CLOUD CHAMBER OBSERVATIONS

OF THE

NEW UNSTABLE COSMIC RAY PARTICLES

Thesis by

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ABSTRACT

Thirty-five cloud chamber photographs of V-shaped tracks apparently due to the decay of a new unstable neutral particle (V°-particle) and five apparently due to the decay of a new unstable charged particle ($V^\pm$-particle) are discussed. It is shown that only a few of these events could be the result of known processes such as stars in the gas, the scattering of a charged particle, electron pair production, pi-mu decay or mu-electron decay. The V-particles are shown to originate in the penetrating showers which were selected to trigger the expansion and also in the associated low energy stars. Some evidence for the nature of the decay products is given, and the decay schemes $V^\circ \rightarrow$ proton + negative meson and $V^\circ \rightarrow$ positive meson + unidentified negative particle are suggested. Calculations of the mass of the V° under the assumption that the decay products are two pi-mesons and again assuming the products are a proton and a pi-meson, do not give consistent results in either case. The discrepant values, 600 to 800 m_e and 2200 to 2500 m_e, are discussed. The possibility of a three body decay is discussed. A mean life (1.3×10^{-10} sec.) is calculated for the V° assuming the decay into two pi-mesons. It is shown that there are about 40 charged penetrating shower particles per V°-particle.

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I. INTRODUCTION

In 1947 G. D. Rochester and C. C. Butler (1) published two cloud chamber photographs which they interpreted as evidence for the existence of two new unstable particles. The first (similar to Fig.1) showed two tracks forming an inverted V with apex in the gas and an angle of about 60°. The curvatures in the magnetic field of the two low ionization tracks could have resulted from two relativistic particles of opposite charge traveling downward from the common origin, and Rochester and Butler concluded that these were the charged secondaries of the decay in flight of a new unstable neutral particle. The second photograph (see Fig. 2) showed the track of a relativistic particle, positive if traveling downward, which changes direction by about 20° at a point in the gas without producing any other ionizing particles. Rochester and Butler concluded that this event must represent the decay in flight of a new unstable charged particle into a charged secondary of the same sign and at least one neutral particle.

In the summer of 1949 a group of observers from this laboratory (2) obtained 35 additional photographs of the first type and 5 of the second type discussed by Rochester and Butler providing ample verification and considerable extension of their conclusions. Since 1949 a number of additional observations by various authors (3) - (8) have been reported; the existence of the new particles has become practically certain; and the name V-particles, suggested by the appearance of the photographs, has crept into the literature.

The term V-particles, due to Blackett, will be used here to refer to both the neutral and charged particles, and where necessary a superscript (0, +, -, or $\pm$ where the sign is uncertain) will be used to specify the charge. This nomenclature has the disadvantage of grouping together types of particles which may be related only historically, but it will be followed with only this brief caution. The term V-particle will frequently be abbreviated by simply dropping the word particle.

It is the purpose of this thesis to give in some detail the evidence contained in the photographs taken by the observers in this laboratory and the arguments basic to their conclusions concerning the existence and properties of the V-particles. Where later work has added to our knowledge these conclusions will be modified, and in some of the many cases where the data are still inconclusive, particularly with regard to the number and type of secondary particles, suggestive arguments will be given.

Although the history of the V-particles is still sufficiently short to be treated with some completeness, no special effort will be made in this direction, since the various independent observations (with the exception of the single case of Hopper and Biswas) are essentially the same as those made in this laboratory. It is significant that all of these observations have been made with cloud chambers controlled by counters sensitive primarily to locally produced penetrating showers, and it will be clear from what follows that such an arrangement is highly advantageous.

It is interesting to note that prior to 1947 at least two published reports contain evidence for the existence of $V^{\pm}$-particles. J. Daudin (9) describes several peculiar "collisions in the gas" of which his Figure 16 is probably a case of $V^{\pm}$-decay, and Janossy (10) published a similar case without comment in 1945. Several other photographs mentioned by Daudin are possibly cases of V^{o}-decay.

Although there have been numerous other reports of new particles, especially various tau-mesons, there is no evident connection between these particles and the V-particles, and it is important to make a clear distinction between them.

II. THE APPARATUS AND ITS OPERATION

The Chamber

The cloud chamber and magnet used in this experiment were the same ones previously described in a report on the decay products of the mu-meson (11). The chamber, of the freely falling type, was cylindrical with a diameter of 30cm and a depth of 12cm. The entire volume was illuminated from the rear and photographed stereoscopically with an angle of about 10°. The chamber was filled with argon at a pressure of about 19cm of Hg above atmospheric pressure (i.e. 95 cm at sea level and 71cm at 3200m) and saturated with a water-alcohol mixture at about 25°C. The strength of the magnetic field was usually about 6300 gauss throughout the chamber.

Geiger Counters and Absorbers

The arrangement of geiger counters and absorbers in and around the chamber (shown in Fig.9) was designed to favor the production and selection of locally produced penetrating showers. The 20cm of lead A, above the chamber and counters, was used as a target for the production of penetrating showers by the very energetic primaries. The lead absorber B, between the two counter banks C_1 and C_2, was 4cm thick and was placed so as to shield C_2 from low energy particles, e.g. knock-on electrons, which pass through C_1. The 2cm lead plate C was placed across the center of the chamber to allow a study of the interactions of the shower particles with the lead. In position, the chamber was held immediately between the pole pieces of the magnet (not shown), which were iron cylinders about 35cm in diameter surroundded by about 10cm of copper. The firing of the chamber was controlled by the three banks of geiger counters C_1, C_2, and C_3. C_1 and C_2, above the chamber, were identical banks of four counters connected so that the voltage on each counter could be adjusted separately to insure equal pulses from the individual counters., In each bank the pulses from the four counters were added and the detector biased so as to select combined pulses due to the simultaneous firing of either two or more, three or more, or all four of the counters. C_3, attached so as to rise and fall with the chamber, was a bank of seven counters simply connected in parallel for the most of this experiment. The chamber was expanded when a coincidence was obtained between selected multiple pulses from C_1 and C_2 and a pulse from C_3. It was thus possible to require up to a nine-fold coincidence using only three separate channels.

The entire apparatus and all auxiliary equipment except electrical power generators were mounted in a large inclosed trailer which was operated first at Pasadena (altitude 230m) and then at White Mountain, California (altitude 3200m).

Counting Rates

Approximately 8,000 photographs were taken in ten weeks of operation at 3200m and about 3000 in a somewhat longer period at 230m. At 3200m a six-fold coincidence of three or more counters in C_1, two or more in C_2 and one or more in C_3 was required. The counting rate was about 10 counts/hr., and with a delay of 2.5min. after each expansion this gave a picture taking rate of about 7.5 per hour. The counting rate for the same requirement was only about one count/hr. at 230m which is consistent with the expected decrease in intensity of the radiation capable of producing penetrating showers. At the lower altitude a less selective coincidence requirement was used for actual observation, since an increase in the counting rate was acceptable and offered the possibility of an increase in the absolute rate at which penetrating showers were recorded, even though the percentage of such photographs decreased. Either a five-fold coincidence (two or more of C_1, two or more of C_2 and one or more of C_3) or a four-fold coincidence (two or more of C_1 and two or more of C_3) were used. Both gave counting rates between two and three counts/hr.

The Photographs

In Table I are listed the percentages of the various types of events photographed. A "penetrating shower" is defined as any group of particles apparently proceeding from a common point and containing two or more minimum ionization particles, other than electrons, at least one of which traverses the lead plate C. All particles of the group except identifiable electrons# are referred to as "penetrating shower particles". Under "electron showers" are listed those photographs not showing a definite penetrating shower but containing a number of particles identified as electrons. These electron showers may also contain some penetrating particles. Cases of a group of relativistic particles, none of which traverses C, and cases of several relativistic particles not concurrent are included under "other multiple events."

#Tracks due to electrons (or any very light particle) of momentum below 100 Mev/c were easily identified by their ionization and curvature in the magnetic field. In addition, most of the electrons of higher momenta are identifiable by their electromagnetic interactions as there is only a small probability of finding a single energetic electron emerging from the heavy material around the chamber unaccompanied by low energy electrons. Also the probability is about e^{-4} of such an electron traversing the four radiation units of the plate C without a very large energy loss or the production of an electronic cascade.

TABLE I. - - Distribution of photographs

Type of Event		% of photographs	
	Altitude	3200m	230m
	Selection	3-2-1	2-2-1, 2-0-2
	Rate	7.5 c/h	2 - 3 c/h
	Tot. frames	8000	3000
Penetrating Showers		40	20
Electron Showers		10	12
Other Multiple Events		15	13
Single Particles		15	25
No Particles or Poor Photography		20	30

Actually many, and perhaps most, of the events selected with the six-fold coincidence requirement but not classified as penetrating showers are of the same type as the showers. That is, they are events which result from the production in A of a group of energetic penetrating particles. This is certainly true of the multiple events containing no particle which traverses C. As for single particles, the probability of a single penetrating particle producing the six-fold coincidence is quite small. Moreover, the approximate constancy with altitude of the percentage of photographs showing these events suggests that many of these are due to showers in which only one particle entered the chamber. The electron showers, too, are in many cases probably penetrating showers accompanied by cascades from the decay near the chamber of energetic neutral pi-mesons.

The chief effect of the use of the less selective coincidence requirements appears to be a decrease in the number of identifiable penetrating showers and a corresponding increase in the number of apparently single particles. These effects are due both to the selection of some actually unaccompanied particles, which produce knock-on electrons to give the multiple coincidence, and to the selection of some smaller penetrating showers with a correspondingly greater probability of sending only one particle through the chamber. The absolute counting rate for showers is probably slightly increased.

Improvements of the Apparatus

Although the apparatus as designed was quite efficient in the selection of local penetrating showers (which are apparently the source of the V-particles), it is somewhat coincidental that the geometry chosen also allowed a reasonable probability of observing V-particle decays.

Obviously the short lifetime of the V^{o}-particles (their mean free path before decay is about 3g cm, where $g=Pc/Mc^{2}$) requires that the target in which they are formed be even much closer to the chamber than the 17cm used here. Some compromise is necessary to allow for a counter system of sufficient selectivity and solid angle, but the scheme employed here is both wasteful of space and too selective. In chambers not of the falling type it may be possible to place most of the counters below the chamber and require multiple coincidences there without greatly reducing the effective solid angle. In Appendix A it is shown also that the effective thickness of the target is limited by the decay of the V-particles and has an optimum value which increases slowly with g. g about three or less is the case of most interest, since it is only for these low momentum V-particles that the decay products can have momenta measurable in the magnetic fields available. For these g the optimum thickness is of the order of 10cm of lead. The use of the plate within the chamber still seems quite worthwhile, since it provides a nearby source of the short-lived $V^{\pm}$-particles and the very slow V^{o}-particles and under conditions where the origin can be accurately located and closely studied. Moreover, additional valuable information as to the nature of the decay products is still to be obtained by observing their interactions with the dense material.

