference surface. A small mirror was mounted parallel to the reference surface, next to the particular tilted mirror being measured. Then a telescope and scale were mounted such that the scale could be read reflected in both the reference and in the test mirror. Then if these two views of the scale gave a difference in reading of δ and if the distance from mirrors to scale was l and the viewing was carried out nearly perpendicular to the mirrors, the tilt angle ϕ is given by the relation

$$\tan (2\phi) = \delta/l \quad (C-1)$$

By this means the tilt angles were found for each of the 143 tilted mirrors in the stereo array. Remeasurement indicated an error in reading the scale of about $\frac{1}{4}\%$ of the measured value. Systematic error in determining l was determined to be the same amount. After the experiment we measured the overall tilt of each mirror plate with a fine-scale bubble level. The plates were all level to within two milliradians, but the measured small tilt of each

has nonetheless been included in the reconstruction program as a correction.

As a check on the height calibrations we performed the following checks:

- (a) The distribution of the beam tracks in height was examined in each chamber. Since the beam was known to be horizontal on the average we expected and found the height distributions of the beam to have the same mean height within about $1/8$ inches, an error which was about what one would have expected with the estimated error in determining ϕ .
- (b) The cosmic ray and off-axis straight tracks were straight in height, on the average, regardless of which three chambers were used to test the straightness.
- (c) A program was made which used the upstream two segments from each prong of a V from our data to predict the downstream height. The measured downstream height was then compared with the predicted one, and no systematic shift in height greater than $1/16$ of an inch was observed of the downstream chamber relative to the upstream ones.
- (d) The distribution of the deviation in height of the fit of the V's from the data to the geometry of two intersecting helices had the correct mean value and shape and agreed within statistics with the analogous histogram made from Monte Carlo generated events which had no systematic errors included in their generation. We would have expected to detect any systematic error in the height of one chamber relative to the others greater than about $1/16$ of an inch with this technique.

APPENDIX D HYDEL ENCODING MACHINES AND SPARK MEASUREMENT ACCURACY

The data photographs for this experiment were measured on our group's two Hydel model 200-A3 encoding machines, which were manufactured and marked by the Raymond-Atchley division of the American Brake Shoe Company. They have been used by this group for the analysis of several previous experiments. These machines accepted our 35mm film on a moveable stage with a vacuum hold-down which secured the film in the object plane of a projection system. The image plane of the optical system displayed the picture on a translucent screen magnified about 25 times, so 40 microns on the film appeared as about a millimeter on the screen. Also displayed on the screen was a white cross: the image of the picture could be moved relative to the white cross with hand-cranks, and the coordinates of the point on the film "under" the center of the cross were recorded on punched IBM cards when a button on the console was depressed. The lines of the cross were about $1/8$ of a millimeter wide on the screen, and hence corresponded to a distance of about 5 microns on the film.

On our film, a coordinate frame was established relative to two fiducial lights appearing on each picture. These fiducial lights appeared on the film as round dots about 20 microns in diameter, each with a fuzzy rim of about 2 microns. For the data in this thesis, the two fiducials used were separated by about 9000 microns and lay in the upstream-downstream direction. The least count of the encoder was one micron. When I measured a single fiducial dot 20 times I found I was able to reproduce its coordinates to slightly better than 3

microns. I had one of our girls measure fiducial dots 100 times and she had a similar result. Since these errors were considerably smaller than the errors in measuring our sparks, we have neglected any contributions from errors in measuring fiducials to the resultant error in measuring our events.

Although the length of a spark was nearly constant at about 200 microns, being limited by the plate structure and not too badly blurred by the poor radial focus of our conical mirror system, we found the width of the sparks varied considerably. In the analysis program we have neglected any possible error in locating a spark along its length because our tracks were incident fairly close to perpendicular to the tangent plane of our electrode structure, and for this case the coordinate of the spark along its length (i.e. the radius of the spark) was not very important in determining kinematical or geometrical calculated quantities used in the analysis of the data. The width of sparks varied between 20 and 100 microns, but 40 microns was representative. Although the reproducibility in measuring typical sparks seemed to be about four microns on the film (corresponding to about .01 inches in the real space of the reconstructed sparks), the actual error in the coordinates of measured sparks for our data was larger because of spark jitter in the detectors, fluctuating ability of the girls doing the encoding, and possible drift of the scales of the measuring machines. To determine the actual error that seemed to be present in our data we examined the distributions of the goodness of fit of individual spark segments to straight lines within a single chamber. We plotted a distribution of

the deviation of this fit for each chamber separately for 3, 4, 5, and 6 sparks per segment. We found the resulting distributions could be understood as a statistical combination of single sparks each with a random "jitter" from all causes. The amount of this jitter varied slightly from chamber to chamber; we chose .029 inches in the reconstructed "real" space as representative for all chambers but the 90° sector chamber, whose value was .035 inches. In addition, the distributions were seen to have long non-gaussian tails which became appreciable at apparent deviations of .045 inches or more. In our reconstruction program we used the formula $\Delta\theta = .029/\sqrt{n} R$ for the error in θ , except for the sector chamber, when .035 was used. If the apparent deviation per spark of the fitted segment exceeded .045 inches, we used the formula $\Delta\theta = \text{the observed deviation per spark} / R$. Similar formulae were used to calculate the Z-errors.

