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THE NEUTRAL K MESON
AS A PARTICLE MIXTURE

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THE NEUTRAL K MESON AS A PARTICLE MIXTURE

Richard Leon Lander

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ABSTRACT

This experiment was designed to demonstrate the recently predicted particle-mixture property of the neutral K meson. The prediction asserts that the neutral K meson contains a short-lived component, θ_1^0 , and a longer-lived component, θ_2^0 . The θ_2^0 should have the property that it regenerates the short-lived component and also produces hyperons upon traversing matter. Under proper conditions the observation of such mesons or hyperons demonstrates the predicted mixture property. The neutral K mesons in this experiment were produced by 1.25 Bev/c π^- mesons striking a 4-x4-x12-inch aluminum target. Neutral particles emitted from the aluminum at an angle of 5 deg with respect to the π^- beam traveled 9.3 ft to a propane bubble chamber operated in a 12-kgauss magnetic field. A sweeping magnet removed charged particles from this beam. θ_2^0 mesons could interact in the walls of the chamber or in the liquid propane, yielding θ_1^0 meson and Λ^0 hyperon decays in the sensitive region of the chamber. Twenty thousand pictures, corresponding to about 3×10^8 pions incident on the aluminum, were scanned for V^0 events. About 14 Λ^0 decays and about 12 θ_1^0 decays were observed. Spurious sources of these decays have been estimated to be negligible.

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I. INTRODUCTION

Under the assumption that the weak decay interactions of K^0 mesons are invariant with respect to the operation of charge conjugation, M. Gell-Mann and A. Pais predicted the existence of a long-lived neutral K meson,¹ which has been called the θ_2^0 meson. The existence of a short-lived neutral K meson, the θ_1^0 meson, which could decay into two pions with a mean life of about 10^{-10} seconds had already been established.² Gell-Mann and Pais suggested that the θ_1^0 meson represented one half of a two-component K^0 meson, called θ^0 . The other half, the θ_2^0 meson, they predicted would appear as a longer-lived neutral K meson for which the two-meson decay mode would be forbidden. Although recent experiments³ suggest that the theoretical grounds for the original prediction are not tenable, alternative formulations with essentially equivalent predictions have been proposed.⁴ The following discussion is an oversimplification, but qualitatively describes the phenomena expected.

In the Gell-Mann and Pais scheme, the creation of a θ^0 corresponds to the creation, with equal probability and prescribed relative phase, of either a θ_1^0 or a θ_2^0 . We may consider the θ^0 wave function to be a superposition of wave functions for θ_1^0 and θ_2^0 ,

$$\langle \theta^0 \rangle = \frac{\langle \theta_1^0 \rangle + i \langle \theta_2^0 \rangle}{\sqrt{2}}$$

Similarly, we have

$$\langle \bar{\theta}^0 \rangle = \frac{\langle \theta_1^0 \rangle - i \langle \theta_2^0 \rangle}{\sqrt{2}}$$

where $\bar{\theta}^0$ is the charge-conjugate antiparticle of θ^0 . The θ_1^0 or θ_2^0 may be considered to be a superposition of θ^0 and $\bar{\theta}^0$,

$$\langle \theta_1^0 \rangle = \frac{\langle \theta^0 \rangle + \langle \bar{\theta}^0 \rangle}{\sqrt{2}}$$

and

$$\langle \theta_2^0 \rangle = \frac{\langle \theta^0 \rangle - \langle \bar{\theta}^0 \rangle}{i\sqrt{2}}$$

To obtain a pure beam of θ_2^0 mesons, it is only necessary to be far enough from the point where the θ^0 are produced. Then the θ_1^0 mesons decay because of their very short life, so that only θ_2^0 are left at the point of observation. K. Lande et al. have indeed observed long-lived K^0 mesons for which the two-pion mode is either nonexistent or rare.⁵ The mixture character of the θ_2^0 meson, however, is not evident from observations of its decay modes alone.

In order to demonstrate the particle-mixture character of the θ_2^0 meson it is necessary to observe its interaction properties. Pais and Piccioni point out that the interactions of the θ_2^0 with matter can result in the regeneration of the short-lived component, θ_1^0 , and the appearance of hyperons and mesons of negative strangeness.⁶ The present experiment was designed to carry out the complete process of production of θ^0 , separation of θ_2^0 , and regeneration of θ_1^0 and hyperons.

II. EXPERIMENTAL METHOD

It should be pointed out that the observation of hyperons arising from interactions of long-lived neutral K mesons is explicit evidence for a particle mixture only if it can also be shown that no K mesons of negative strangeness were produced at the source of the long-lived K^0 's. The particle-mixture theory states that a θ^0 meson is produced with positive strangeness, but may exhibit negative strangeness some time later after the θ_1^0 component has decayed. The production of negative-strangeness K mesons would allow one to postulate the presence of long-lived K^0 mesons in the neutral beam. A K^0 meson is produced with negative strangeness and thus need have no mixture property in order to form a hyperon when absorbed by a nucleon. Hence the observation of hyperons might be explained without resort to the mixture theory unless one were assured that no K^0 were produced. The present experiment was designed to obtain this assurance. (The observation of regenerated θ_1^0 mesons does not suffer from this requirement.)

According to presently accepted classification systems for strange particles,⁷ in which the various particles are assigned a strangeness quantum number, S, as shown in Table I, the strange particles are produced in association with one another in such a way that the sum of their strangeness quantum numbers is zero.

We note that there are no positive strangeness hyperons. This situation requires that, for each strangeness - 1 meson (K^- or K^0) produced, a strangeness + 1 meson be produced in the same interaction. On the other hand, K mesons of strangeness + 1 can be produced in association with hyperons without the simultaneous production of strangeness - 1 mesons. A glance at the mass values involved shows that it is possible to produce K mesons of positive strangeness at such an energy that K mesons of negative strangeness cannot be produced. For example, consider the following reaction, where the total energy of the π^- is less than 1.5 Bev, and therefore no K^0 can be produced:

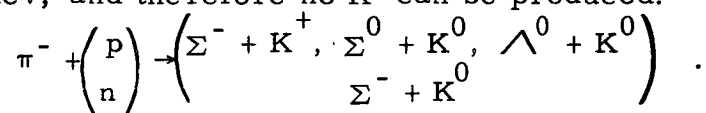


Table I

Strangeness quantum numbers and mass values for
"strange particles."

"Strange particle"	S	Approximate mass (Mev)
K^+ meson	+ 1	494
K^0 meson	+ 1	494
K^- meson	- 1	494
\bar{K}^0 meson	- 1	494
Λ^0 hyperon	- 1	1115
Σ^+ hyperon	- 1	1188
Σ^0 hyperon	- 1	1193
Σ^- hyperon	- 1	1196
Ξ^- hyperon	- 2	1315
Ξ^0 hyperon	- 2	1315

The strangeness + 1 quantum number is carried by the K meson, and the - 1 quantum number is carried by the hyperon. All of these hyperons are known to have mean lives of the order of 10^{-10} sec, so that at a distance of several feet from the point of production there should be no - 1 component. The lifetime of the 2-pion decay mode is also of the order of 10^{-10} sec. If a magnetic field is used to sweep K^+ mesons and other charged particles from the beam, the only strange particles remaining would be long-lived K^0 mesons, in particular, the θ_2^0 . The reappearance of hyperons in such a beam would then be explicit evidence for the re-creation of negative strangeness particles as predicted by the particle-mixture theory.

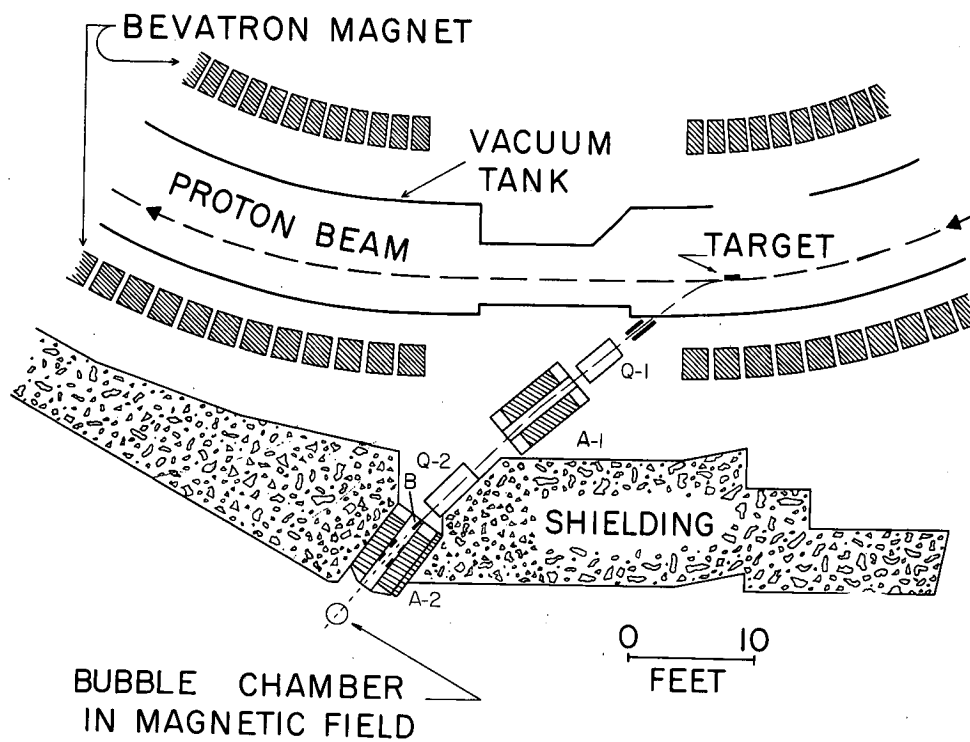
III. EXPERIMENTAL ARRANGEMENT AND REDUCTION OF OBSERVATIONS

A. Experimental Procedure

The experimental arrangement is shown in Fig. 1. The 6.2-Bev kinetic-energy internal-circulating proton beam of the Berkeley Bevatron was allowed to strike a 6-in. -long beryllium target located 5° from the end of the quadrant. Particles emitted forward from this target entered a momentum-analyzer system designed to accept negative particles of $1.25 \text{ Bev}/c \pm 5\%$. The analyzer consisted of the Bevatron field, two quadrupole-focusing magnets, Q_1 and Q_2 , and a bending magnet, A-1, Fig. 1. This beam, consisting primarily of negative pions, was focused on a 4- by 4- by 12-in. block of aluminum, B. Neutral particles produced in this aluminum at an angle of 5° with respect to the incident-pion beam traveled 9.3 ft to a propane bubble chamber 3.25 in. deep by 6 in. wide by 12 in. long operated in a 12-k gauss magnetic field. Charged particles were swept aside by a second bending magnet, A-2. The momentum channel was patterned after that of Cork et al.⁸ A beam-momentum check was performed with counters at the beginning of this experiment, but the momentum spread quoted is taken from Reference (8). The composition of the beam was determined by Cork et al. to be primarily pions, with a contamination of about one antiproton per 70,000 pions and about one K^- per 150 pions at the producing target. Electron and muon contaminations are expected to be small and cannot produce a spurious effect in this experiment.