Momentum Measurements

The measurements of momentum based upon track curvature in the magnetic field were severly limited throughout this experiment by movements of the chamber gas which produced sizeable distortions in the tracks. Although the walls of the chamber and the magnet pole pieces were thermostated with some care, there still remained temperature differences between various parts of the chamber of about 0.1°C or less. The slow gas currents set up before the expansion by these differences were sufficient to produce large distortions during the 0.3 sec. in which the chamber was falling out of the magnet gap and into view of the camera. The effect of this long delay, coupled with the extra difficulties in thermostating falling chambers, would seem, thus far, to render them unsuitable for accurate momentum measurements. In the most favorable cases observed here it was impossible to detect curvatures corresponding to momenta above 700 Mev/c or to make quantitative measurements above 500 Mev/c. In unfavorable cases, especially for tracks near the solid parts of the chamber, the distortions were sufficient to produce S-shaped tracks with curvatures of the segments corresponding to momenta of the order of 100 Mev/c in the 6300 gauss field. It is thus necessary to use considerable caution in drawing conclusions from these photographs based upon individual momentum estimates. In only one extremely favorable case is any emphasis placed on such a measurement, and in most other cases a perhaps exaggerated conservatism is invoked. Even so, the presence of the magnetic field is indispensable to a rapid and accurate qualitative understanding of the events observed, and no complete analysis of the properties of the V-particles will be possible without the use of momentum measurements.

III. THE V-TRACKS

Among the 8000 photographs taken at 3200m there were 27 examples of V-tracks which probably result from the decay of V°-particles. Two of these V-tracks appear on one photograph. Eight of the 3000 photographs taken at 230m also show a probable case of V°-decay. Most of the data pertinent to these 35 cases is in Table II. There were in addition five photographs showing a possible case of $V^{\pm}$-decay, all taken at 3200m. They are described in Table III.

The number of V-tracks per photograph is, of course, strongly dependent upon the size and geometry of the apparatus and the type of counter selection. To minimize the effect of counter selection we can consider the number of V-tracks per penetrating shower as defined in Section II. We have observed about one V-track (of the V° type) per 100 penetrating showers at both altitudes (120 ± 20 at 3200m and 75 ± 50 at 230m) or about one per 30 hours of operation at 3200m and one per 200 hours of operation at 230m. There are also about one track of the $V^{\pm}$-type to five of the V° type. Armenteros et al (6), using the original apparatus of Rochester and Butler which is very similar to ours, observed 22 V°-particles and 4 $V^{\pm}$-particles in 7500 photographs taken at 2867m. They counted 1500 "penetrating showers" on these photographs giving about one V°-particle per 70 penetrating showers. Their definition of a penetrating shower was more restrictive than ours, and a similar criterion applied to our data gives comparable results. Further experiments in these laboratories (under Prof. R. B. Leighton) using several modified geometries give ratios of the same order of magnitude.

Examples of the photographs showing V-tracks are included in Figures 1-8. The cases photographically most satisfactory have naturally been chosen. Only the front view of the stereoscopic pair is shown.

Figures 1 and 2 show more or less typical cases of V°-decay where the decay products are relativistic and form an angle considerably less than 90°. Both are associated with visible showers and seem to preserve the general direction of the shower. Figures 7 and 8 show two of the cases of V--decay where the V-particle appears to originate in a nuclear reaction in the lead plate. Figures 3 to 6 illustrate various special cases. All of these will be discussed in more detail elsewhere.

It must be emphasized that in many cases it may be impossible to distinguish between V-tracks resulting from the decay of V°-particles and those from the decay of $V^{\pm}$-particles, especially if the decay schemes are unknown. Cases like those of Figures 1 and 2 are most likely associated with V°-decays. V-tracks like those in Figures 7 and 8 are undoubtedly due to $V^{\pm}$-particles, if they are produced by a V-particle at all. There are many cases, however, where the angle included between the two segments is more than 90°, and the orientation of the V-track is such that its classification is quite ambiguous. In two cases (9-54 and 1-116) where one track segment appears to enter from above the cases were included with the $V^{\pm}$-decays. 9-54 is especially uncertain, however. In several cases similar to P 42-86 (Figure 4), where a line dividing the angle of the V-track points downward and roughly in the direction of associated shower particles, the tracks were included among the V°-decays. These assignments are arbitrary, however, and conclusions drawn from these cases should be subject to special scrutiny.

In ten cases one or both of the particles resulting from the V-decay enters the 2cm lead plate along such a direction that the particle or its interaction products should be visible below the plate (except, of course, for particles scattered parallel to the plate or absorbed in it). The results of the interactions of these particles with the lead are given in Table IV and provide valuable clues to the identity of the decay products.

The subscripts 1 and 2 in Table IV refer to the particles 1 and 2 as identified in Tables II and III. I' and P' are the ionization and momentum of the particle after traversing the plate. Under Trav. 1 and 2 are listed the results of the interactions. In one case a three pronged star (S_3) was produced, and in a second case the particle apparently stopped in the plate without producing visible secondaries. In all the remaining cases only one visible particle emerged, apparently the original particle scattered through the angle given.

TABLE II: THE V°-PARTICLES

The quantities listed in the various columns have the following significance:

No. is the reel and frame number of the photograph. P indicates that the reel was exposed in Pasadena at an altitude of 230m.

ϕ is the total angle of the V-track calculated graphically from the two stereoscopic views.

I_1 is the estimated ionization of the particle whose track forms the first side of the V, counting counter-clockwise. In many cases upper and lower limits are given. These estimates are in units of minimum ionization for a single charge, and are obtained by visually comparing the track to tracks of relativistic particles on the same photograph or adjacent photographs. They represent a consensus of several observers, and, judging from observations on recognizable protons, seem to be reliable at least in distinguishing factors of two in ionization.

P_1 is the momentum of the first particle calculated from its curvature in the magnetic field. These measurements are discussed in Section II. They are very unreliable and in most cases only a lower limit, indicated by parenthesis, is given. These limits are obtained by comparison of the projected track with a set of drawn circles and vary with the length of the track, its position in the chamber, etc. p and n indicate the sign of the charge where it appears to be detectable. p indicates that the particle is positive if moving away from the apex of the V. Tracks clearly too short or distorted to be measured are indicated.

θ_1 is the angle between the first track and the supposed path of the V-particle. The path of a V°-particle is here taken as a line joining the origin of an apparently associated nuclear event (penetrating shower or star) and the apex of the V. Values are given for those cases in which the assumed path lies within a few degrees of the plane of the V. The angle is positive if the path lies between the sides of the V. The error in θ_1, due to uncertainty in the location of the origin of the associated event, is usually less than $\pm$ 4°.

I_2, P_2 and θ_2 are the ionization, momentum and angle of the second track.

Accomp. indicates the type of visible nuclear events accompanying the V-particle. S_n refers to a penetrating shower of n-particles originating above the chamber. These are apparently the events which provide the triggering coincidence. s_n indicates a secondary nuclear interaction of n-particles produced in the plate C or in the chamber walls by a particle of a shower.

W is the angle between the plane of the V-track and the particle path associated with the given accompanying event. The errors listed are estimated maximum errors due to uncertainties in the location of the accompanying event and the plane of the V.

d is the distance between the points at which the extended path of the V-particle enters and leaves the clearly illuminated portion of the chamber. Where no nuclear event is observed a line bisecting the angle ϕ is arbitrarily assumed to be the path.

X is the distance between the point at which the V-particle path enters the illuminated portion of the chamber and the point at which the V-particle decays.

TABLE LI

No.	ϕ (deg)	I_1 (x min)	P_1 (Mev/c)	θ_1	I_2	P_2	θ_2	Accomp.	w (deg)	d (cm)	x (cm)
11-440	3.5	1	(200)	0	1	(200)	3	S5	3 ±4	23	2.5
16-429	4	1	(300)	0	1	(300)	4	S2	±7	25	18
6-336	4	1	(200)	4	1	(200)	0	S2 s2	±7 60	25	18
8-134	7	1	dist.	4	1	dist.	3	S7	3 ±4	15	4
14-453	7	1	(400)n	6	1	(500)	1	S9	0 ±4	26	14
2-120	8	1	short		1 - 2	(300)		S?		27	6
6-106	8	1	(500)		1	(600)				23	2.5
2-181	10	1	short		1	short		S2?		25	8
P5-A	12	1	(200)		1	(200)				20	11
4-171	14	1	(600)	3	1	(400)n	11	S3	3 ±4	23	13
9-88	14	1(	(300)	2	1	(500)	12	S3	1 ±5	22	3
1-126	18	1	(300)		1	(300)				23	3

6-153	20	3 - 6	(400)		1	short				14	2
5-121	21	1	(300)	8	1	(600)	21	S2	3 ± 5	24	2.5
				15			6	S2	3 ± 5	24	2.5
17-285	23	1 - 2	(300)n		2 - 3	(300)p				22	2
13-198	24	1	(500)n	6	1	(300)p	18	S3	4 ± 5	25	17
9-103	26	1	(500)		1	(200)				12	2
7-120	26	1		11	1		15	S7	0 ± 2	25	5
13-246	26	1	(200)		1	(600)				15	2
P42-77	32	1	dist.		3 - 6	dist.		S8	90		
				20			12	s10	2 ± 7	14	4
2-255a	32	1	(400)	15	1	short	17	S6	1 ± 7	20	9
11-130	37	1	(300)	0	3 - 8	90n?	37	S2	0 ± 5	17	2
3-163	40	1	short		1	short		S2	8 ± 4		
				6			24	s2	0 ± 4	13	10
8-479	54	1	(400)		1	short		S4	18 ± 7	9	2
P5-B	56	1	dist.		1	dist.		S3	60	22	9
P6-589	56	1	dist.		1 - 2	short		S3	?	17	3
2-255b	68	1	(400)	18	1	short	50	S6	6 ± 7	20	4
P44-66	68	1	dist.		1	80n - 150		S2	20 ± 9		
				11			57	s6	5 ± 9	12	7

11-66	90	2 - 4	74n 6		2 - 4	dist.				20	0
P4-A	100	1	dist.		1 - 2	dist.				15	1
6-498	100	2 - 5	(150)		1 - 2	dist.		s1	?	13	3
5-438	100	3 - 5	(300)p		3 - 6	short		S5	7 ± 2	11	1
3-183	110	3 - 8	dist.		1	(300)		S4	30		
				110			0	s3	±7	10	3.5
P42-86	126	5 - 10	24n - 60		3 - 5	80p- 160		S2	16 ±10		
				115			11	s?	5 ± 10	10	2.5
P6-204	160	1 - 2	short	90	1 - 2	short	70	S4	?	22	16

TABLE III: THE $V^{\pm}$-PARTICLES

The quantities listed in the various columns have the same significance as the similar quantities listed in Table II with the following exceptions:

Subscripts 1 & 2	refer to the upper and lower segments of the V-track. It is assumed that track 1 was produced by the V--particle moving generally downward.
ϕ	is the angular deflection of the V-track at the apex of decay point. It is the angle between track 2 and the extension of track 1.
	Accompanying events are listed for those cases in which track 1 actually originates in the event.
d & x	are measured either from the point at which track 1 enters the chamber or from the point at which it is first visible.