The Monte Carlo program was used to generate events which were jittered in their coordinates according to a Gaussian distribution with characteristic width of the observed data for each chamber. This program also included the effects of multiple coulomb scattering in the material of the spark chamber plates. We first generated a group of events at a production angle in the center-of-mass system whose cosine was 0.97. The resulting events were jittered and then analyzed by our V-fitting program with the appropriate three constraints applied for elastic charge exchange. The distribution of the center-of-mass cosine for these events is presented in Figure 20. The accuracy of determination of this quantity with our sources of error,

then, seems to be about $\pm .007$ in $\cos \theta_{\text{cm}}$ of the production angle in the region of our charge-exchange data. This corresponds to .7 of the bin size used for plotting our data.

The same run with these Monte Carlo events yielded a "first K mass" for each event that was the apparent kaon mass calculated from the raw data, before any iteration on the constraints had taken place. The distribution of this quantity is presented in Figure 21. This distribution shows the resolution of our system for the kaon mass is about $50 \text{ Mev}/c^2$ for kaons at about $8 \text{ Gev}/c$ momentum. The distribution of the same quantity for that portion of our data successfully iterating to the charge exchange hypothesis is shown in Figure 21 also (lower graph). The two curves can be seen to be essentially the same shape, except for about 10% of the data events which have large K masses. An examination of the thirty events with a K mass larger than $650 \text{ Mev}/c^2$ showed twelve without gamma-ray tracks, and of these six had a χ less than 3.5. These events have been shaded in the plot of χ for the data (Figure 12). These events have been re-examined and some of them have been improved by re-measurement but others were difficult to measure for various reasons. All would have fit the charge exchange hypothesis well if the value for K mass had been smaller.

The agreement between the data and the Monte Carlo generated events in the conditions of height described in the previous Appendix at the end and in kinematical quantities such as the first K mass indicates that our estimates of accuracy for the equipment, based on the deviation

observed for the fit of sparks within a single segment of a chamber to a straight line, are cross-checked successfully by the spread in other quantities measured in the equipment.

APPENDIX E FILE NUMBERS OF DRAWINGS AND DIAGRAMS

This Appendix presents a complete list of all mechanical drawings or diagrams which were made in conjunction with this experiment and are on file in the Laboratory for Nuclear Science Drafting Room or at the Cambridge Electron Accelerator Drafting Room.

On file at C.E.A.:

1309 → 1326	}	Magnet Frames and Coils
1331 & 1332		
1386 & 1387		

On file at M.I.T.:

4840	Mechanical Assembly, Spark Chamber
4841	High Voltage Probes (obselete)
4842	Hodoscope Assembly
4843	Circulating System (obselete)
4872	Misc. Assy. Tables, Jigs, Etc.
4897	Diagrams
4985	External Optics
4989	Hydrogen Target "Jason"
5008	Neon Recovery System

The high voltage probes used for the main run were never drafted. The neon recovery system was used during much of our test work to recover the neon spark chamber gas. It has been described in the literature^{*} and was a highly successful system enabling us to re-use the spark chamber gas.

* "Liquid-Nitrogen-Cooled-Adsorption Neon-Recovery System",
Bruce Bailey and A. Buffington, Nuclear Instruments & Methods 42, 307

APPENDIX F RESOLVING TIME MEASUREMENTS FOR THE SPARK CHAMBER

This Appendix reports on the technique and results of measuring the resolving time for the spark chamber system. These measurements were made during the preliminary test run. Because the mechanics of the thin-foil spark chambers used in the test run were essentially unaltered for the data run, and because the powering system used was also essentially the same, we feel these measurements represent well the resolving time for both configurations.

We measured the resolving time by observing the efficiency of the thin-foil chambers for straight-through tracks while varying the delay of the high voltage, the sweep voltage, and the magnetic field. The magnetic field and sweep voltages were set, and a rough delay (the delay varied from trigger to trigger when the spark gap trigger was not run as normally, just below breakdown) was introduced by lowering the voltage on the trigger spark gap. An observer was stationed viewing an oscilloscope whose trace was initiated by the fast logic trigger. He measured the delay for each trigger by observing how far along the oscilloscope trace the "pick-up" pulse from the spark chamber firing occurred. With a suitable transformation of scales and addition of the extra delay before the oscilloscope trace started, this yielded the delay from initiating straight-through particle to sparks in the chamber. The observer called this number to another observer who watched the tracks in the spark chamber through its associated optics. He was able to estimate the efficiency for each track. After seeing many tracks to

3

be provided with a good average, this second observer recorded an average delay time and average efficiency of the chambers for that delay. Then the rough delay, sweep voltage, or magnetic field were changed and the process was repeated. Interchange of observers and repeatability of the results proved this technique was reliable and independent of observer.