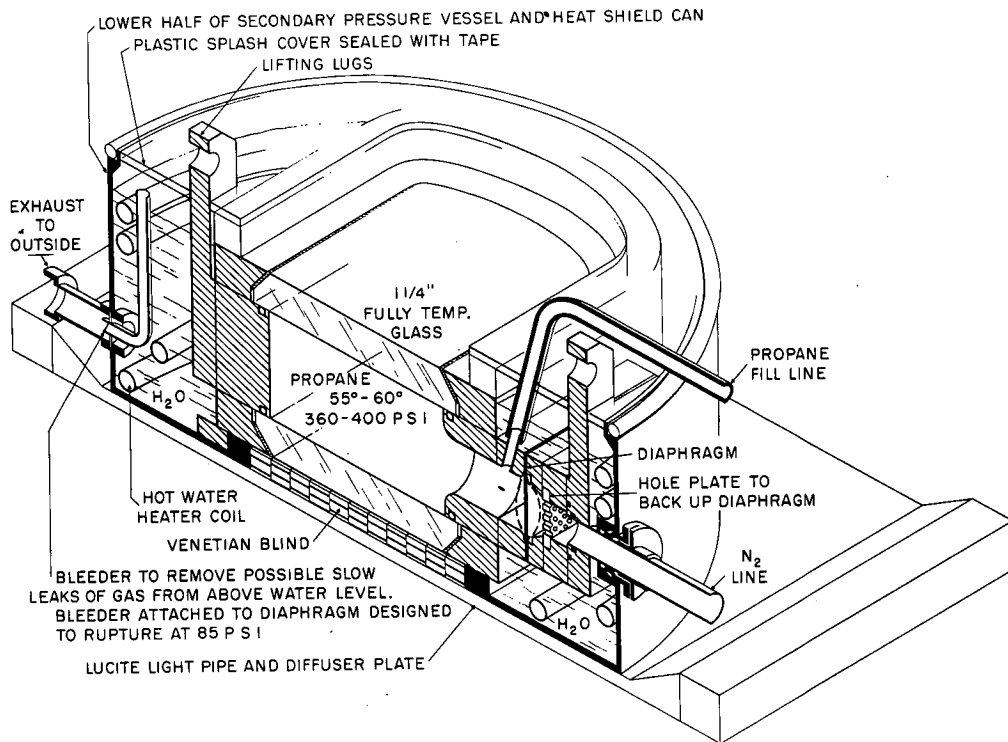
The pion flux was not directly monitored and can only be estimated roughly. The effective aperture of the quadrupole lens was determined by magnetic analysis to be about 40% of that used by Cork et al. A knowledge of their pion flux at the second quadrupole per 10^{10} circulating protons in the Bevatron gave an estimate of 15,000 pions per pulse at an average beam level of 5×10^9 protons circulating. This resulted in an estimated total of 3×10^8 pions on the A1 target for the 20,000 pictures analyzed.

The bubble chamber (Figs. 2 and 3) used to observe the events was of the propane type and has been described elsewhere.⁹ It was operated at a repetition rate of 10 cpm in a magnetic field of 12-kgauss,



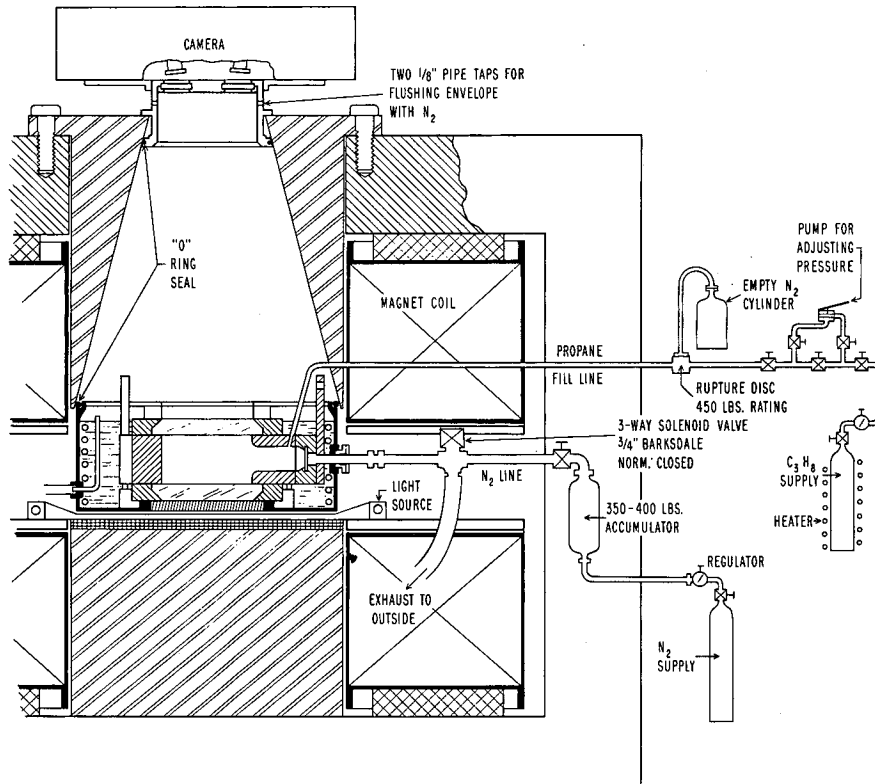
MU-12575

Fig. 1. Experimental arrangement.



MU-12052

Fig. 2. Chamber assembly.



W-12049

Fig. 3. Chamber in magnet.

Figs. 2 and 3. Pictures of track formation in the liquid propane were taken by a power-operated stereo camera mounted 30 in. directly above the center of the propane. This camera also recorded the picture number and magnet current for each picture. Two 90-mm Leitz Elmar lenses were used. The film used was Kodak Linagraph Pan 1.8 in. wide in 400 ft rolls. The stereo angle was 10° included angle between the normals to the film planes.

The time duration during which the chamber was sensitive to ionizing radiation at each expansion was about five msec, so that any timing variation that allowed the pion beam to strike the aluminum before or after this sensitive period made that particular pulse ineffective. Also, the pion beam duration itself had to be kept less than 5 msec for efficient operation. Some variation of the beam both in timing and duration occurred during the run. The effective pion flux was probably not decreased by more than 15% in this way.

B. Scanning of Film

The developed film was scanned on a modified stereo projector mounted overhead so as to project an image on a white table top. Either stereo view could be projected alone or both simultaneously. The film was scanned essentially for neutral V-particle decays only, as these were the most readily identified events. There were many thousand charged-particle scatters which had recoil nuclei too short to be observed. Because these scatters could not be distinguished from charged-particle decays without complete measurement and analysis, scanning for charged decays was not practicable. The events recorded in the first scan were reexamined on a table-model three-dimensional viewer. Those events that passed this second examination were then measured. This procedure was repeated again after all the film had been scanned once. In this second scan a considerable number of new events was found, indicating a low scanning efficiency, perhaps 50%. All the film was scanned in this manner twice, detecting perhaps 75% of the actual events. Of 371 V^0 type events, 115 were suitable for measurement, the remainder having one or more prongs too short for accurate curvature measurement. Several

events with short prongs that stopped within the propane were used, because the momentum could be determined from the range and the particle identification.

C. Measurement of Events

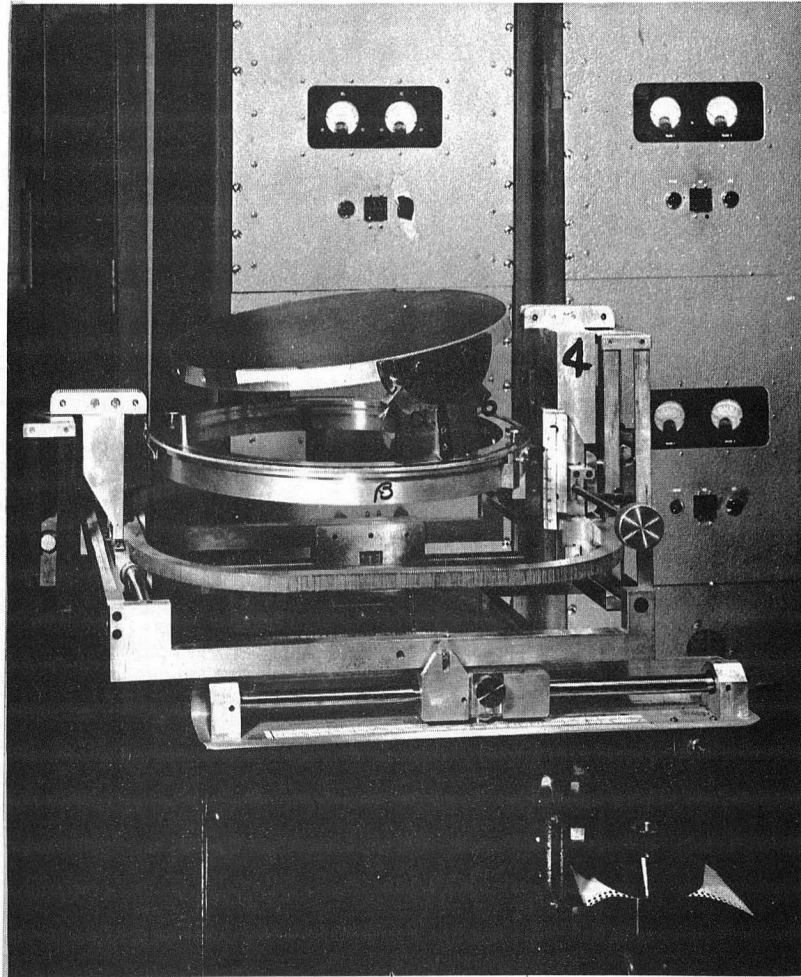
Measurement was effected by means of a stereoscopic projector,¹⁰ Fig. 4, which permitted reconstructing in space the events photographed in the chamber. A schematic drawing of the space table is shown in Fig. 5. The projector reproduced the optical conditions of the original photography except for the foreshortening effect of the propane. Corrections for this effect were calculated and applied at a later stage of the analysis.

The following data were recorded on Keysort filing cards:

- (1) picture number.
- (2) x, y, and z coordinates of the apex of the event
- (3) magnet current
- (4) dip angle, α , of each track
- (5) azimuthal angle, β , of each track
- (6) the radius of curvature, ρ , of each track
- (7) radial distance, r_m , from the magnet axis, and vertical coordinate, z_m , of the center of each track (used for determining effective magnetic field)
- (8) visible track length
- (9) estimated upper and lower limits of ionization of each track
- (10) estimated upper and lower limits of α , β , and ρ

The dip angle, α , is the angle between the track and a line perpendicular to the horizontal plane of the chamber. The azimuthal angle, β , is the angle between the projection of the track on the horizontal plane and the incoming-beam direction. The radius of curvature, ρ , is measured in the plane containing the track by means of scribed plastic templates. In addition, when curvature and ionization values made particle identity obvious, the identification was noted on the filing card.

Discussions of the errors associated with such measurements can be found in published literature.¹¹ We mention only the following points peculiar to this experiment. Multiple scattering in the propane



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Fig. 4. Space table.