TABLE III

No.	ϕ (deg)	I_1 (x min)	P_1 (Mev/c)	I_2	P_2	Accomp.	d (cm)	x (cm)
1-331	7	1 - 2	short	1 - 2	(400)	s3	13	4.5
1-116	15	1	(200)	1	(600)		25	5
13-336	34	1	short	1	(600)	s3	13	4.5
5-128	40	1	short	1	(300)	s3	13	8.5
9-54	60	4 - 10	dist.	4 - 10	dist.	S5?	15	7

TABLE IV. - Interactions of the decay products with 2cm of lead.

No.	Trav. 1 (deg)	I_1' (x min)	P_1' (Mev/c)	Trav.2	I_2'	P_2'
2-150				0	2 - 4	dist
2-181	0	1	short	0	1	short
9-88	0	1	short	5	1	(500)
1-126	s3			10	1	(300)
5-121	6	1	(300)	0	1	(600)
17-285	0	1 - 2	2 - 500	40	2 - 3	(300)
11-130	1	1	(300)			
2-255b	0	1	dist			
11-66				stop		
1-116#				0	1	(600)

#charged V-particle

IV. AN INTERPRETATION OF THE V-TRACKS

We shall now examine several known processes to determine the extent to which they can account for the V-tracks. We shall see that with the large number of cases reported here it is possible to give real significance to arguments of the type originally made by Rochester and Butler (1) excluding any such processes as a valid interpretation of all the data. In addition, it will be clear that the assumption of a new decay process as the origin of the Vtracks is consistent with the data, and in the following sections a number of deductions from such an assumption will be discussed.

Neutron induced stars in the gas

The 8000 photographs taken at 3200m show about 14000 tracks of charged penetrating shower particles from which the neutron flux in the chamber can be estimated. Measurements of ionization and curvature indicate that about 1700 of these particles are protons of momentum less than 800 Mev/c. The data above 800 Mev/c are consistent with a differential momentum spectrum approximately of the form p^{-2} containing an additional 3600 protons. If we correct for the protons lost by ionization in the lead above the chamber and assume that the protons and neutrons are produced in penetrating showers roughly in proportion to their numbers in the target nuclei, then we estimate that there should be about 7000 neutrons of momentum greater than 800 Mev/c traversing some part of the chamber. From the space distribution of the charged particles it appears that the mean path in the chamber of the shower particles was about 20cm, and about 65% traversed the 2 cm lead plate. The total path length for the neutrons was thus about 210 gms of argon (density of argon: 1.5×10^{-3} gm/cc at

25°C and 71cm of Hg) and 114,000 gms of lead. If the mean nuclear interaction lengths for neutrons in argon and lead are 55 gms and 160 gms respectively,# they should produce four nuclear interactions in the gas and 700 in the lead plate.

We have observed, in addition to the V-tracks, four events classed as stars produced in the gas by a neutral particle. One contains eight heavily ionizing tracks (probably protons and alpha-particles) and one seven. The other two have two heavily ionizing tracks each, all probably protons or heavier fragments. About 100 stars apparently produced by neutral particles were observed in the lead plate. For the nuclear events due to charged particles each 100 visible stars are accompanied by 200 to 300 other nuclear interactions such as large angle scatterings and anomalous absorptions. The estimated neutron flux thus appears to be slightly high, and we conclude that unless there is some very special reaction taking place no more than two or three of the V-tracks can be due to neutron induced stars.

It should be noted, moreover, that the type of two-pronged star which could simulate the appearance of the V-tracks is quite rare in most materials, if it exists at all. Fewer than 20 of the interactions observed in the lead are even remotely similar. If the cross-section for the production of V-tracks were proportional in argon and lead to the

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#These values are in the ratio of the geometric cross-sections with the value for lead taken about equal to that commonly observed for particles producing penetrating showers or nuclear stars. Observations on 3000 charged penetrating shower particles (protons and pi-mesons) in these photographs indicate an upper limit to the mean interaction length in lead of 230 ± 30 gms.

geometrical cross-sections, then about 5000 V-tracks originating in the lead should have been observed. On the other hand, if the V-tracks are due to the decay of particles originating above the chamber, fewer than three should appear to originate in the plate.

Scattering of charged particles in the gas

The charged penetrating shower particles (almost entirely protons and pi-mesons) can be scattered by interaction with either the electrostatic or nuclear force field of an argon nucleus. Their deflected tracks might be classed as V-tracks provided there were no evidence of the scattering in the form of charged recoil particles. The probability per centimeter of track of a coulomb scattering between a and a + da degrees is just $2\,k\,da / a^3$, where k is $4\pi Nz^2 e^4/(pv)^2$. N is the number of scattering centers of charge ze per cc; e, p and v are the charge, momentum and velocity of the scattered particle (we assume that v does not change appreciably in the scattering). For the chamber argon (at 70cm of Hg and 25°C) $k = 1.8 \times 10^{-3}/(pv)^2$, where p is in Mev/c and v in units of C. According to Williams (12) this formula holds for small angles up to a maximum of the order $\hbar/pb$ where the finite size of the nucleus causes a large decrease in the scattering. $\hbar$ is Planck's constant divided by 2π and b is the nuclear radius of the scatterer. For argon $\hbar/pb$ is of the order of 40/p, where p is in Mev/c. Finally, the probability per cm of a scattering through an angle between a and the maximum (where a is considerably less then the maximum) is approximately $6/(pva)^2$, where a is in degrees, p in Mev/c and v in units of C.

Now consider the expected frequency of cases like 1-331 (Table III) where a particle of momentum greater than 400 Mev/c is apparently deflected through an angle of 70°. For a particle of 400 Mev/c momentum the probability of a coulomb scattering much larger than 7° is negligible, and for a pi-meson of that momentum the probability of a scattering say greater than 3° is about 5×10^{-5} per cm. Momentum measurements indicate that there are perhaps 1500 mesons with momenta between 300 and 500 Mev/c, with a total visible path of about 3×10^{4} cm. Thus one might well expect to observe such a scattering. Similarly if we assume in 9-54 (Table III) and P42-86 (Table II and Fig.4) that the deflected track is that of a pi-meson ionizing at 5 x min, the expected frequency of scatterings greater than say 20° is again of the order of 5×10^{-5} per cm. Here, however, the total visible length of such tracks is smaller by perhaps a factor of ten. On the other hand the appearance of two deflections as large as those in 13-336 and 5-128 (Table III) due to coulomb scattering seems quite improbable.

There is, however, another important consideration, namely the disposition of the momentum and energy transferred in the scattering. In 1-331 this amounts to at least 40 Mev/c of momentum (which is about the maximum for coulomb scattering) or at least 20 kev of energy if the recoil particle is an argon atom. This is sufficient energy, if dissipated in ionization, to produce about 1000 ion pairs and a distinct blob on the cloud chamber track. The velocity of such an argon nucleus is, however, only about 0.001c. This is about the same order as the orbital velocities of the outer electrons, hence little ionization may occur. In several similar cases (not included as V-tracks) distinct blobs have been observed at the deflection point, however they may have resulted from direct nuclear scatterings, in which the energy transfer is much greater, especially if only a part of the nucleus recoils.

We shall assume (see footnote above) that the mean length for direct nuclear interactions of the charged penetrating shower particles is 55 gms in argon. For this case the 14,000 particles visible on the 3200m photographs should have produced about eight nuclear scatterings in the gas. For such scatterings the angle is not limited. However, large energy transfers producing visible stars should occur, since the incident particles, of wavelengths less than 10^{-13}cm, interact primarily with single nucleons. Six cases of such stars in the gas containing recoil protons, alpha-particles or heavier fragments were observed. There is the possibility that cases like 13-336 and 5-128 represent nuclear interactions in which only neutrons are ejected and no residual excitation is dissipated in ionization. Although the possibility seems remote there is little data for quantitative arguments.

Electron pair production

The possibility that the V-tracks include examples of the production of electron pairs in the gas can be limited on two counts. There is direct evidence in many cases that the particles producing the V-tracks are not electrons (see Section V). Also the cross-section for pair production as a function of included angle of the pair is negligible for angles several times MC^2/pc where both particles have appreciable momentum. Here M is the electron mass and p the momentum of the incident photon. In most of these cases the resultant momentum of the two V-track particles is greater than 300 Mev/c which corresponds to mean electron pair angles less than 0.1 degree. The smallest V-angle recorded here is 3.5 degrees. Actually, no cases of apparent electron pairs in the gas have been observed outside of large electron showers.

Pi-Meson Decay

It can easily be shown from the observed angles and momenta that most of the V-tracks are not due to the decay in flight of pi-mesons. If the pi-meson (275 electron masses) decays into a mu-meson (210 electron masses) and a neutrino, then the ejection velocity of the mu-meson in the center of mass system (CM system) is $v = 0.26c$. Its momentum in the CM system is $p = 29.5$ Mev/c and its momentum, p_1, in the lab system is variable. If the pi-meson has a velocity greater than v (a momentum p_o greater than 38.5 Mev/c), then the angle a (in the lab system) between p_o and p_1 has a maximum value such that $\sin a = 38.5/p_o$, where p_o is in Mev/c. This result follows immediately if one first writes an expression for $\tan a$ in terms of v; the pi-meson velocity; and the angle b (in CM system) between them and then maximizes $\tan a$ with respect to b. It is obvious also that if a has a maximum value, it is given as well by $\sin a = 29.5/p_1$, for a fixed p_1, since the maximum sidewise component of p_1 is just the momentum of the mu-meson in the CM system.

We can now see that if both particles in a pi-mu decay are ionizing at minimum, then the momentum of the mu must be above 100 Mev/c and the deflection angle must be less than 20^o. P6-204 (Table II) could be such a case of pi-mu decay, however the other cases of angles below 20^o (1-331 at 7^o and 1-116 at 15^o) have momenta probably sufficiently large to exclude the pi-decay interpretation.

In 9-54 (Table III) and P42-86 (Table II and Fig. 4) tracks of very uncertain curvature and of ionization between four and ten times minimum undergo deflections of 60^o and 54^o respectively. If these are cases of pi-mu decay, the momentum of the pi must be less than 45 Mev/c and its ionization more than six times minimum. In addition, if the mu-meson is to have an ionization as low as ten times minimum, then the pi-meson must be ionizing at about ten times minimum.# However much this would seem to stretch the estimated ionizations and curvatures one cannot definitely exclude the possibility that one or both of these cases represents a pi-meson decay. This point is especially critical since the case P42-86 gives a low V°-particle mass if it is actually a case of V°-decay.

It is interesting that the expected frequency of pi-meson decay in the chamber is not negligible. If the mean lifetime at rest is $t_o = 2 \times 10^{-8}$ sec, then the probability of decay per centimeter of path is about $M/p_o t_o C$ which is nearly $1/4p_o$, where M is the pi-meson rest mass in Mev and p_o its momentum in Mev/c. An estimated 1000 to 5000 cm of track due to mesons below 100 Mev/c momentum were observed. These should have shown about ten pi-mu decays. One such case was definitely observed. There were an estimated 2000 mesons between 100 and 500 Mev/c traversing an average of 20cm of the chamber. About twenty-five of these should have decayed in the chamber and about 90% should have shown deflections greater than 3°. No definite cases were recorded. Apparently the observation efficiency for small deflections unaccompanied by recoil particles was about zero.