If the magnetic field and sweep voltage were held constant and the delay gradually increased, the efficiency was seen to be constant out to a certain delay, and then rapidly drop to a very low figure. For example, the efficiency, at 100 volts clearing and the magnet off, dropped from 90% efficiency to about 10% as the delay was increased from 400 nanoseconds to 500 nanoseconds. The point of 50% efficiency provided a good measure of the resolving time. The delay for this 50% efficiency point is presented in Figure 22 as a function of sweep voltage for various values of magnetic field. The resolving time for the full field ($B = 15$ kilogauss) and typical clearing voltage (100 volts) of the second run is about one microsecond. The actual delay during this run was about 500 nanoseconds.

APPENDIX G COMPOSITION OF THE PICTURES

Table II of the text gives an accounting of the composition of the pictures that were produced by our kaon trigger. The pictures that seem to be legitimately produced by V-particle decay within the detectors comprise about a third of the total. The remainder of the pictures are apparent violations of the anti-coincidence scintillator condition, the last beam counter condition, or the hodoscope count condition. This Appendix is a discussion of possible causes for these "false triggers" and of ways one could avoid them in the design of a new experiment.

(1) Apparent violations of the anti-coincidence scintillator

About 5% of the kaon-induced pictures show a charged prong coming out the top, bottom, or incoming beam hole of the anti-coincidence scintillator. About $\frac{1}{2}\%$ of the pictures show a straight-through beam particle which managed to miss counting in the anti-coincidence scintillator and then reacted in the thin foil of the subsequent spark chambers to provide the multiple prongs necessary to give the hodoscope count condition. The absolute rate of this second process is not contradicted by our measured 99.998% efficiency (see page 20) for the scintillator. The first of these backgrounds could be eliminated by capping the ends of the anti-coincidence scintillator and by making a tube of anti-coincidence material upstream of the target assembly which would veto any charged prongs coming back upstream. The absolute rate of these backgrounds was about 6 triggers per 10^6 kaons incident, with a target $2\frac{1}{4}$ inches thick.

(2) Violations of the last beam counter condition.

About 15% of the pictures had no beam particle going into the target region. Presumably the rest of the trigger conditions were met in some fashion and a noise pulse in the last beam counter happened to coincide and allow a trigger. Most of these pictures appear to be one or several off-axis tracks, probably due to a beam particle which interacted upstream of the target and the charged secondaries from the interaction did not pass through the anti-coincidence scintillator. The absolute rate of this background was about 16 triggers per 10^6 kaons incident. This rate does not require an unreasonably large noise rate in the photomultiplier of the last beam counter to provide an explanation. These background processes could be eliminated in the design of an experiment investigating secondaries forward of 90° from the target by installing a large flat scintillator perpendicular to the beam line at the location of the target which would veto any event with off-axis tracks passing beside the target assembly.

(3) Violations of the hodoscope counting condition.

About 30% of the pictures, or an absolute rate of 35 triggers per 10^6 kaons incident, show an incident beam disappearing into the hydrogen target and various numbers of gamma-ray tracks in the lead chambers. A check of the electronics during the run showed the requisite pulses were invariably present in the hodoscope array output for all triggers. Further, since the rate of these background triggers was nearly independent of the width of the time gate for the coincidence, the spurious triggers could not have been chance coincidences with noise pulses in the hodoscope members.

Blocking off the light-pipes at their lower ends removed the pulses and hence proved that they were coming from the scintillators themselves. A calculation based on the premise that the extra pulses were due to pair production from the gamma-rays in the final state of reactions in the hydrogen target (an average number of four was assumed) gave a result that was an order of magnitude too small. The only mechanism which seems capable of explaining the presence of the spurious pulses in the hodoscope members was suggested to us by P. Sonderegger of CERN in a private communication. He suggested that showers developing in the lead plates of the spark chambers had an appreciable fraction of the energy of the shower in the form of soft (~ 3 Mev) gamma rays. These gamma rays would be radiated much more isotropically in the detectors than the visible shower of electrons in the lead and would pass through the lead, because of their energy being close to the minimum in the cross-section curve, much more easily than higher energy gamma rays. These gamma rays then might give pulses in the hodoscope members from the Compton recoil or soft pair induced by the incident gamma ray. A very crude calculation suggests this is a reasonable mechanism to explain the effect. If so, these types of spurious triggers could be reduced by installing a double hodoscope system which would require a coincidence between two members, one immediately behind the other, before accepting pulses as true charged particles passing through the inner hodoscope. Such a configuration would also eliminate the few pictures involving chance coincidence with noise pulses in the hodoscope members.

(4) Violations of both the hodoscope and last beam counter conditions.

About 6% of the pictures are blank, yielding no clue as to their origin.