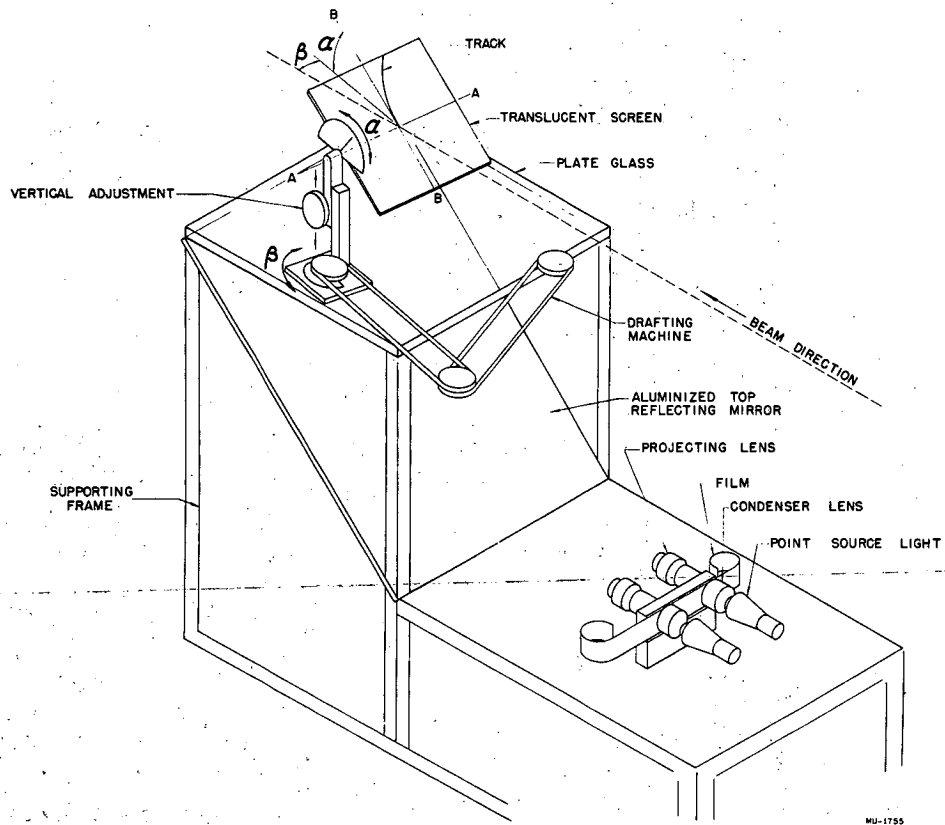


Fig. 5. Space-table schematic.

can contribute to the error in curvature measurements. For propane at a density of about 0.44 g/cc, this uncertainty has been estimated to be 10%. Tracks may suffer detectable small-angle scatters. Such tracks have shorter lengths suitable for curvature measurements, resulting in larger limits of error. Turbulent motion of the liquid propane has been investigated, using photographs of tracks taken without a magnetic field. Turbulence has been found to be negligible except very near to the expansion ports. Measurements in general were not made near these ports. When secondaries of neutral V events stopped within the chamber, their energies could be determined from range measurements. Range-energy curves for polyethylene (CH_2) were used for this purpose as an approximation to propane (C_3H_8). In those cases where curvature and range measurements were both available, the values agreed within the errors.

D. Data Reduction

Once an event had been measured, the data so obtained were processed on an IBM 650 computer programmed to yield the following:

- (1) The Q value or energy release between the two prongs, assuming a π^- and either a π^+ or proton.
- (2) The error ΔQ .
- (3) The calculated ionization of each prong corresponding to the measured curvature and assumed particle.
- (4) The direction and momentum of the V particle before decay.

The calculated ionizations were then compared with the visual estimates to determine particle identification. When necessary, and provided the bubble density and picture quality allowed, microscope bubble counting was used to determine a better estimate of ionization. Of the 115 measured events, 7 were rejected because the estimated ionization was not consistent with that of either a pion or a proton.

IV. RESULTS AND DISCUSSION

A. Results

A total of 108 events containing only a positive and negative particle were measured. Sixty-five were identified, by ionization and momentum, as consistent with a proton and a negative pion. Thirty-seven were identified as consistent with a positive and a negative pion, muon, or electron, but not consistent with a proton and a negative pion. Six were consistent with either classification. The $Q(p, \pi^-)$ values of the 65 Λ^0 types plus the six which could be either Λ^0 or θ^0 types were plotted in weighted histogram form (Fig. 6). Because the Q value for $\Lambda^0 \rightarrow p + \pi^-$ is known to be 37 Mev, a peak should appear at this value in the curve of Fig. 6 if the data include an appreciable number of Λ^0 decays. The striking peak near the known Λ^0 Q -value (37 Mev) suggests that we are indeed observing Λ^0 decays. To ascertain that such a distribution could not come from two-prong neutron stars, we scanned for neutron stars with three or more prongs and calculated the $Q(p, \pi^-)$ values between the π^- and each of the positive prongs. The 39 Q values obtained from a sample of such stars are plotted in Fig. 7 and clearly show no peak near 37 Mev. This distribution does have the same shape as the Λ^0 type distribution except for the peak near 37 Mev, indicating that a background of 2-prong neutron stars, probably of the type $n + n \rightarrow n + p + \pi^-$, is present. If this background curve (normalized to the estimated number of non- Λ^0 -type events in the Λ^0 -type distribution) is subtracted from the Λ^0 -type distribution, the distribution shown in Fig. 8 is obtained, displaying somewhat more clearly the peak near 37 Mev.

Of the 71 Λ^0 -type events, 24 had $Q(p, \pi^-)$ values consistent with 37 Mev. If the background distribution is considered, it is estimated that at least 14 of the 24 must be genuine Λ^0 events. A plot of the Λ^0 -type Q values differing from 37 Mev by less than three times their errors is shown in Fig. 9.

Those events which were θ^0 types, plus the six which fell into both categories are plotted in weighted histogram form in Fig. 10. The lack of a well-defined peak near 214 Mev indicates that not many of the

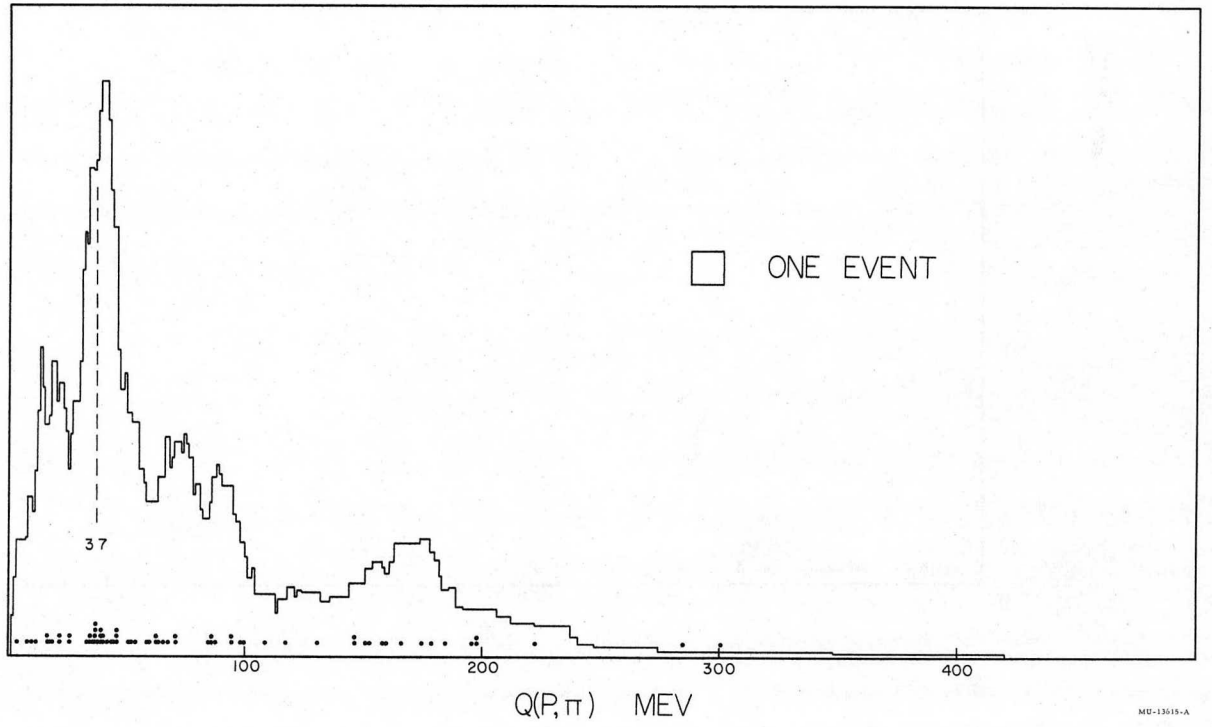


Fig. 6. $Q(P, \pi)$ distribution of 71 Λ^0 -type events.

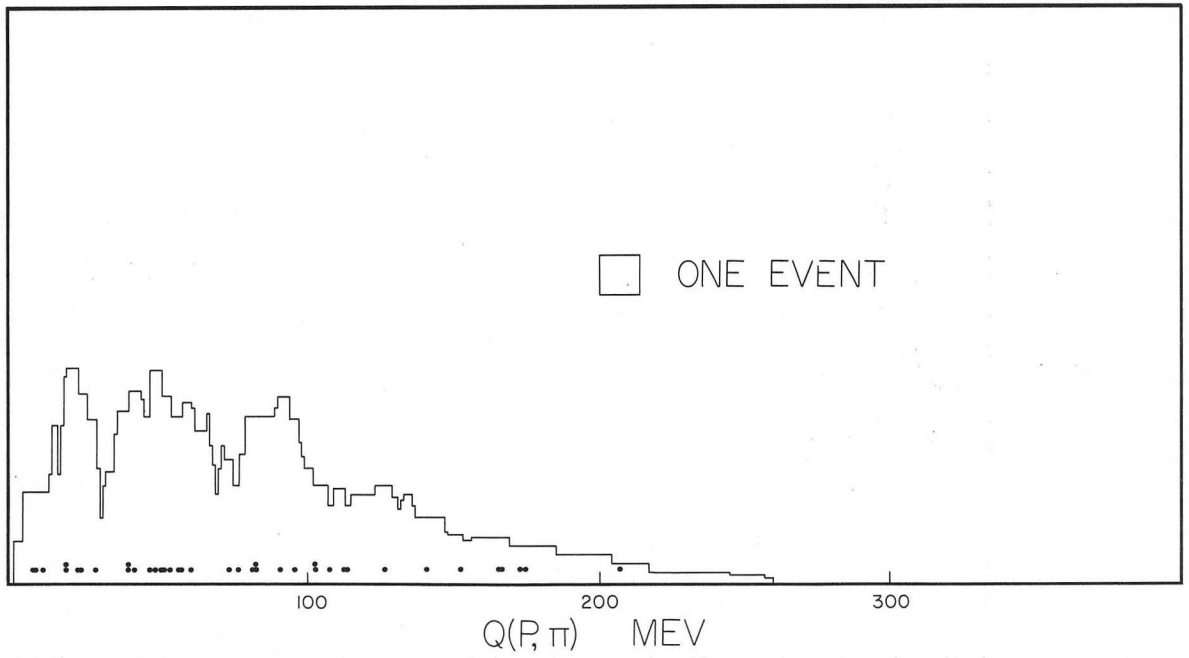


Fig. 7. $Q(P, \pi)$ distribution for protons and π^- from neutron stars in the propane.