Mu-Meson Decay

The number of mu-mesons decaying in flight in the chamber should be negligible. If all of the mu-mesons are produced by the decay of pi-mesons, their flux should be about 1% of the pi-meson flux. The

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This results from the fact that for a pi-meson momentum as great as 45 Mev/c and an angle a = 60° the mu must have been ejected backwards at a large angle in the CM system, its velocity in the lab system being reduced below the value corresponding to an ionization of 10 x minimum.

probability per centimeter of mu-decay in flight is also about 1% of the probability for pi-mesons, so that the expected number of mu-decays is less than the expected number of pi-decays by a factor of 10^4. None of the observed V-tracks are consistent with the angles and momenta expected in mu-decay.

We conclude that the large majority of the V-tracks result from some new process -- in all probability the decay of one or more new particles. Probably no more than five of the cases listed in Table II can be explained by the processes discussed, and though the percentage of doubtful cases in Table III is much higher, several of the cases of $V^{\pm}$-decay reported by other observers (6)(4) are quite convincing. We shall assume in what follows that V°-particles and V--particles exist and decay to form the observed V-tracks.

SECTION V: THE DECAY PRODUCTS

Though it is still not possible to definitely identify the decay products of the V-particles, some information as to their charge, mass and interaction with nuclei exists.

V°-Particles

The V°-particles are observed to decay into two charged particles. The possibility that neutral secondaries are also produced can as yet neither be confirmed nor excluded. In most cases one or both of the visible decay products are ionizing at a rate indistinguishable from that of relativistic electrons, and it is concluded that these decay products carry a unit electronic charge. Both positive and negative charges have been observed, and wherever the signs of both particles were determined they were opposite. We assume that this is always the case thus conserving charge in the decay.

The presence of electrons (or any very light particles) among the decay products is quite doubtful, since electron secondaries were produced in none of the 13 cases where a relativistic decay particle struck the 2cm lead plate (see Table IV). Ten of these cases were from five V-tracks in which both particles struck the plate. In 12 cases the particle emerged unaccompanied below the plate and in one case a nuclear star was produced. The probability of an electron traversing the four radiation units of lead without multiplication or large energy loss is about e^{-4}.

Measurements of ionization and curvature of the tracks of the decay particles permit meaningful estimates of their mass in only a few favorable cases. The first track of 11-66 (Fig.6) is 13cm long, apparently undistorted and of large curvature yielding an excellent momentum measurement of 74 $\pm$ 6 Mev/c. The ionization, 2 to 4 x min, is in a range easily estimated, and the track is near several tracks of known ionization. The calculated mass of this particle lies between 150 and 350 electron masses. The sign of its charge is negative. In 5-438 (Fig.5) the first track is clearly ionizing above minimum, and its momentum is almost certainly above 300 Mev/c. The mass of this particle is well above 1000 electron masses and consistent with that of a proton. The charge is positive. This V-track occurs near the top of the chamber, however, and may be part of a star in the gas. In two additional cases (17-285 and 6-153) one particle seems to have a mass well above that of a pi-meson and consistent with that of a proton.

The measurements of mass have been considerably improved by Armenteros _et al_ (6) and by other observers in this laboratory. Armenteros reports four cases in which the mass of both particles has been measured. In all of these the positive particle mass is approximately that of a proton and the negative particle mass is below about 350 electron masses. In 21 additional cases the mass of one particle can be placed within limits, and all of these are considerably less massive than a proton. Three are positive and 18 negative. The measurements in this laboratory are in general agreement with these results but they give some indication that the positive particle may sometimes have a mass between those of the proton and pi-meson.

The 13 particles striking the 2cm lead plate give evidence of having a strong interaction with nuclei. In addition to the star produced in 1-126 the positive particle in 17-285 is scattered through an angle of 40° in traversing the plate. The particle has an estimated momentum greater than 300 Mev/c for which the probability of coulomb scattering (multiple or single) greater than 20° is less than 10^{-3}. Armenteros has also observed at least one nuclear interaction in six traversals of a 3cm lead plate. Combining all of the data we get a mean path for nuclear interaction in lead of the order of 150 gms. Clearly, at least one of the decay particles has a strong nuclear interaction represented by a cross-section of about the geometrical size of the nucleus.

Although we must emphasize that none of the secondary particles have been definitely identified, most of the evidence is consistent with the conclusion that V°-particles decay in two ways, producing as charged products: (i) a proton and a negative meson (pi or mu)(ii) a positive meson (pi or mu) and some negative particle. The identity of this negative particle is a particularly intriguing mystery. If it is a negative meson, then there must be two very different modes of decay or two different V°-particles. More exciting is the possibility that the two modes of decay are very similar, the second producing a negative proton. In either case, from the relative numbers of observed positive and negative mesons it appears that process (i) occurs in the chamber two to five times as frequently as process (ii).

$V^{\pm}$-Particles

The $V^{\pm}$-particle decays into a single charged particle, and presumably at least one neutral particle is required to conserve momentum. The V-particle and its charged decay product both have a unit charge. According to Armenteros both have the same sign and can be either positive or negative. Decay products of a mass consistent with a pi or mu-meson have been observed (6)(4), and in (4) evidence for a nuclear interaction of the product is given.

VI. THE ORIGIN OF THE V-PARTICLES

V°-Particles

From Table II we see that 24 of the 35 V°-tracks were accompanied by penetrating showers produced above the chamber. Six of these cases where the V-track was below the 2cm plate were also accompanied by a secondary nuclear interaction in the plate. In one case there was a possible event in the plate but no shower. The ten remaining cases showed either electron showers, single particles or no accompanying particles. This data bears on two important questions (i) the origin of the V°-particles and (ii) the number of decay products they produce.

High Energy Events

In all of the cloud chamber experiments in which V°-particles have been observed the expansions were triggered by counters designed to select penetrating showers. In this experiment 70% of the photographs showing V°-particles also show penetrating showers, whereas the average percentage of showers for all of the photographs is about 40%. There is, however, much more direct evidence of the association of V°-particles and showers.

Figure 2 is more or less typical of 14 cases in which the V-track is oriented so that one or both charged decay particles are travelling generally in the direction of the particles of a clearly defined shower, just as would be expected if the V-particle came from the shower origin and decayed in flight at a velocity large compared to the ejection velocities of the decay particles. More precisely, a line drawn from the shower origin through the apex of the V appears to lie within a few degrees of the plane of the V, and its projection on the plane lies within the smaller angle between the two tracks. As in Section III such a line will be referred to as the "path" of the V-particle.

In order to satisfy this criterion of association a shower origin must lie above the V in a solid angle s which is approximately equal to $2\phi \tan w$, where ϕ is the angle of the V and w is the allowed angular deviation between the path of the V and its projection on the plane. The observed values of w are given in Table II. For the 14 cases discussed here w is less than the estimated errors of measurement, which are in most cases about 4° and certainly less than 7°. For w equal to 5° s is approximately 0.003ϕ, where ϕ is in degrees. Since the showers are observed to occur above the chamber within a cone of about unit solid angle and since in most of the cases there is only one clearly defined shower, the probability of observing an accidental coincidence between a V-particle and a shower is about equal to s. The probability of observing 14 accidental coincidences (and also the 5 probable correlations with stars in the plate) out of 24 cases is negligible.

We conclude that a large majority of the V°-particles are associated with the penetrating showers visible on the photographs and are probably produced in these events. The only other reasonable possibility is that the V°-particles result from a secondary nuclear interaction produced within the cone of s by one of the shower particles. For some of the cases there appear to be as much as 100cm of path of shower particles (charged and neutral) in lead ~~most of which is~~ within the cone of s. There should be about five nuclear interactions within this cone but probably very few if any relativistic tertiary particles which enter the chamber. Without a knowledge of the expected number of V° decays in the chamber from each of these types of events, it is impossible to decide between them as a source of the observed V°-particles. However, if the small angle V-tracks represent very high momenta V°-particles, then it is difficult to see how they could result from the generally low energy secondary reactions of the shower particles. We are inclined to believe that most of these 14 V°-particles originate directly in the very energetic nucleon-nucleon collisions which produce the penetrating showers.

The energy of these events can be estimated as follows. The average number of visible particles per shower is about 4.6. From the solid angle subtended at the upper lead by the chamber and the angular distribution of shower particles observed in photographic emulsions, we estimate that there are about 15 energetic charged particles and hence about 25 energetic particles including neutral pi-mesons and neutrons produced per shower. The momentum distributions observed for the charged shower particles in this experiment are consistent with a mean particle energy of about 1.3 Bev. Hence the mean shower energy must be in excess of 30 Bev.

<u>Secondary Events in the Plate</u>

Figures 1 and 3 are examples of the six cases in which a V°-particle below the lead plate is accompanied by both a penetrating shower and a secondary nuclear event in the lead plate. In Figure 3 the V-track, which is nearly horizontal, does not appear related to the shower, but has an angle w of only 2° with the star as an origin. In Figure 1 the angles w with star and shower are 5° and 20° respectively. We have assumed in these and three other similar cases, where w is nearly zero only for the star, that the V°-particle is produced in the relatively low energy secondary event in the plate. It is interesting to note from Table II that all of these V-tracks have large angles or particles ionizing above minimum as might be expected from low energy V-particles. On the other hand, especially for large angles, some of the correlations may be meaningless.

Although it appears that V°-particles can be producēd in both the high and low energy nuclear disruptions, little is known about the threshold for their production, the type of producing particle, the multiplicity of production, etc. The star in Figure 1 is apparently produced by a negative particle of only a few hundred Mev/c momentum, and all of its particles except the heavily ionizing one could be electrons. This could be interpreted as the production of a neutral pi-meson and a V°-particle by a negative pi-meson. The star in Figure 3 apparently contains only slow protons or heavier particles and contains a total energy in protons of about 350 Mev. V°-particles have been observed by others in this laboratory apparently produced in stars containing only two or three slow protons. As for multiplicities, we have observed one case (2-255) with two V°-particles apparently produced in a shower above the chamber, and McCusker and Millar (8) have reported one case in which possibly three V°-particles are produced in a star in the lead plate. If the probability of observing the decay of a V°-produced above the chamber is about 0.1 (see Section VIII), then the production of several V°-particles per shower may be quite common.

<u>The Number of Decay Products</u>

If the V° decays into only two particles, namely the two charged particles observed, then the conservation of momentum requires (i) that the path of the V° lie in the plane of the V-track, i.e., that the angle w of the path from the actual origin be zero and (ii) that the projections of the momenta of the charged particles perpendicular to the path of the V°

be equal in magnitude and oppositely directed. (ii) implies that the path of the V° must lie within the smaller angle of the V-track.