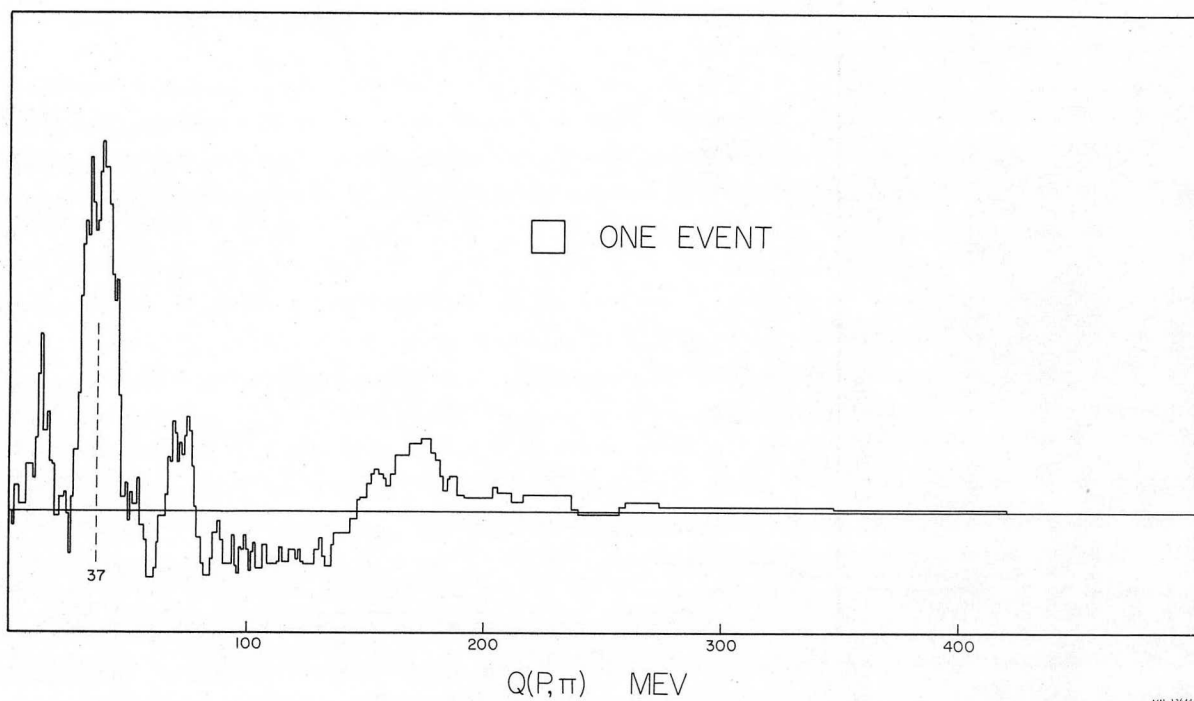
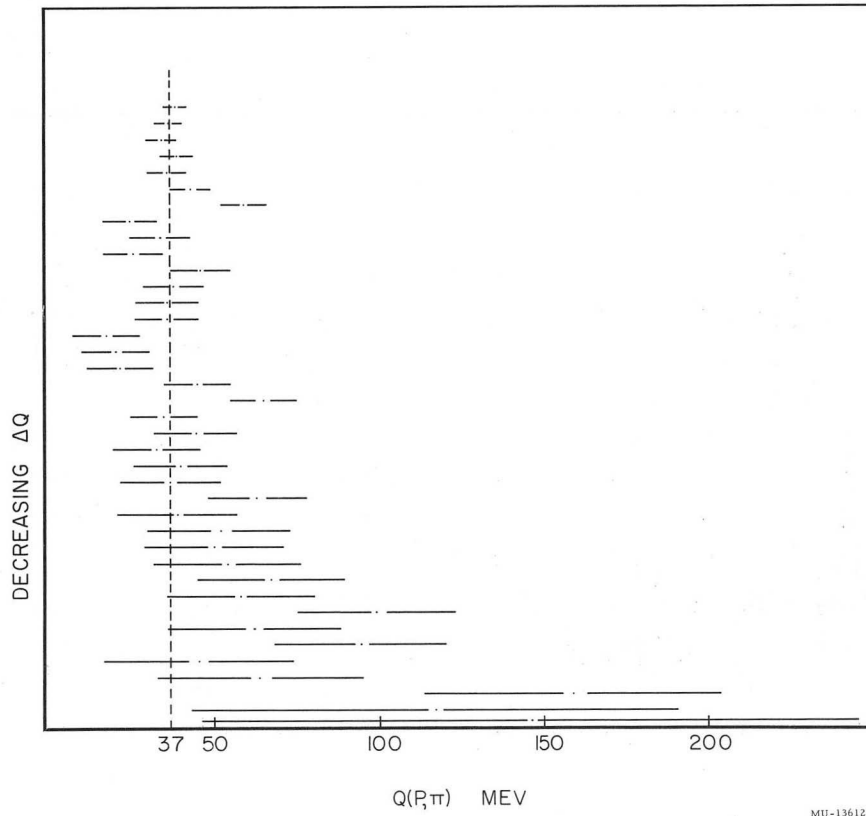


Fig. 8. $Q(P, \pi)$ distribution of Λ^0 -type events minus $Q(P, \pi)$ distribution from neutron stars.



MU-13612

Fig. 9. $Q(P, \pi)$ and $\Delta Q(P, \pi)$ for Λ^0 -type events with $Q - 3\Delta Q \leq 37 \text{ Mev} \leq Q + 3\Delta Q$.

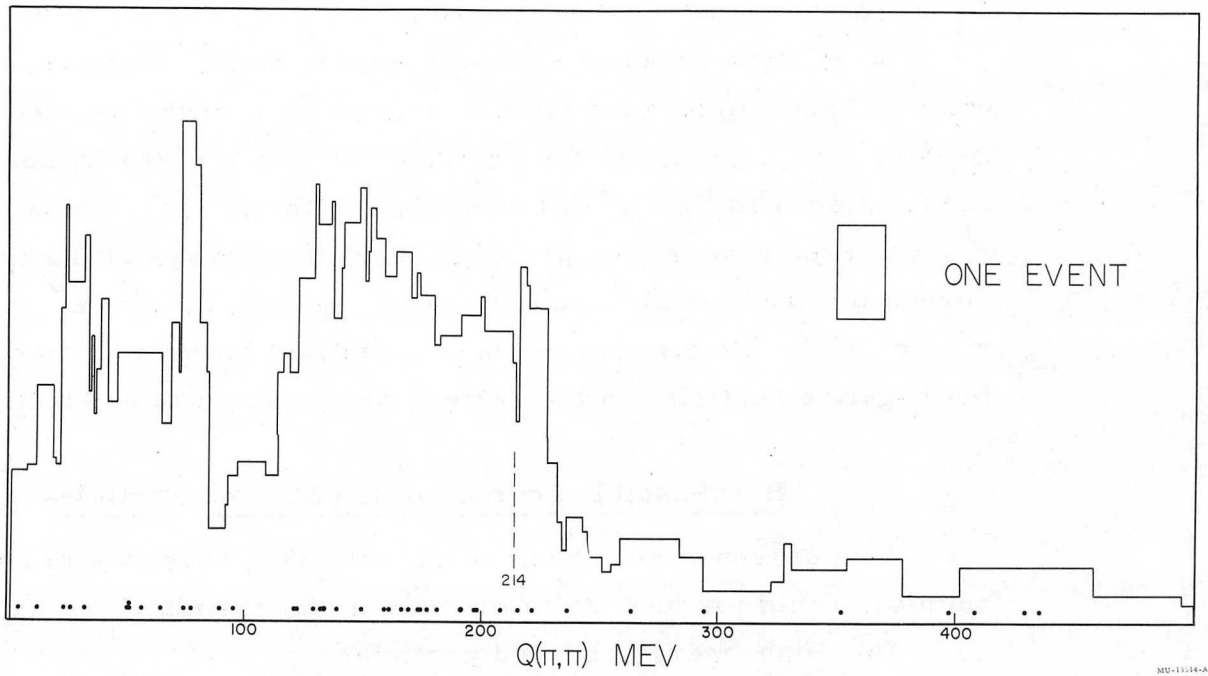


Fig. 10. $Q(\pi, \pi)$ distribution for 43 θ^0 -type events.

43 events are θ_1^0 decays. Twelve of these events, however, had $Q(\pi, \pi)$ values consistent with 214 Mev. Also, of these twelve events, four were associated with stars in the propane. None of the remaining 31 events was associated with a star. If these four stars were chance coincidences, the probability that all four would be found among the twelve events consistent with 214 Mev is about 7×10^{-3} . These four events are then probably not coincidences, but probably indicate that θ_1^0 mesons originated in the propane.

A θ^0 -type background would require double meson production, which is known to be rare from an examination of the neutron stars of greater than 2 prongs in the propane. Only one of the 39 cases appeared inconsistent with $p + \pi^-$ but consistent with $\pi^+ + \pi^-$. Most of the θ^0 -type events were then probably θ_2^0 direct decays of the type observed by Lande et al:⁵ namely $\pi^\pm + \mu^\mp + \nu$, $\pi^\pm + e^\mp + \nu$, and $\pi^+ + \pi^- + \pi^0$. Electrons have been identified in three of these cases, and the negative particles in four others are believed to be electrons.

B. Possible Sources of the Strange Particles

The presence of any one of the following particles in sufficient numbers could produce Λ^0 's or θ_1^0 's in the chamber:

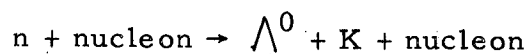
- (a) High-energy charged particles.
- (b) High-energy neutrons.
- (c) High-energy gamma rays.
- (d) Long-lived neutral mesons produced with negative strangeness in the aluminum.
- (e) The predicted θ_2^0 mesons.

Cases (a), (b), and (c) represent local sources; that is, production by background particles near or within the chamber. Case (d) represents the possibility that there might be a long-lived neutral \bar{K}^0 meson, independent of the mixture theory.

(a) Few charged particles were expected in the neutral beam because of the strong sweeping magnet interposed between the aluminum producer and the chamber. Double or triple scatters might allow charged particles

to enter the chamber, but they should be few in number and predominantly π^- , because a π^- beam was used. Very few negative particles other than low-energy electrons were observed to enter the chamber, indicating that the sweeping magnet was performing as expected. The charged particles observed were probably produced by neutron interactions in the walls of the chamber, and should thus be unable to produce hyperons (see Appendix B for a discussion of the neutron flux.) A direct check on the charged particles as a source of hyperons is available from the observed momenta of the charged particles entering the propane. The estimates of Appendix A indicate that this source is unlikely.

(b) The threshold for the process



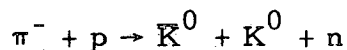
is 2.33 Bev/c momentum in the laboratory. The maximum momentum possible for the recoil nucleon from $\pi^- + p$ elastic scattering is 1.6 Bev/c for 1.25 Bev/c π^- mesons incident on stationary nucleons. The nucleons in the aluminum target, however, are not stationary, nor are those in the steel walls of the chamber or the carbon of the propane. The momenta of the aluminum nucleons could yield recoil neutrons above 1.6 Bev/c. The possible momenta of the recoil neutrons would depend upon the momentum distribution within the aluminum nucleus, the high momentum tail of which is not well known. In addition, the momenta of the iron or carbon nucleons could reduce the effective threshold for the above reaction. In view of the large difference between the free-nucleon recoil momentum, 1.6 Bev/c, and the free-nucleon threshold, 2.33 Bev/c, for the above reaction, it seems likely that internal momentum would have to be utilized twice --- once in the aluminum and again in the iron or carbon. The probability of such a two-step process yielding a significant number of Λ^0 's is expected to be small. Estimates given in Appendix B indicate less than 0.1 Λ^0 should be observed from this source. This expectation is supported by the observation of only one case of double meson production in a 10% sample of the film. Because double meson production by neutrons is known to be prominent at energies above the Λ^0 threshold,¹² the low frequency in this experiment implies no large flux of neutrons above this threshold. The chamber was shielded

against high-energy neutrons coming directly from the Bevatron target by about 8 ft of concrete, 4 ft of iron, and 1 ft of lead.

(c) The available evidence for the photoproduction of K mesons indicates a rather small cross section.¹³ In Appendix C it is estimated that less than $1/36 \Lambda^0$ decays should be observed from photoproduction during the entire experiment. The estimate is based on the failure to observe any electron-positron pairs above 0.670 Bev in sample of one hundred pictures.

(d) The pion beam is known to have a contamination of about one K^- per 150 π^- at the internal Bevatron target. These K^- mesons could suffer charge-exchange scattering in the aluminum and become K^0 mesons. If there existed long-lived K^0 mesons, they might then arrive at the bubble chamber and interact to produce the observed Λ^0 hyperons. The uncertainty in the K^- -meson cross sections and angular distributions at this energy, similar uncertainties for this supposed long-lived K^0 , plus the difficulty of estimating the effects of secondary scattering processes in the thick---4- x 4- x 12-inch--target combine to reduce the reliability of estimates of the number of Λ^0 's that might appear in the bubble chamber from K^- mesons.

The possibility of producing a K^0 meson by the reaction



has also been considered, taking into account the internal-momentum distribution of the aluminum nucleons.

The pion beam also has about one antiproton per 70,000 pions. These antiprotons would strike the aluminum and possibly produce long-lived K^0 mesons.

The total contribution from all three of these sources is estimated in Appendix D to account for less than one of the observed Λ^0 's reported here.