If there is at least one neutral decay product, then both criteria (i) and (ii) must occasionally fail to be satisfied by a clearly measurable amount. It is impossible, however, to give any general argument for the expected frequency of these failures, since it depends critically on the masses of the decay products, the energy released in the decay, the velocity of the V°-particle, and the coupling among the various particles (that is the existence of preferred angles and energies in the decay).

We have observed three cases (8-479, 5-438 and P5-B) in which w for the only visible nuclear event is definitely greater than the errors of measurement. Of the remaining 21 cases accompanied by nuclear events, 18 have one value of w consistent with zero, and in 3 cases the origin of the associated event is not clearly defined. In all of the cases where w is nearly zero the path of the V° lies between the two decay particles or nearly along one of them.# However, in P42-77 (Fig. 3) the path of the V° lies closest to the particle of higher ionization and lower velocity. If the V° originates in the indicated star, then either the charged decay particles are of unequal mass or a neutral decay particle is produced.

These data, though not conclusive, are strongly suggestive of a two body decay, especially in cases like 7-120 where the V-track is nearly parallel to the line of sight and errors in w are small. From the three

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#One can calculate the expected distribution of the ratios θ_1/θ_2 for certain two body decay schemes and show, for instance, that its mediam value is much higher if the two particles are of unequal mass than if they are equal. This data seems to favor the case of unequal masses, but the results are statistically poor and dependent upon the identification of an origin. In any case, there is now direct evidence that in many decays the two charged particles have quite different masses.

cases in which criterion (i) was definitely not satisfied we cannot exclude a two body decay, since it is never certain that the V°-particle has not suffered a nuclear scattering or that for all of the cases the apparent nuclear event is actually the origin of the V°-particle. This is particularly true for V°-particles which originate outside the chamber.

On the other hand, certain many-particle decay schemes cannot be excluded. First we note that in six cases where more than one possible origin is visible we have selected one favorable to the two body decay scheme. Moreover, the errors in measurement of w (due to the limited accuracy with which the origin and the plane of the V could be located) were in many cases comparable to the size of one of the angles θ_1 and θ_2 and hence probably sufficient to mask many cases where w was not zero. Here again the difficulty of dealing primarily with V°-particles which originate at large distances from the chamber is apparent. If these particles have a mean life of the order of 10^{-10} seconds as concluded in Section VIII, then they must have large time dilatation factors and ~~hence~~ high velocities if they are to reach the chamber. In this case the angles θ_1 and θ_2 (in the lab system) would probably be small. In the many cases where the path of the V° falls nearly along one of the segments of the V-track we cannot exclude the possibility that (ii) is not satisfied, especially where no reliable estimates of momenta are obtainable.

One can inquire into the expected frequency of large deviations from (i) and (ii) and the statistical significance of the number of cases observed. Thus far we have not treated this question in a satisfactory manner, but it appears possible to demonstrate decay schemes for which the expected number of large deviations is low. If, for example, we consider the case where one of the decay products is a proton and the others no heavier than pi-mesons, and if the energy release is about 100 Mev, then the maximum ejection velocity of the proton (in the CM system) is about 0.21C. For cases where the proton is relativistic in the lab system its angle with the V° path must be less than 12°. Since w must be less than the angle between the V° path and that of either charged decay fragment, it should average considerably less than 10°.

One can readily calculate for various assumed decay schemes the expected distribution in size of the angle formed by the projection of ϕ on a plane perpendicular to the path of the V°, since this angle is transformed unchanged from the CM system to the lab system. However, in the numerous cases where θ_1 or θ_2 is about the size of the errors in θ or w this projected angle cannot be measured, and the remaining cases seem inconclusive.

The practical necessity of observations in which the momenta of both particles can be measured is thus quite apparent, as it would provide one with a more sensitive test of (ii) for any assumed origin. Even in the absence of an origin, the consistency of the mass values for the V°-particles calculated from these measurements (see Section VII) would provide a keen test for the hypothesis that the V-tracks result from one (or perhaps two) types of two body decay.

The V$^{\pm}$-Particles

In three of the five cases of V$^{\pm}$-particles reported here the particle originates in a star in the lead plate. Most of the cases reported by other observers (4)(6) also originate in such events. The doubtful small angle case in Fig.8 originates in a very low energy event apparently produced by a neutral particle and containing only two slow secondaries. Another case Fig.7 originates in a much more energetic event also apparently produced by a neutral particle. The third case originates in a star produced by a charged particle.

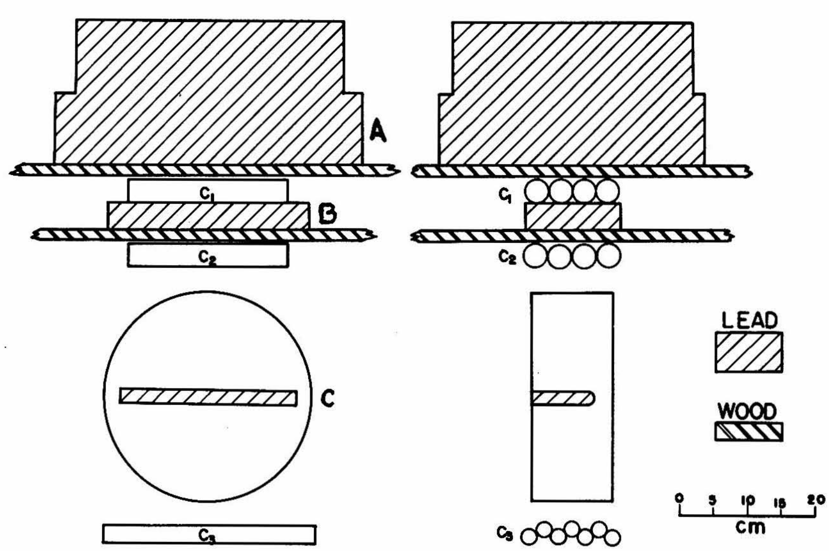

Figure 9

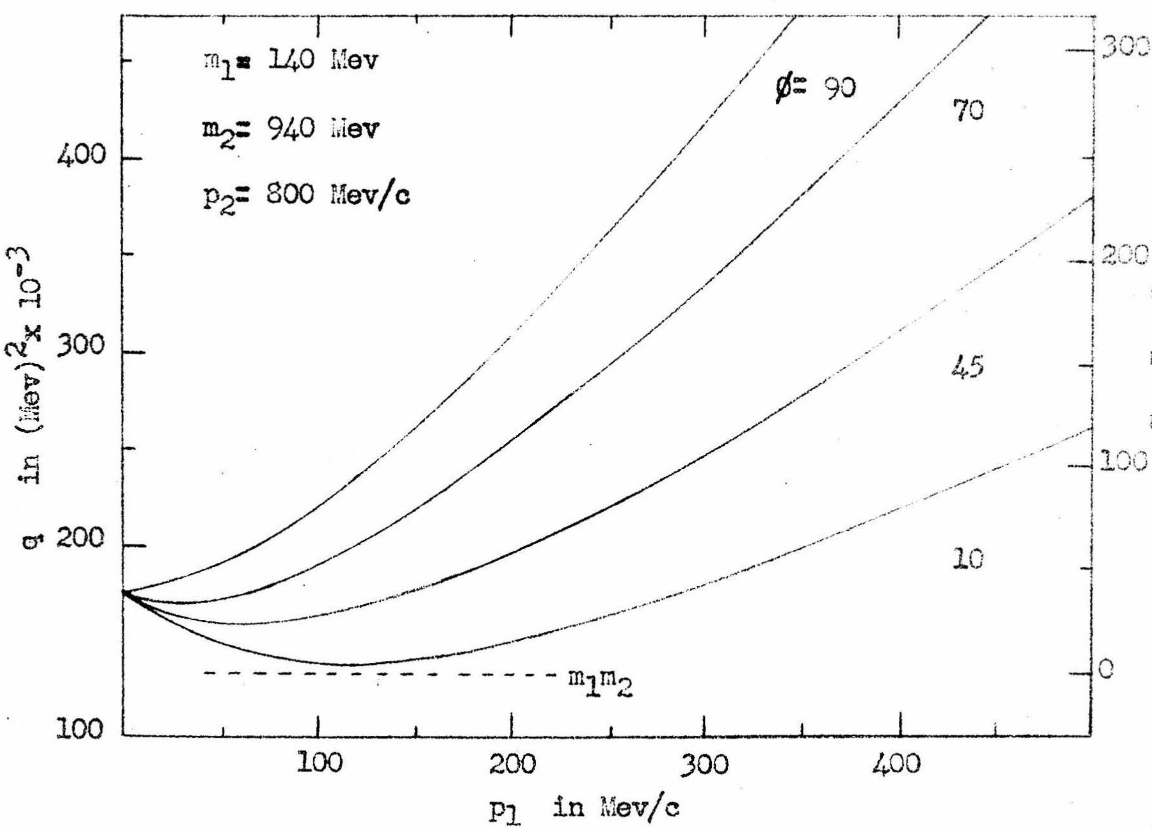

Figure 10

VII. - THE MASSES OF THE V-PARTICLES

V°-Particles

If the V°-particle decays into only two particles, of known masses m_1 and m_2, then the mass, m_o, of the V° can be calculated from a knowledge of any three of the quantities ϕ, θ_1, p_1 and p_2. If only lower limits are available for p_1 and p_2, say from ionization estimates, one can calculate a lower limit to m_o. If upper limits to the momenta are known, then an upper limit to m_o can be given. A convenient expression for m_o can be written from the conservation laws in the form

$$m_o^2 = m_1^2 + m_2^2 + 2\,(W_1\,W_2 - p_1\,p_2 \cos \phi),$$

where $W^2 = p^2 + m^2$. If the term in parenthesis, call it q, is small with respect to $(m_1 + m_2)^2$, then we can write

$$m_o \approx m_1 + m_2 + (q - m_1\,m_2)/(m_1 + m_2).$$

In any case, q is a useful parameter since it characterizes the energy release in the decay. (Note that in most of the equations in this thesis we have written masses and momenta as if they were in energy units, i.e., c equals one).