(e) According to Gell-Mann and Pais the state vector representing a θ^0 mesons at the time of production consists of two orthogonal components, θ_1^0 and θ_2^0 , each of which represents a distinct particle with a definite lifetime against decay. The resultant decay and interaction within the 12-in.-long aluminum producer lends a complicated structure to the K^0

beam within this producer.¹⁴ The number of θ_2^0 mesons traversing the bubble chamber may be crudely estimated, however, by assuming that one-half of the K^0 mesons are produced as θ_2^0 , that these θ_2^0 interact with a cross section equal to one-half that of the K^- , and that the loss due to the finite lifetime of the θ_2^0 can be neglected. In Appendix E it is estimated that about 250 Λ^0 decays should have occurred during the experiment. Neutral decay modes (one third of the total¹⁵) and scanning efficiency (about 0.75) would reduce the number of observed Λ^0 's to about 125. Because only about one-third of the observed possible V^0 events had sufficiently long tracks to be analyzable, about 40 Λ^0 decays should have been observed. At least 14 but probably less than 24 Λ^0 decays were observed. In view of the crudeness of the estimate, 40 is probably not inconsistent with the observed number.

V. CONCLUSIONS

The Q value distribution for the Λ^0 -type events leaves little doubt that Λ^0 hyperons are present in the chamber. It is extremely unlikely that they arise from local production by ordinary particles. The possibility that the Λ^0 's were not produced by the negative-strangeness component of a particle mixture, but by a long-lived K^0 meson would be interesting in its own right, but seems unlikely inasmuch as the possible sources of such K^0 's appear insufficient to account for the number of Λ^0 's observed. Further, a long-lived K^0 would not explain the regeneration of the short-lived θ_1^0 . The only remaining explanation for the presence of θ_1^0 's and Λ^0 's in the chamber is the particle-mixture prediction. The observations appear consistent with this prediction. It is difficult to avoid the conclusion that a neutral K meson having essentially the properties predicted by Gell-Mann and Pais does indeed exist.

ACKNOWLEDGMENTS

The advice, encouragement, and support received from Professor Wilson M. Powell throughout the course of this experiment are recorded with great pleasure.

Dr. William B. Fowler's continued assistance at all stages of the experiment contributed in a large part to its success.

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Data reduction was handled by Howard White, who programmed the IBM 650 computer and, together with Mrs. Shirley Dahm, processed the data.

Yuriko Hashimoto, Ronald Hintz, Alan Ryall, and Joseph Wenzel did most of the film scanning.

Complete cooperation was given by the Bevatron staff under the direction of Dr. Edward J. Lofgren.

APPENDIX

In Section IV the following were given as possible sources of the observed strange particles:

- (a) High-energy charged particles.
- (b) High-energy neutrons.
- (c) High-energy gamma rays.
- (d) Long-lived neutral mesons produced with negative strangeness in the aluminum.
- (e) The predicted θ_2^0 meson.

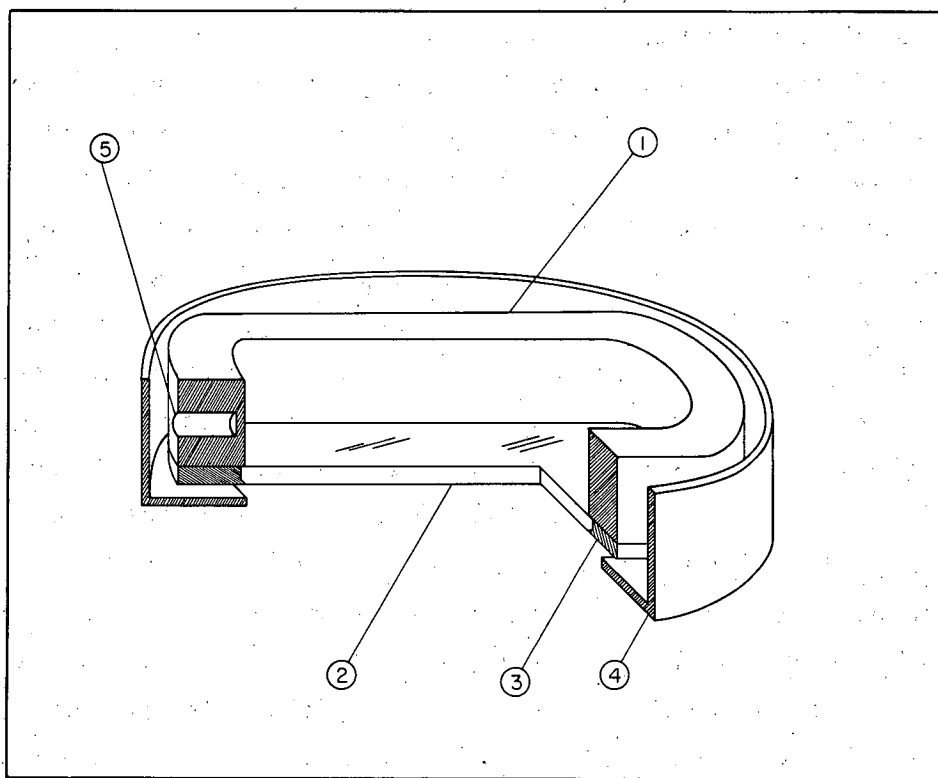
Section IV also gave the estimated contribution to the observed data from each of the above sources. This appendix presents the details of those estimates.

A. Λ^0 Production by Charged Particles

If the neutral beam used in this experiment were contaminated with high-energy pions or protons, these charged particles could interact in the walls of the chamber to yield Λ^0 decays. An estimate of the expected number of such Λ^0 decays can be obtained from the frequency of observation of high-energy charged particles entering the chamber.

The bubble-chamber end wall, pressure tank, and water bath present 46.5 gm/cm^2 to the beam (see Figs. 2 and 11). The propane presents about 12 gm/cm^2 . The side walls of the chamber and the bottom glass present more than a foot of material to particles traveling the length of these parts. If the particle traverses one of the side walls, it can pass through one foot of iron, or about 237 gm/cm^2 . The area of the propane is 21 in.^2 perpendicular to the beam direction. The sides and bottom glass together constitute 23.5 in.^2 . The top glass was shielded from the beam.

Figure 12 shows the attenuation of the charged particles in the entrance end section of the bubble chamber assuming mean free paths of 125 gm/cm^2 , 120 gm/cm^2 , and 103 gm/cm^2 for high-energy charged particles in iron, water, and propane respectively. These numbers correspond to a cross section of 30 mb per nucleon. Figure 13



MU-13513

Fig. 11. Schematic of bubble-chamber body (1), bottom glass (2), clamp ring (3), safety pressure tank (4), and 1-in. -diam. hole (5) in body.

represents the fraction of Λ^0 hyperons that will not decay before entering the propane, as a function of their place of origin in the end section. The average momentum of the Λ^0 's is assumed to be that of the 24 Λ^0 -type events consistent with 37 Mev, namely, 0.7 Bev/c. Using these curves, it is possible to calculate the efficiency of the end section for producing Λ^0 's that do not decay before reaching the propane. Assuming that the fraction of interactions resulting in strange-particle production is 1/30, that all the hyperons produced are Λ^0 's, that none of the Λ^0 's interact in the chamber wall, and that all of the Λ^0 's reaching the propane decay within it, the fraction of the charged particles traversing the end section that yield Λ^0 decays within the propane is found to be 0.006. This number is probably an overestimate because not all the Λ^0 's will proceed straight forward nor will all the hyperons produced be Λ^0 's. Thus at least 160 charged particles above threshold are needed for every Λ^0 decay. Only 69 percent of the 160 charged particles will enter the propane, so at least 112 charged tracks above threshold should be observed to enter the chamber for every Λ^0 originating in the end section and decaying inside the propane. A second group of charged particles traverses the sides and bottom glass. If all of these charged particles traversing the length of the side walls and bottom glass are assumed to interact, then 30 particles are required to produce one hyperon. Not all of the hyperons will be directed toward the inside of the chamber. Twenty-five percent is probably an upper limit. Then 120 particles are needed to produce in the side walls and bottom glass a Λ^0 that decays in the chamber, or for 200 charged particles, 1.6 Λ^0 's appear in the propane. Thus if 112 charged particles above Λ^0 threshold are observed, a probable upper limit of 2.6 Λ^0 decays should have occurred within the chamber.

The scanning efficiency for charged particles is nearly 100%, while the efficiency for Λ^0 decays is about 0.75. Invisible decay modes, amounting to one third,¹⁵ would further reduce the number of observed Λ^0 's. Thus about

$$(2.6) (0.75) (2/3) = 1.3$$

Λ^0 decays should be observed. Only about 1/3 of the observed possible Λ^0 decays in this experiment had sufficiently long tracks to be analyzable,

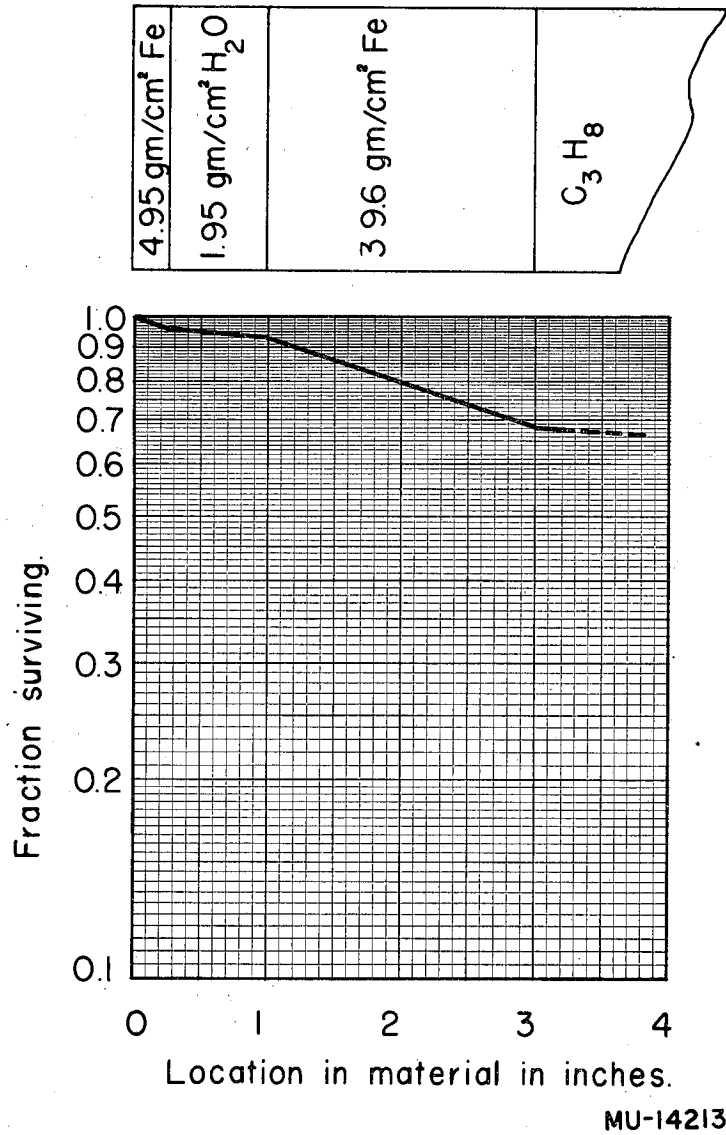
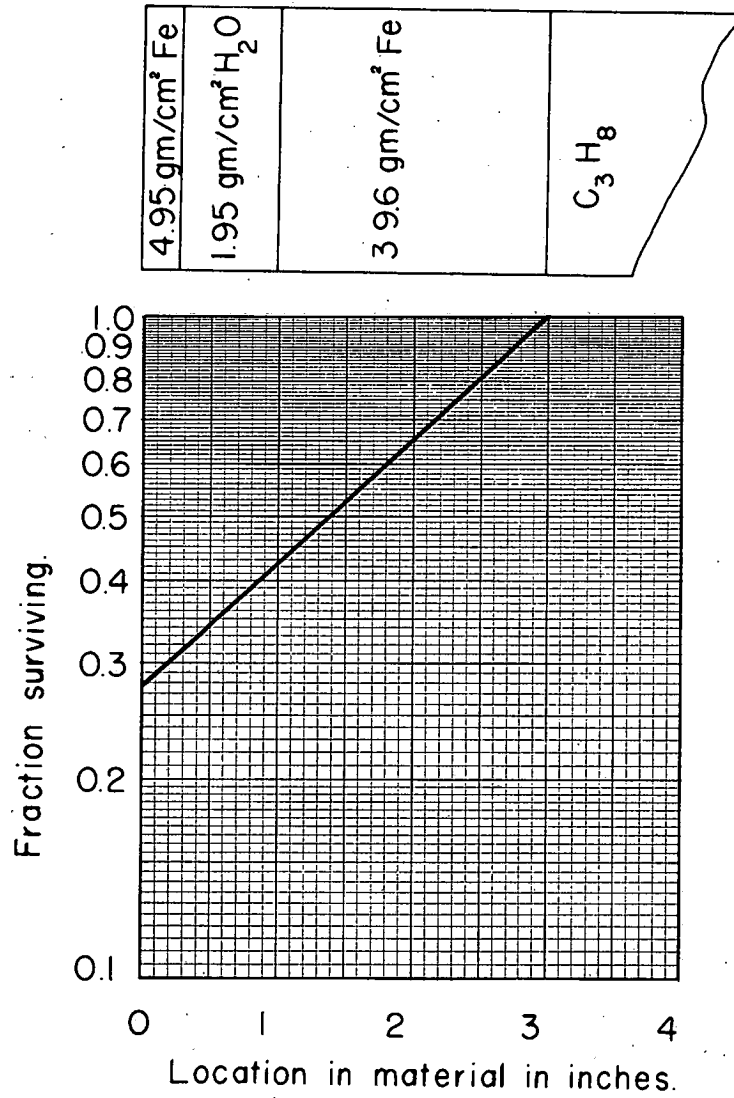