In Figure 10 we have plotted values for q as a function of p_1 in the case where one of the decay products is a pi-meson and one a proton with a momentum, p_2, of 800 Mev/c. For such a proton the ionization is about 1.6 times minimum. A more general set of curves, but very similar to these, can be obtained by plotting q/W_2 as a function of p_1. We see that for given values of p_2 and ϕ, q goes through a minimum as p_1 varies. Curves representing the variation of q with p_2, for p_1 fixed, are similar. Most observed cases yield only the value of ϕ and lower limits on the momen-

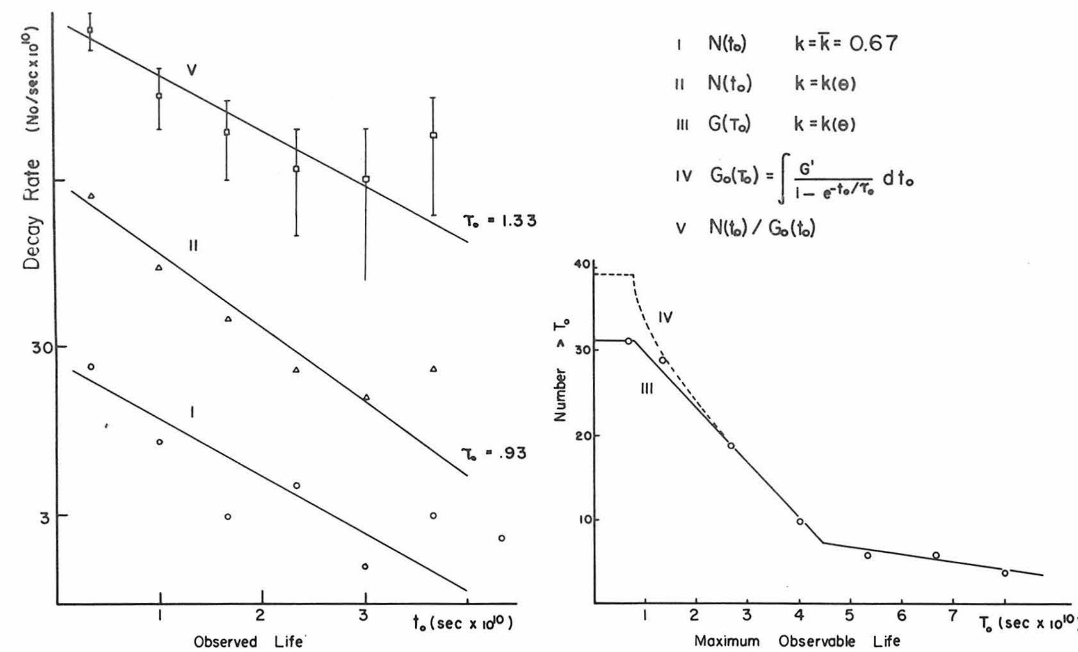

Figure 11 Lifetime Calculation

ta. These cases give a lower limit on q for some $\frac{p_1}{p_2}$, consistent with their limiting values. If in addition we assume that the V°-particle comes from the apparent origin without being scattered, then θ_1 and the ratio p_1/p_2 are fixed, and the lower limit on q will be above the previous one unless the two ratios p_1/p_2 are accidentally equal. For most values of cos ϕ and for p_1 and p_2 well above the rest energies of the particles an increase in either p_1 or p_2 increases the value of q.

The results have been calculated assuming first that the decay products are a pi-meson and a proton and again assuming that the V° decays into two pi-mesons. In each case we have obtained limits ignoring the values of θ_1 and θ_2 and again using their values given in Table II. In the case where a proton is produced the decay products weigh 2125 electron masses to which must be added $(q - m_1 m_2) / (m_1 + m_2)$ to give m_o. Most of the cases with ϕ less than 68° gave lower limits on q ranging from 140 to $175(\text{Mev})^2 \times 10^{-3}$, even if the values of θ_1 are taken into account along with estimates of ionization and lower limits to the momentum. This corresponds to lower limits on m_o between 2135 and 2205 electron masses. (In the units used (q - 132) is numerically almost equal to the energy release in Mev). In 2-255a, however, the lower limit on q is about 350 if the value of θ_1 is not ignored. In P42-77 we get an upper limit of only 175 for q if we use the indicated value of θ_1. For the two cases with ϕ = 68° we get a lower limit on q of about 210 if θ_1 is ignored and about 330 if the momenta are taken consistent with θ_1. For most of the large angle cases θ_1 is unknown, but one of the tracks usually shows ionization greater than minimum from which fairly reliable upper limits to p and q can be obtained. These upper limits range from about 190 for 11-66 to 165 for P42-86. The questionable case P6-204 gives a value of about 265 for q if the ionization of its tracks is just barely above minimum. These results can be summarized approximately as follows. The large angle cases show evidence of low momenta and occasionally of identifiable protons and give values for m_o between about 2180 and 2250 electron masses. The small angle cases give evidence of high momenta and in some cases seem to require values of m_o as high as 2500 electron masses.

If the decay products are two pi-mesons, weighing 550 electron masses, the same situation holds with the same photographs playing roughly identical roles. Excluding cases like 5-438 and P42-77 which show evidence for protons or unequal mass products, we get the same two groups of cases. This time the large angle cases give upper limits below about 610 electron masses (with P6-204 going as high as 670), while the small angle cases give lower limits ranging up to 770 electron masses for the 68° cases and 810 for 13-198 if consider the values of θ_1 and the estimated limits to the momenta of the products.

The discrepancy indicated by these results seems to be real and finds some support in the measurements of other observers in this laboratory and those of Armenteros et al. Both find many cases giving fairly well defined values near 2200 electron masses for the first decay scheme, but there are a few values apparently well above these. This situation suggests the possibility that there ~~indeed~~ are at least two quite different decay schemes with considerably different energy releases.

If the V°-particle decays into three or more particles, then no consistency of the calculated mass values would be expected. In fact a continuous spread of the values would be evidence for such a decay process, though the decay of a particle with several mass states (perhaps an excited neutron) could give similar results even for a two body decay. In any case, the energy release calculated for the two body decay schemes forms a lower limit to the energy release in a decay producing neutral particles and the same charged particles.

$V^{\pm}$-Particle

The data on the $V^{\pm}$-particle is still far too scanty to allow any significant conclusions as to its mass. In several cases the charged decay product has a component of momentum perpendicular to the path of the V-particle well above 100 Mev/c, indicating an energy release above 30 Mev if this particle is as light as a pi-meson.

VIII. - LIFETIME AND ABUNDANCE

Estimates of Mean Life

There are several fundamental observations from which an estimate of the mean life of the V°-particles can be made. (i) From Table II we note that the distances x (the distance travelled by the V° in the visible portion of the chamber) are characteristically very much less than the distances d (the maximum distance which the particular V° could have travelled in the chamber and still produce a visible decay). This interpretation assumes only that the path of the V° is approximately that assumed in the previous sections and implies that the mean life is considerably shorter than the time required for the V° to traverse the chamber and of the order of 3×10^{-10} seconds in the lab system. (ii) Most of the V°-particles originating above the chamber show evidence (the small angles of their V-tracks and the minimum ionization and high momenta of the secondaries) of high velocities. If this is the case and if low velocity V°-particles are also frequently produced (as in the cases apparently originating in the plate in the chamber), then we conclude that the rest life time is short compared to the time required to travel the distances from A to the chamber, and only particles with large time dilatations reach the chamber. (iii) Particles produced at a distance l above a chamber of width d have a probability of decaying in the chamber given by

$$e^{-l/gc\tau_0} \quad (1 - e^{-d/gc\tau_0}),$$

where g is the ratio of momentum to mass for the V° and τ_0 is its mean life at rest. If τ_0 is less than $10^{-10}/g$ seconds or greater than about $5 \times 10^{-8}/g$ seconds, then this probability is less than 0.01 where l and d are roughly the distance from the top of the chamber to A and the diameter of the chamber. If the probability of observation is less than 0.01 then there must have been about 3000 V° particles directed at the chamber produced in these showers. If this were the case, then for the small lifetime one would have expected numerous observations of V° particles associated with stars in cloud chambers and photographic emulsions. If the lifetime were large then one might expect to observe V tracks at large distances from penetrating showers, and their secondaries must comprise about one third of the charged particles in such showers at large distances from their origin.

Momenta of the V°-Particles

In order to make a more detailed calculation of τ_0 based on the data in (i) it is necessary to know the type of decay process as well as the value of g for each case. Since there is little direct information we have estimated g on the assumption that the V° particles are all of the same type, decaying with the same mean life into two pi-mesons. We have used a mass of 750 electron masses for the V°. It now appears that there are possibly two different decay schemes and certainly protons among the decay products. We shall, however, present these calculations in order to demonstrate the method and the orders of magnitude involved.

For the case of a decay into two equal mass secondaries it is easily shown that when the velocity of the V° exceeds the ejection velocity of the pi-mesons there is a maximum angle ϕ in the lab system for any momentum p_o of the V°. Also for any angle less than this maximum (about 82° for m_o = 750 electron masses) there is a maximum value of g given by

$$g_{max} = \left(\frac{m_o^2}{m_1^2} \csc^2 \phi - 1 \right)^{\frac{1}{2}} .$$

We see that for most values of ϕ, g_{max} is about proportional to m_o and varies less than a factor of two for the range of m_o values from 600 to 900 electron masses.

In Figure 12 we have shown the probablility of an angle greater than ϕ as a function of ϕ for various values of the V^o momentum. These curves were obtained by calculating the value of ϕ corresponding to an angle a in the CM system between the directions of the V^o and the pi-meson , weighting these angles ϕ according to the sin a, and graphically integrating to obtain the probabilities plotted. It is clear that for about 90 per cent of the cases the angle ϕ lies within a few degrees of the maximum value of ϕ for the given p_o, and that for most cases g must be very near to g_{max} for the given angle ϕ. We have used the values of g_{max} in calculating the lifetime unless there was some more direct information from ionization or curvature, but in no case was a value greater than seven taken.

If these calculations were repeated for the case in which a proton is one of the decay products, then the asymmetry of the decay would produce additional complications, especially in the region where the velocity of the V^o is greater than the ejection velocity (in the CM system) of the proton but less than that of the meson. Since, however,t he energy release is probably a much smaller fraction of the total mass of the V^o, we can see that in general somewhat smaller values of g would be obtained and hence a somewhat longer mean life. However, since g must be almost one for the cases where both decay products are relativistic, and since the values of g used were no larger than seven, the lifetime should not be off more than a factor of about two on this accoũnt.

A Lifetime Calculation

Using the values of g calculated as above we have converted the distances d and x to times in the rest system which we shall refer to as T_0 and t_0 respectively. These times are the "maximum observable life" and "observed life" in each case. The steps in the calculation of the mean life are given in Figure 11.

Curves I and II give the rate at which particles are observed to decay as a function of the time after which they enter the chamber. I is calculated using simply a mean value of $k = 1/g$ to convert from x to t_0. It represents essentially the raw data. The vertical scale for all three curves I, II, and V is logarithmic,but the absolute values are arbitrary. Actually the curves should be nearly superimposed. The statistical error in the points is about the same for all three and is shown for V. Curve II shows the decay rate again but here each distance x has been converted to a time using the value of g calculated for that case as above. The value of τ_0 taken from the slope of curve II must be corrected for the fact that due to the geometry of the apparatus many particles pass out of the chamber before decaying and all values of t_0 are not equally probable.

In order to correct for this effect we have plotted in curve III the number of cases with T_0 greater than a given time against the time. Within the statistical uncertainties this is a first approximation to the number of particles which can produce a visible decay with a value of t_0 greater than the given time. This, however, must also be corrected since particles with large values of d are more readily observed due to the higher probability of decaying in the chamber. Curve IV is the corrected version of curve III, where the correction was made according to the formula on the figure.G^1 is the slope of curve III and was calculated graphically. The effect on the finally calculated value of τ_0 produced by the approximate value used to make this correction is very small, and indeed the process can be repeated through a set of converging steps if the effort is warranted. The corrected curve IV, $G_0(t_0)$, is then the number of particles which traverse the chamber in such a direction that they can stay in the chamber for a time greater than t_0.

We can now write the observed decay rate as a function of time, $N(t_0)$, in the form

$$N(t_0) = \frac{G_0(t_0)}{\tau_0} e^{-t_0/\tau_0}$$

Now the log $N(t_0) / G(t_0)$ should be a straight line if plotted against t_0. We have shown its values in curve V. The value of the slope gives τ_0. Here $\tau_0 = 1.3 \times 10^{-10}$ sec with a probable error due to statistical uncertainty of about $\pm$ 50%.

The abundance of the V°-particles

In order to calculate the abundance of the V°-particles it is necessary to know the relative numbers produced at various distances above the chamber and with various momenta. If the statistics were improved, we could estimate the number of particles of each momentum which decay in the chamber. From this and a knowledge of the total number of V-particles produced at each distance above the chamber the momentum spectrum at production could be calculated. We can for the data available calculate at least a mean observation probability for intermediate momenta with a mean value of 1/g about that for the cases observed. Assuming that the V° origins are distributed almost uniformly in the lead above the chamber gives a mean observation probability of about 0.1 for these momenta. There were thus an estimated 350 such V°-particles produced in the showers above the chamber and directed towards the chamber. In the same photographs there were about 15,000 charged penetrating shower particles which entered the chamber. Thus about one V°-particle is produced per 40 penetrating shower particles or about one per eight showers.

The $V^{\pm}$-Particles

Here again the data available is quite scanty, especially for statistical arguments. It appears that either these particles are produced much less frequently than V°-particles, or have a mean life shorter by a factor of at least 1/3, or perhaps show a combination of both effects. The large numbers observed from the plate relative to those observed from above would tend to suggest the shorter mean life.

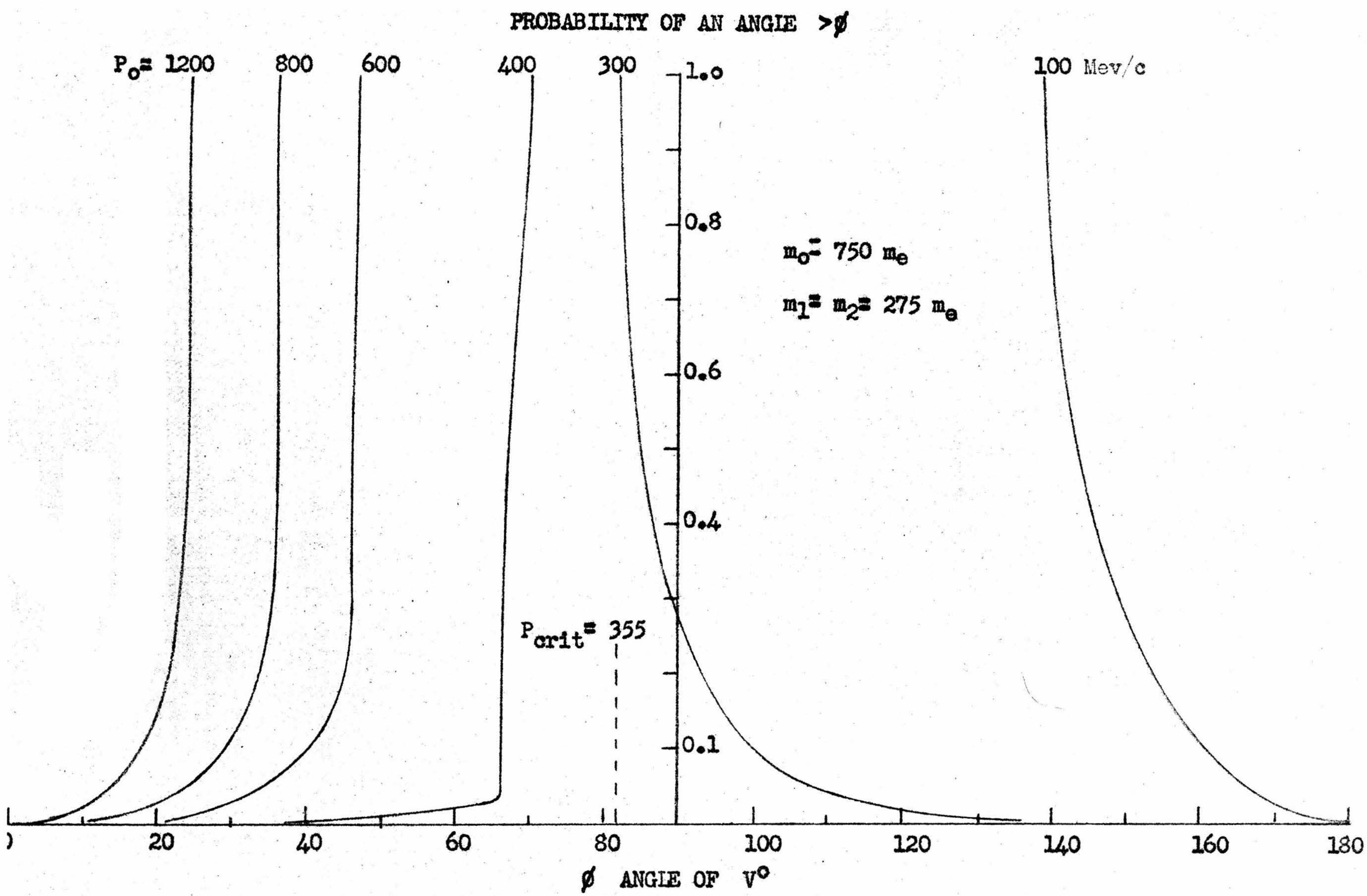
PROBABILITY OF AN ANGLE >ϕ
Po= 1200
800
600
400
300
100 Mev/c
1.0
0.8
0.6
0.4
0.1
mo= 750 me
m1= m2= 275 me
Pcrit= 355
0
20
40
60
80
100
120
140
160
180
ϕ ANGLE OF V°

Figure 12

IX. SUMMARY

We conclude:

1. The V-tracks observed here require the assumption of a new decay process. They are not consistent with any phenomenon whose frequency is dependent upon the density of nucleons. No more than 10% can be explained in terms of any known process.

2. V^0 and $V^{\pm}$ particles exist and decay to give the observed V-tracks.

3. The V-particles are produced in nuclear disintegrations in the lead, usually in the very energetic reaction producing the penetrating showers but frequently in the lower energy stars produced by the shower secondaries.

4. In the energetic reactions there is about one V^0 particle per 40 charged shower particles. More than one V^0 can be produced per event.

5. The decay products do not include electrons or any particles much lighter than ordinary mesons.

6. The V^0-particle decays into two charged secondaries of unit electronic charge and opposite sign and perhaps one or more neutral secondaries.

7. The measurements of the masses of the decay particles are consistent with the decay schemes:

$$V^0 \rightarrow \text{proton} + \text{negative meson}$$

$$V^0 \rightarrow \text{positive meson} + \text{unidentified negative particle}$$

8. At least one of the decay particles of the V^0-particle has a nuclear interaction cross section in lead of about the geometrical size of the nucleus.

9. The V^0 mass calculations are not consistent with a single two-body decay process. They are at present consistent with two two-body decay processes including one in which the energy release is about 40 Mev and one in which the energy release is 100 Mev at least. They are also consistent with a three-body decay.

10. The V^0 particles decay with a mean life of about 1×10^{-10} sec. This is probably correct within a factor of two for any of the suggested decay schemes.

11. The V^+-particle produces one visible decay particle, of the same sign and of unit charge. This particle is not an electron. The energy release is at least sufficient to give the charged particle a momentum of 100 Mev/c in the CM system. The lifetime of the V^+ particle must be shorter than that of the V^0-particle by about a factor of 1/3 or its production frequency less by at least the same factor.

References

1. G. D. Rochester and C. C. Butler, Nature 160, 855 (1947).
2. A. Seriff, R. B. Leighton, C. Hsiao, E. Cowan and C. D. Anderson, Phys. Rev. 78, 290 (1950).
3. W. B. Fretier, Bull. Am. Phys. Soc. 26, No. 1.
4. H. S. Bridge and M. Annis, Phys. Rev. 82, 445 (1951).
5. V. D. Hopper and S. Biswas, Phys. Rev. 80 , 1099 (1950).
6. R. Armenteros, K. H. Barker, C. C. Butler, A. Cachon and A. H. Chapman, Nature 167, 501 (1951).
7. R. W. Thompson, H. O. Cohn and R. S. Flum, Bull. Am. Phys. Soc. 26, #3.
8. C. B. A. McCusker and D. D. Millar, Il Nuovo Cimento VIII, 289 (1951).
9. J. Daudin, Annales de Physique 19, 110 (1944).
10. L. Janossy, G. D. Rochester and D. Broadbent, Nature 155, 142 (1945).
11. R. B. Leighton, C. D. Anderson and A. J. Seriff, Phys. Rev. 75, 1432 (1949).
12. E. J. Williams, Proc. Roy. Soc. A 169, 513 (1939).

Appendix A: - An Optimum Target Thickness

We wish to calculate the thickness of lead for which M vertically incident primaries will produce the maximum number of V°-particles emerging below the lead. Assume that the V°-particles and all other shower secondaries travel vertically downward.

The primaries interact with a mean path of = 15cm of lead to produce showers of say $m = 10$ particles (charged and uncharged) as well as n = 1/8 V°-particle. These numbers represent roughly the average number of particles which enter the chamber in these showers. The V°-particles decay with a mean path l = 3g. The shower particles again interact with a mean path and produce about f = 1/100 V°-particles and no other particles energetic enough to continue reacting. This value of f is estimated from the number of stars observed in the plate and the number of V°-particles which originate in the plate corrected for those which are not observed. This value of f is quite uncertain.

Now let x and y be distances measured upward from the bottom of the lead and used to locate primary and secondary reactions respectively. Now we can write for N, the number of emerging V°-particles from a layer of thickness t,

$$N = \int_0^t e^{-x/\ell} \left(\frac{Mn}{\lambda} e^{-\frac{t-x}{\lambda}} dx \right)$$

$$+ \int_0^t e^{-\frac{t-x}{\lambda}} \frac{Mm}{\lambda} \int_0^x e^{-y/\ell} \left(\frac{f}{\lambda} e^{-\frac{x-y}{\lambda}} dy \right) dx.$$

This can be integrated and simplified to give

$$N = \frac{Mm}{\lambda/\ell - 1}\left[\left(\frac{n}{m} - \frac{f}{\lambda/\ell - 1}\right)\left(e^{-t/\lambda} - e^{-t/\ell}\right) + \frac{ft}{\lambda} e^{-t/\lambda}\right] .$$

The first term in the brackets has a maximum between 0.4 and 0.9 as g varies from 1 to 4. The second term has its maximum at λ. For f = 1/100 the second term dominates and for f = 1/200 the first term dominates. Thus we see that the optimum value lies somewhere between about 10 and 15cm of lead. If we include the possibility of oblique traversals the optimum thickness must be somewhat reduced. The values obtained for N/M are of the order of .05 at the maximum for small g.