Fig. 12. Charged-particle attenuation curve.



MU-14214

Fig. 13. Δ^0 survival curve.

so that only 1/3 of the 1.3, or 0.4, Λ^0 decays would be included in the analyzed data. Thus for every 112 charged particles above Λ^0 threshold observed, about 0.4 Λ^0 decays would be detected, or about 260 charged particles per Λ^0 .

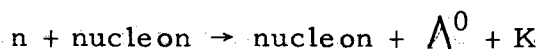
The free-particle threshold for Λ^0 production is 0.900 Bev/c for pions and 2.33 Bev/c for protons. No positive track above 2.33 Bev/c or negative track above 0.900 Bev/c was observed in a sample of 100 of the 20,000 pictures taken in this experiment. For the 14 Λ^0 's to have been produced by charged particles, 18 pions or protons of the required energies should have been observed.

One positive track above 0.900 Bev/c in every two pictures was observed. If these were all π^+ mesons they would be sufficient to account for the observed Λ^0 's. It is highly probable that all of these were protons, as is evidenced by the fact that there were no π^- mesons above this momentum. Actually relatively few π^- were observed to enter the chamber, and all were below 0.900 Bev/c. The interpretation that the high-momentum positive tracks include positive pions produced by neutron interactions in the walls suffers from the lack of similar negative pions. Moreover, the momenta of negative pions from neutrons are well below 0.900 Bev/c, which suggests that positive pions would also have low momenta.

B. Λ^0 Production by Neutrons

If the neutrons present in the beam used in this experiment were sufficiently energetic, they could produce Λ^0 's at the bubble chamber. An estimate has been made of the number of Λ^0 decays that might result from such neutron interactions, taking into consideration the momentum distribution within the aluminum nuclei from which the neutrons are emitted and also within the nuclei in which the Λ^0 's are produced. The production of high-energy neutrons by antiproton annihilations in the aluminum is considered in Section D of the appendix.

The threshold for the reaction



is 2.33 Bev/c for the incident neutron in the laboratory. If the target nucleon has 20 Mev kinetic energy in the laboratory, the threshold can be reduced to 1.9 Bev/c. The neutral beam used in this experiment was produced by 1.25-Bev/c π^- mesons incident on aluminum nuclei. Neutral secondaries emitted between 2^0 and 8^0 in the laboratory with respect to the incident pions could traverse the propane or the chamber walls. In order that a nucleon should have 1.9-Bev/c momentum in the laboratory after being struck by a pion of 1.25 Bev/c, the nucleon must have about 0.500-Bev/c (127-Mev kinetic energy) forward momentum at the time of collision.

The nucleons within the aluminum nuclei are assumed to have a momentum distribution given by¹⁶

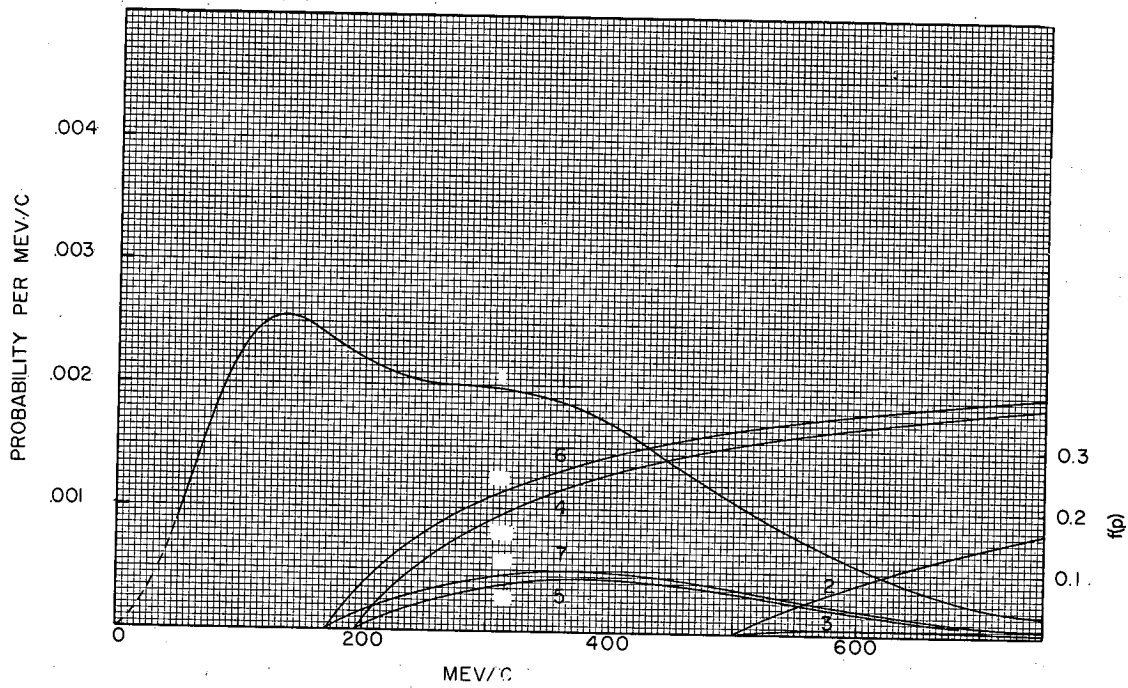
$$N(p) = \text{const. } (T) (e^{-T/7} + 0.15 e^{-T/50}),$$

where $N(p)$ is the probability that a nucleon has momentum of magnitude p , and T is the corresponding kinetic energy. The distribution is arbitrarily cut off at $p = 0.750$ Bev/c. This distribution, normalized to unity, is plotted in Fig. 14, Curve 1. Although a nucleon must have at least 127 Mev in order to contribute to the recoils above 1.9 Bev/c, not all nucleons of greater than 127 Mev will be effective, because only those with a component of momentum greater than 0.500 Bev/c antiparallel to the incident direction will contribute. If isotropy is assumed, the fraction of nucleons of given momentum, p , that has a component of momentum greater than 0.500 Bev/c antiparallel to the incident direction is given by

$$f = 1/2 (1 - 0.500/p) .$$

This function has been plotted in Fig. 14 for $p \geq 0.500$ Bev/c, Curve 2. The product of this curve and the momentum-distribution curve, 1, is taken to represent the probability of finding a nucleon effective in producing a 1.9 Bev/c recoil, and is plotted in Fig. 14 as Curve 3. The integral of the product is then the fraction of nucleons effective. This fraction is found to be 0.93%.

The angular distribution of these recoil nucleons may be approximated by using the distribution given by Walker for 1.0 Bev $\pi^- + p$ collisions.¹⁷



MU-13611

Fig. 14. Curve (1) represents the internal-nucleon momentum distribution. Curves (2), (4), and (6) represent the function $f(p) = 1/2(1 - p_0/p)$ for $p_0 = 500$ Mev/c, 194 Mev/c, and 170 Mev/c respectively. Curves (3), (5), and (7) represent the products of (1) with (2), (4), and (6) respectively.

The fraction of elastic recoil nucleons that scatter forward in the center of mass at such an angle that they lie between 2° and 8° in the laboratory is about 2%. The smearing effect of the internal momentum distribution of the aluminum nucleons is not likely to enhance the forward scattering.

About 25% of all $\pi^- + p$ interactions are elastic at 1.5 Bev.¹⁸ This fraction is assumed to hold for the neutrons also. Because charged particles from the aluminum do not reach the chamber, $\pi^- + p$ collisions can contribute high-energy nucleons (neutrons) to the beam only through charge exchange. About 25% of all $\pi^- + p$ collisions yield charge-exchange neutron recoils.¹⁸ The total cross section at 1.5 Bev is about 35 mb.¹⁸ Then if we use

$$(35)A^{2/3} = 315 \text{ mb}$$

for the total $\pi^- + \text{Al}$ cross section at 1.26 Bev, the mean free path in Al is given by

$$\lambda = \frac{A}{\sigma N_0} \cong \frac{27}{(315 \times 10^{-27})(6.02 \times 10^{23})} = 142 \text{ gm/cm}^2$$

Twelve inches of Al equals 82 gm/cm^2 ; hence the fraction of pions that interact is given by

$$1 - e^{-82/142} = 0.44$$

Then the fraction of the π^- beam that will yield neutrons above 1.9 Bev/c directed between 2° and 8° in the laboratory is given by

$$(0.44) (0.25) (0.02) (0.0093) \cong 2 \times 10^{-5}$$

A sizeable fraction of these neutrons is expected to interact within the 12-in. aluminum producer, but this attenuation will be neglected. The solid angle included between 2° and 8° is

$$\pi 2 (\cos 2^\circ - \cos 8^\circ) = 0.0182 \pi \text{ steradians.}$$

The solid angle subtended at the aluminum producer by the propane is

$$21 / (12 \times 9.3)^2 = 0.0017 \text{ steradians,}$$

where 21 in.^2 is the area of the propane, perpendicular to the beam, and 9.3 ft. is the distance between the aluminum and the chamber. The side walls and bottom glass together subtend

$$23.5 / (12 \times 9.3)^2 = 0.0019 \text{ steradians,}$$

where 23.5 in.^2 is the perpendicular area of the side walls and bottom glass. Then the fraction of the 2° to 8° solid angle intercepted by these parts is 0.03 for the propane and 0.033 for the chamber walls and bottom glass.

The number of neutrons above 1.9 Bev/c traversing the propane is

$$N(\pi^-) (2 \times 10^{-5}) (0.03) \cong N(\pi^-) (6.0 \times 10^{-7}),$$

and the number striking the side walls and bottom glass is

$$N(\pi^-) (2 \times 10^{-5}) (0.033) \cong N(\pi^-) (6.6 \times 10^{-7}).$$

$N(\pi^-)$ has been estimated to be 3×10^8 ; hence the total number of neutrons above 1.9 Bev/c traversing the chamber is

$$180 + 198 \cong 400.$$

This number is most probably an overestimate.