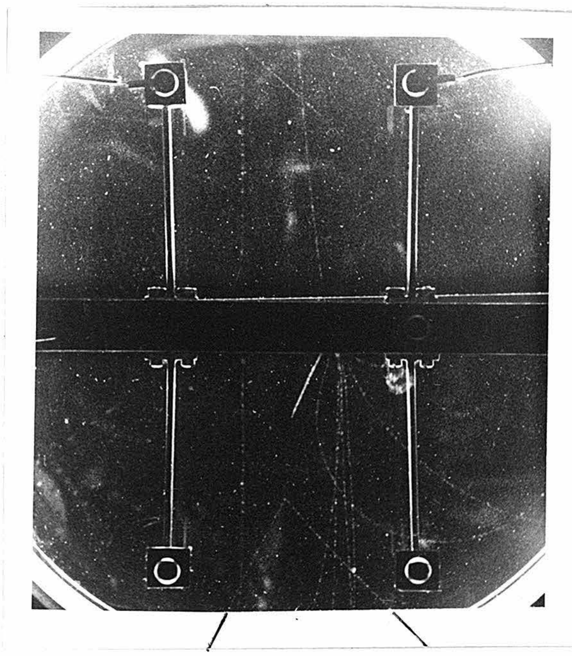

Fig. 1. V^o decay. P44-66. V^o possibly originates in the nuclear disintegration visible in the plate. The large angle (68°) indicates a large decay energy.

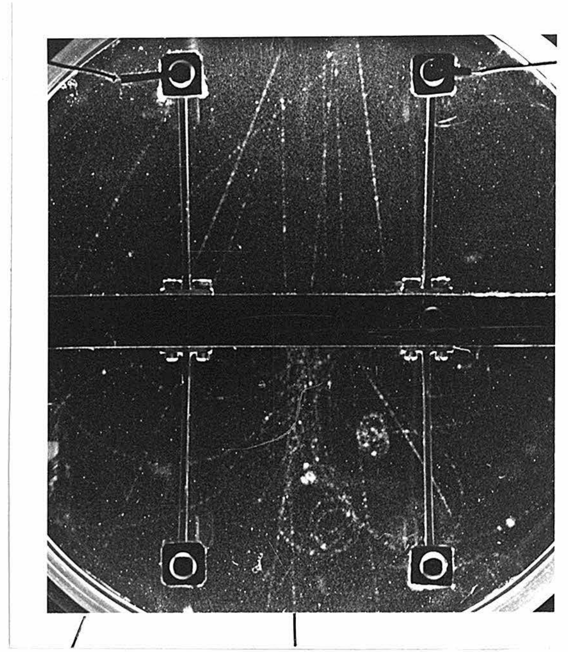

Fig. 2. V^o decay. 5-121. V^o appears to be part of the shower. Both particles traverse the plate without producing visible secondaries.

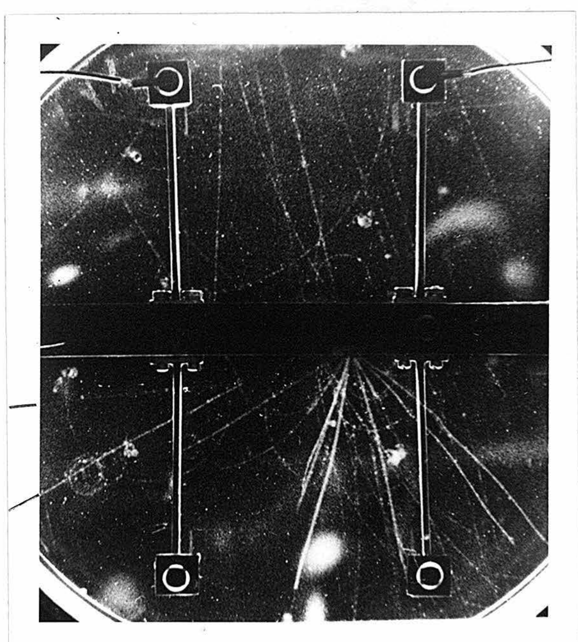

Fig. 3. V^o decay. P42-77. Origin of V^o in the star requires decay products of unequal mass or a three-body decay.

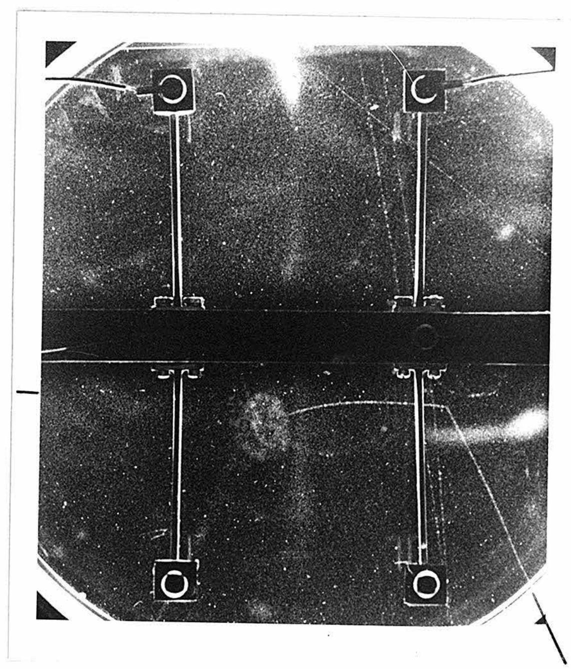

Fig. 4. V^o decay. P43-86. High ionization of both products indicates a small decay energy. May be a case of pi-me decay.

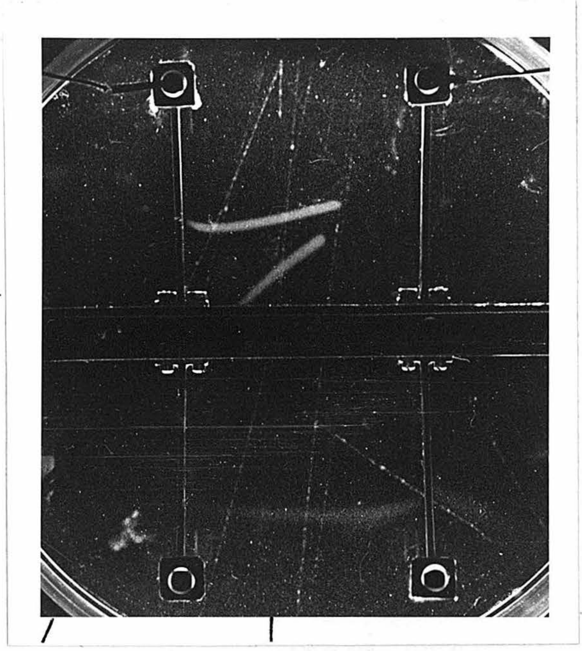

Fig. 5. V^o decay. 5-438. Particle 1 is probably heavier than a meson.

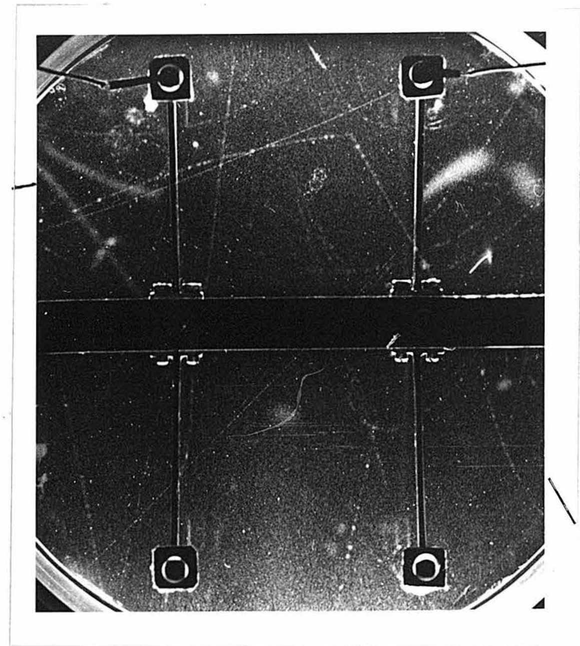

Fig. 6. V^o decay. 11-66. Particle 1 is negative with a momentum of 74 Mev/c and an ionization of 2-4 x min., indicating a mass between 150 and 350 m_e.

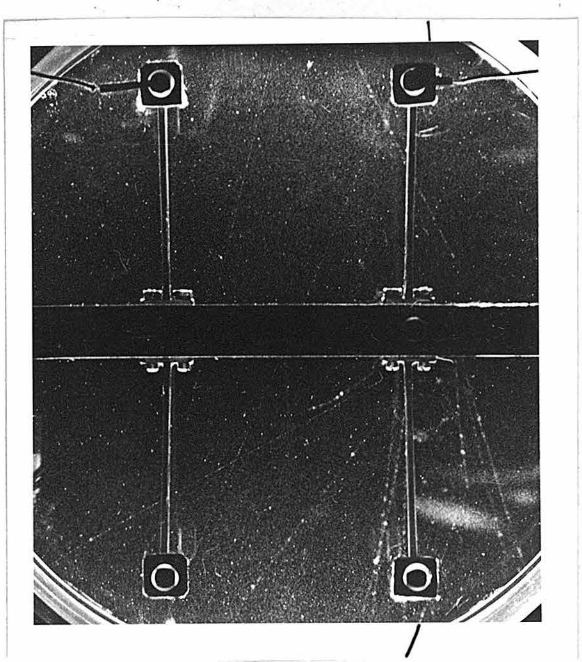

Fig. 7. V decay. 5-128. Particle originates in star. Deflection angle is 40^o.

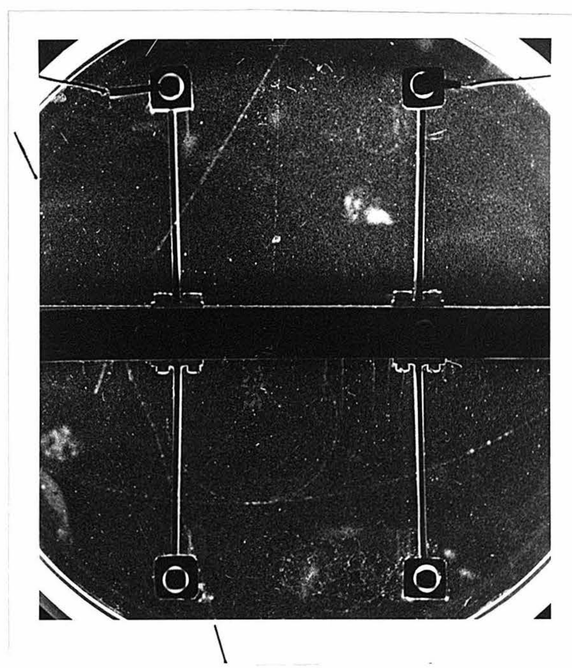

Fig. 8. V decay. 1-331. Particle originates in star. Small deflection angle (7^o) may be due to scattering in the gas.