In order to produce a Λ^0 hyperon, these neutrons must strike a nucleon that has more than 194 Mev/c momentum antiparallel to the incident neutron. The fraction of carbon and iron nucleons effective is estimated to be 15%. See Fig. 14, Curves 4 and 5. It is assumed, as in Appendix A, that all the neutrons traversing the walls interact, 3.3% produce hyperons, all are Λ^0 's, and 25% of these Λ^0 's decay within the propane; that 0.006 of the neutrons incident on the end section yield Λ^0 decays from end wall interactions; and that an additional 0.003 of the neutrons incident on the end section yield Λ^0 decays from propane interactions. Then

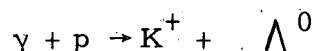
$$(0.15) (180) (0.006 + 0.003) + (0.15) (198) (0.25)(0.033) \cong 0.5$$

is the expected number of Λ^0 decays within the propane. Two-thirds of these will have visible decay products, and about 0.75 of the visible decays will be detected. Thus a probable upper limit of about $0.25 \Lambda^0$

decays should be observed from neutron interactions during the entire run. Because only about one-third of the possible V^0 events were suitable for analysis, the expected number of observed Λ^0 's is about 0.08, or less than one-tenth.

C. Λ^0 Production by Photons.

The data on photoproduction of K mesons¹³ indicate a cross section for the reaction



of about 1.3×10^{-31} cm²/sterad for a laboratory emission angle of 35° and photon energies of about one Bev. If the total cross section for Λ^0 production per nucleon is taken to be one microbarn, then for iron the total cross section is probably not larger than 56 μ b. The mean free path for Λ^0 production by photons in iron is then given by

$$\lambda = \frac{A}{\sigma N_0} = \frac{56}{(56 \times 10^{-30})(6.02 \times 10^{23})} = 1.7 \times 10^6 \text{ gm/cm}^2.$$

The radiation length for iron is 14.4 gm/cm²,¹⁹ so only about

$$\frac{14.4}{1.7 \times 10^6} = 8 \times 10^{-6}$$

of the photon interactions can produce Λ^0 hyperons. In Appendix A, Figs. 12 and 13, curves were shown for the estimated production and decay of Λ^0 particles in the end section of the chamber due to the charged particle flux. Figure 15 shows a similar curve for photoproduction. It is found that 47% of the Λ^0 's produced would decay within the propane. Then approximately

$$(8 \times 10^{-6})(0.47) = 0.38 \times 10^{-5}$$

of the photons yield such decays, so 2.6×10^5 photons per decay are required. It was also estimated in Appendix A that 25% of the Λ^0 's produced in the side walls would decay within the propane, so that 2.6×10^5 photons on the side walls would yield $1/4 \Lambda^0$ decays within the propane. If the

photons are uniformly distributed across the chamber, then 4.2×10^5 photons incident on the whole chamber are required for each Λ^0 decay within the propane. Fifty-three percent would strike the side walls (23.5 in.²), and 47% would strike the end wall (21 in.²). Of the 47% striking the end wall, 4.3% would survive the 1/4-in. steel pressure vessel, 3/4-in. water bath, and 2-in. steel chamber end wall. Also, 3.7% of the 47% would strike the 1-in. -diam. thin window area--1/4-in. - steel pressure vessel, 2 5/8- in. water bath, and 1/8- in. steel thin window. The fraction surviving this material is 0.51. Thus

$$(0.043) (0.47) + (0.037) (0.47) (0.51) \cong 0.02 + 0.09 = 0.029$$

of the incident photons should enter the chamber. If the radiation length of propane is taken to be 2 m, about 10% of the photons traversing the propane should produce observable electron-positron pairs. Thus

$$(0.0029) (4.2 \times 10^5) \cong 1200$$

electron-positron pairs above 0.670 Bev should be observed in 20,000 pictures for every Λ^0 decay present. Invisible decay modes (1/3) and scanning efficiency (0.75) would increase the required number of photons to 2400 for every observed Λ^0 decay in 20,000 pictures. In one hundred pictures there should then be about 12 such pairs. No pairs above or near 0.670 Bev were observed in a sample of 100 pictures. Scanning efficiency for pairs should be about 100% for this sample. Thus 1/12 Λ^0 decays from this source should be observed during the entire run. Because only about one-third of the possible V^0 events were suitable for measurement, the estimate is reduced to about 1/36.

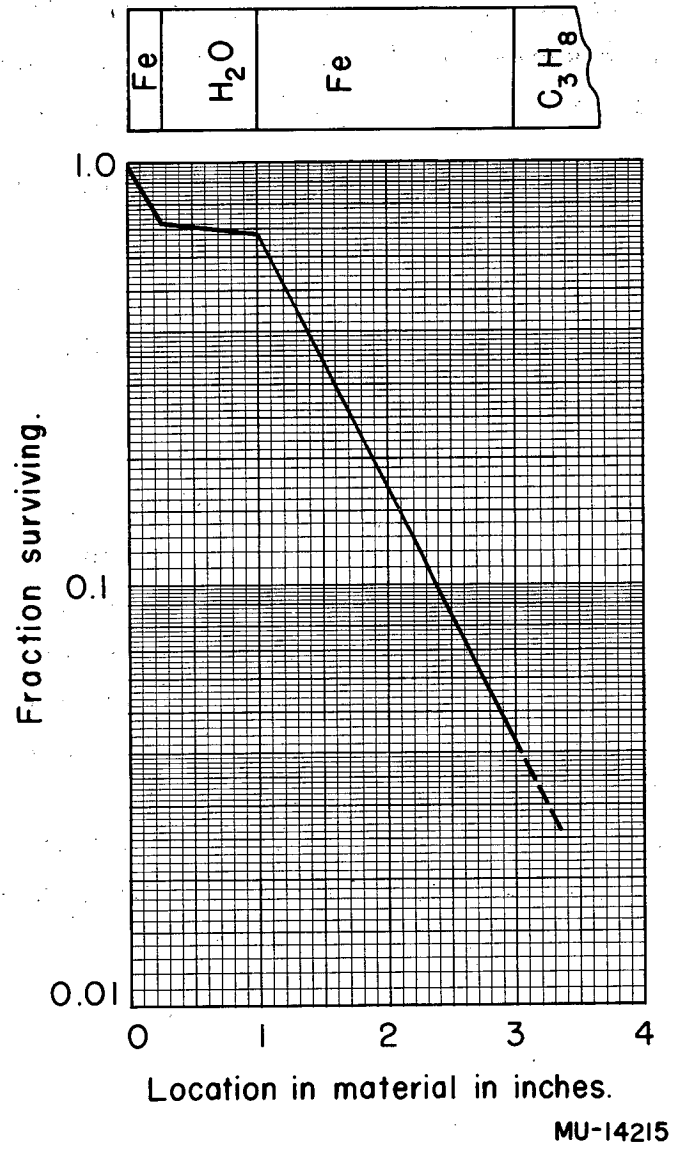


Fig. 15. Photon attenuation curve

D. Λ^0 Production by Long-lived $\overline{K^0}$ Mesons

The assumption of a long-lived $\overline{K^0}$ meson admits the possibility that the Λ^0 hyperons observed in the present experiment result from the absorption of such long-lived $\overline{K^0}$ mesons, rather than the $\overline{\theta^0}$ component of the θ_2^0 . These assumed $\overline{K^0}$ mesons might originate either in charge-exchange scattering of K^- mesons, which are known to be present in the pion beam used, or in various production interactions within the aluminum producer.

Consider first the known⁸ contamination of one K^- per 150 π^- at the Bevatron internal target. The beam momentum was 1.25 Bev/c, for which the K^- has $\beta\gamma = (pc)/(mc^2) = 2.53$. If a mean life equal to 0.95×10^{-8} sec²⁰ is used, the mean free path for decay in the laboratory is

$$L = \beta\gamma ct_0 = (2.53) (3 \times 10^8) (0.95 \times 10^{-8}) = 7.2m .$$

The distance from the Bevatron target to the aluminum is 9.75 m. The fraction of the K^- reaching the aluminum is given by

$$e^{-9.75/7.21} = e^{-1.35} = 0.25 .$$

The 12 in. of aluminum constitute 82 gm/cm^2 . The total $K^- + p$ cross section has been measured to be $52 \pm 9 \text{ mb}$ at 0.9 Bev/c.²¹ If the $K^- + \text{Al}$ cross section is

$$(52) (27)^{2/3} = 468 \text{ mb},$$

the mean free path is

$$\lambda = \frac{A}{\sigma N_0} = \frac{27}{(468 \times 10^{-27})(6.02 \times 10^{23})} = 96 \text{ gm/cm}^2 .$$

If the fraction of $K^- + \text{Al}$ collisions that result in $\overline{K^0}$ mesons is denoted by f , then the number of $\overline{K^0}$ mesons produced in a layer, dt , at a depth, t , in the aluminum block is given by

$$N(K^-) (e^{-t/\lambda}) f \frac{dt}{\lambda} ,$$

where $N(K^-)$ = number of incident K^- particles and λ = mean free path for K^- in aluminum. A certain fraction of these $\overline{K^0}$ mesons will be directed

toward the bubble chamber, at 5° to the incident beam. This fraction will depend upon the angular distribution of the scattered $\overline{K^0}$ mesons, and is denoted by g . If the total $\overline{K^0} + \text{Al}$ mean free path is assumed equal to the $K^- + \text{Al}$ mean free path, λ , and the $\overline{K^0}$ lifetime is assumed infinite, then the number of $\overline{K^0}$ mesons reaching the chamber is given by

$$N(\overline{K^0}) = \int_{t=0}^{t=\ell} N(K^-) (e^{-t/\lambda}) \frac{f \cdot dt \cdot g}{\lambda} (e^{-\frac{(\ell-t)}{\lambda}}) = \frac{N(K^-) f g \ell e^{-\ell/\lambda}}{\lambda}$$

where ℓ = length of aluminum producer = 82 gm/cm^2 ,

$$N(K^-) = \frac{(3 \times 10^8)}{150} (0.25) = 0.5 \times 10^6,$$

and $\lambda = 96 \text{ gm/cm}^2$.

Then we have

$$N(\overline{K^0}) = (0.5 \times 10^6) f g \left(\frac{82}{96} \right) (e^{-82/96}) = 0.18 \times 10^6 f g.$$

Production and decay curves for $\overline{\Lambda^0}$'s from the end section of the chamber are shown in Figs. 16 and 13 respectively. The total $\overline{K^0} + \text{Fe}$ cross section is assumed to be given by

$$52(56)^{2/3} = 761 \text{ mb},$$

and

$$\lambda(\overline{K^0} + \text{Fe}) = 122 \text{ gm/cm}^2$$

is then the mean free path in iron. The total cross section for $\overline{K^0} + \text{H}_2\text{O}$ is taken to be $2(52) + 52(16)^{2/3} = 434 \text{ mb}$, and $\lambda(\overline{K^0} + \text{H}_2\text{O}) = 68.8 \text{ gm/cm}^2$ is the mean free path. If e is the fraction of $\overline{K^0}$ interactions that yields $\overline{\Lambda^0}$ hyperons, then $0.18e$ of the $\overline{K^0}$ incident on the entrance end of the chamber are effective in producing $\overline{\Lambda^0}$ decays within the propane. Sixty-eight percent of the incident $\overline{K^0}$'s will reach the propane, and in 20 cm of propane, assuming $\sigma(\overline{K^0} + \text{C}_3\text{H}_8) = 1.23 \text{ b}$, 14% of these will interact, so that about

$$(0.68) (0.14) e = 0.095e$$

of the incident $\overline{K^0}$'s will interact in the propane and yield $\overline{\Lambda^0}$ decays within the propane.

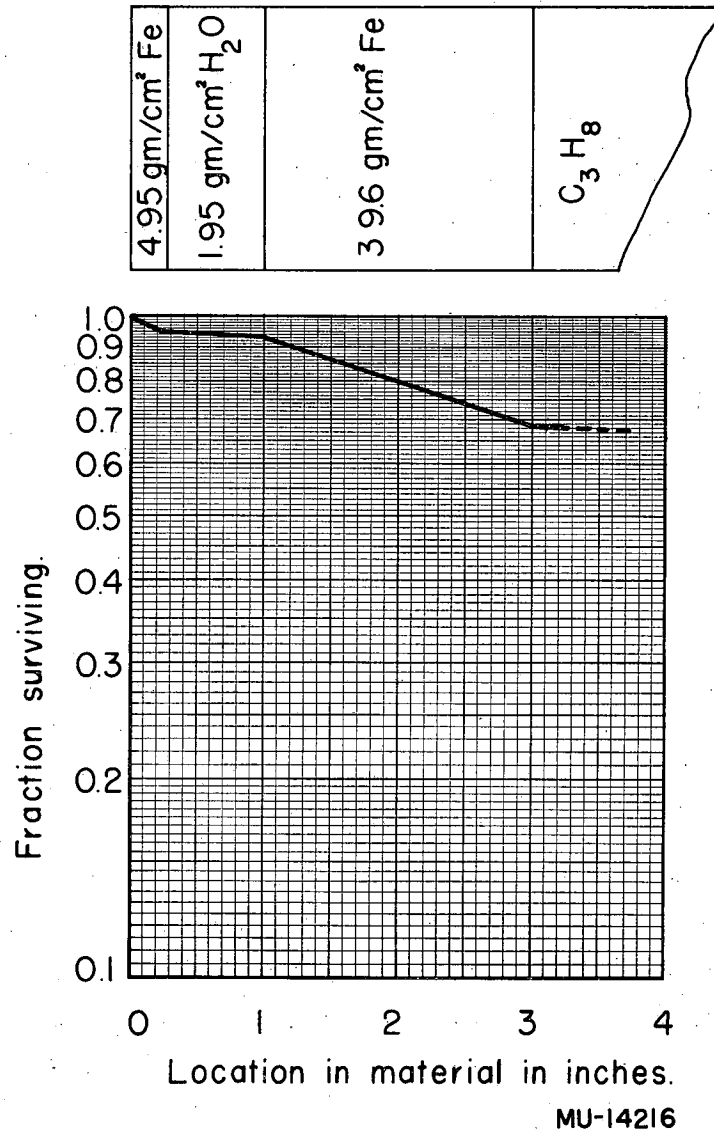


Fig. 16. K^0 attenuation curve.

Of the \overline{K}^0 's traversing the side walls, 0.25e might yield decays within the propane. Thus about

$$\frac{(0.18e + 0.095e) + (0.25e)}{2} = 0.26e$$

of all the \overline{K}^0 's striking the chamber might yield Λ^0 decays within the propane. Then a total of

$$(0.18 \times 10^6) fge (0.26) = 4.7 \times 10^4 fge$$

decays might occur.

K^- absorption at rest by protons indicates that $e \sim 1/9$.²² The value of f is not well known, but is probably small.²³ It is taken to be 0.05. The value of g depends on the angular distribution of scattered \overline{K}^0 mesons. If they are assumed to be uniformly distributed within a cone of 25° laboratory half-angle, then we have

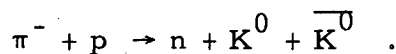
$$g = \frac{(\text{chamber})}{(25^\circ \text{ cone})} = \frac{3.6 \times 10^{-3}}{0.59} = 6 \times 10^{-3}$$

The number of Λ^0 decays within the propane is then given by

$$(4.7 \times 10^4) (0.05) (1/9) (6 \times 10^{-3}) = 1.7,$$

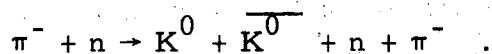
or about two. Invisible decay modes, $1/3$, and scanning efficiency, 0.75, would reduce the number of observed Λ^0 decays to about one during the entire run.

Consider now the production of \overline{K}^0 mesons in the aluminum. Because a K meson of negative strangeness must be produced in association with another K meson of positive strangeness according to presently accepted classification schemes,⁷ the threshold for \overline{K}^0 production by pions on nucleons is determined by the following reaction:



The threshold is 1.5 Bev/c momentum in the laboratory for the incident pion. If the struck nucleon has 170 Mev/c momentum (15.5 Mev kinetic energy) antiparallel to the pion beam, the threshold can be reduced to 1.25 Bev/c. Pions on neutrons would require more momentum, because the reaction

would require the production of a pion to conserve charge,



The number of \bar{K}^0 mesons produced by these reactions which subsequently escape the aluminum block and are directed toward the bubble chamber may be approximated by

$$N(\bar{K}^0) = \int_{t=0}^{t=\ell} N(\pi) (e^{-t/\lambda_\pi}) \frac{f \cdot g \cdot dt \cdot q}{\lambda_\pi} (e^{-\frac{(\ell-t)}{\lambda_{\bar{K}^0}}}),$$

where $N(\pi^-)$ = number of π^- incident,

λ_π = mean free path for π^- in aluminum,

f = fraction of π^- interactions yielding \bar{K}^0 ,

q = fraction of aluminum nucleons effective,

g = fraction of \bar{K}^0 directed toward bubble chamber,

ℓ = length of aluminum,

and

$\lambda_{\bar{K}^0}$ = mean free path for \bar{K}^0 in aluminum.

Then we have

$$N(\bar{K}^0) = \frac{N(\pi) f q g \lambda_{\bar{K}^0}}{(\lambda_\pi - \lambda_{\bar{K}^0})} \left[e^{-\ell/\lambda_\pi} - e^{-\ell/\lambda_{\bar{K}^0}} \right].$$

If

$$N(\pi^-) = 3 \times 10^8,$$

$$\lambda_{\bar{K}^0} = 96 \text{ gm/cm}^2 \text{ aluminum,}$$

$$\lambda_{\pi^-} = 150 \text{ gm/cm}^2 \text{ aluminum } (35 \text{ mb} \times A^{2/3} = 315 \text{ mb}),$$

and

$$\ell = 82 \text{ gm/cm}^2 \text{ aluminum,}$$

then we have

$$N(\bar{K}^0) \cong (0.82 \times 10^8) f q g.$$

The value of f may be very roughly estimated as follows: Strange particle production is assumed to account for 3% of the total $\pi^- + \text{Al}$ cross section. Bevatron K-meson beams indicate a K^+/K^- production ratio at the same momentum of about 60 for 6.2-Bev kinetic-energy nucleon-nucleon collisions.²⁴ Using this number for the total K^0/\bar{K}^0 production ratio at 5° in $\pi^- + \text{Al}$ collisions near threshold, and assuming that all of the K-meson pairs produced are neutral, it is estimated that

$$(0.03)(0.02) = 6 \times 10^{-4}$$

of the $\pi^- + \text{Al}$ collisions will yield \bar{K}^0 mesons. The value of q is determined to be about 0.16 from the curves in Fig. 13. The value of g is taken to be that used in Appendix D above, namely 6×10^{-3} . Then the number of \bar{K}^0 mesons striking the bubble chamber is given by

$$N(\bar{K}^0) = (0.82 \times 10^8) (6 \times 10^{-4}) (0.16) (6 \times 10^{-3}) = 47.$$

Following the preceding treatment for \bar{K}^0 mesons incident on the bubble chamber, the fraction of these which yield decays within the propane is 0.033. Invisible decay modes and scanning efficiency reduce this number by one-half, so the expected number of observed Λ^0 decays from this source is

$$47(0.033)(1/2) = 0.8,$$

or about one during the entire run.

Consider the known pion beam contamination of about one antiproton per 70,000 pions.⁸ There would be about

$$(3 \times 10^8) / (7 \times 10^4) \approx 5 \times 10^3$$

antiprotons incident on the aluminum block. The secondaries from the p^- annihilations should be widely distributed in solid angle in the laboratory, because about 1.9 Bev is available in the center of mass. The angular distribution is therefore assumed to be isotropic in the laboratory. The solid angle subtended by the chamber at the aluminum is only 3.6×10^{-3} steradians, and the total number of neutral and charged K mesons emitted per annihilation is about 0.1.²⁵ Then the number of long-lived \bar{K}^0 mesons striking the chamber is probably less than

$$\frac{(5 \times 10^3) (3.6 \times 10^{-3}) (0.1)}{2} = 0.3 .$$

Using preceding interaction estimates for the $\overline{K^0}$ mesons traversing the chamber, one can estimate that

$$(0.3) (0.033) (1/2) \approx 5 \times 10^{-3}$$

Λ^0 decays might be observed from this source of long-lived $\overline{K^0}$ mesons during the entire run.

Because no high-energy nucleons were observed in a sample of 36 annihilations,²⁶ an upper limit to the expected number of neutron-produced Λ^0 's is probably

$$\frac{(0.3) (0.0075)}{3} = 0.001$$

where the estimates of Appendix B have been used.

The total contribution from long-lived $\overline{K^0}$ mesons, if they were to exist, is thus about 1.7 observed Λ^0 decays during the experiment. Because only about one-third of the observed possible V^0 events were suitable for the analysis, long-lived $\overline{K^0}$'s can account for less than one of the observed Λ^0 's reported here.

E. Λ^0 Production by θ_2^0 Mesons

The number of θ_2^0 mesons traversing the bubble chamber is very roughly estimated as follows: The number of θ^0 mesons produced in a layer dt at a depth t in the aluminum producer is given by

$$N(\pi^-) (e^{-t/\lambda_\pi}) \frac{f \cdot dt}{\lambda_\pi} ,$$

where

$N(\pi^-)$ = number of pions incident,

λ_π = mean free path of π^- in aluminum,

and

f = fraction of π^- collisions that yield θ^0 's

One half of these θ^0 's are assumed to be θ_2^0 mesons. Then the number of θ_2^0 mesons that escape the aluminum and are directed toward the chamber is given by

$$N(\theta_2^0) = \frac{1}{2} \int_{t=0}^{t=\ell} N(\pi^-) (e^{-t/\lambda_\pi}) \frac{f \cdot dt}{\lambda_\pi} (e^{-\frac{(\ell-t)}{\lambda_2}}) g,$$

where

ℓ = length of the aluminum producer,

λ_2 = mean free path of θ_2^0 in aluminum,

and

g = fraction θ_2^0 directed toward the chamber.

Then we have

$$N(\theta_2^0) = \frac{N(\pi^-) \lambda_2 f g}{2(\lambda_\pi - \lambda_2)} (e^{-\ell/\lambda_\pi} - e^{-\ell/\lambda_2})$$

Using

ℓ = 82 gm/cm² aluminum,

λ_π = 150 gm/cm² aluminum,

λ_2 = 2 $\lambda(K^- + Al)$ = 2(96) = 192 gm/cm²,

we find $N(\theta_2^0)$ to be

$$N(\theta_2^0) = \frac{(3 \times 10^8) (192) f g}{2(150 - 192)} (e^{-82/150} - e^{-82/192}) = 48 \times 10^6 f g.$$

The angular distribution of θ^0 mesons from $\pi^- + p$ collisions at 1.43 Bev/c indicates that about 18% of the θ^0 mesons are emitted between 2° and 8° in the laboratory.²⁷ The fraction of the 18% that will strike the chamber was seen in Appendix B to be about 0.063; hence we find

$$g \approx 0.18 (0.063) = 0.011.$$

The fraction of $\pi^- + Al$ collisions which yield strange particles has been taken to be about 0.03. If this number is used for f , then we have

$$N(\theta_2^0) = (48 \times 10^6) (0.011) (0.03) \approx 15800.$$

If the additional approximation is made that one-half of the θ_2^0 mesons

are $\bar{\theta}^0$ mesons, and if the estimates of Appendix D for the interaction of \bar{K}^0 mesons are used, then

$$(1/2) (15\ 800) (0.26) (1/9) \cong 230$$

Λ^0 decays within the propane might be expected. Neutral decay modes and scanning efficiency would reduce the number of observable decays to about 115. About one-third of the possible V^0 decays were actually measured, so the expected number of observed decays is thus about 40.

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