Cloud-Chamber Observations on Charged V Particles*

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In an experiment utilizing the double cloud-chamber technique at an altitude of 10 600 ft, 46 charged V particles have been observed. Where possible these have been classified according to the value, p^*, of the momentum of the charged decay particle in the rest system of the primary particle. On this basis decaying particles have been classed as:

1. Consistent with two-body decay of known heavy mesons and not consistent with known hyperons.
2. Consistent with two-body decay of heavy mesons but also consistent with two-body decay of hyperons.
3. Not consistent with two-body decay of heavy mesons.

In the first group it is generally not possible to distinguish between the possibilities $\theta \rightarrow \pi+\pi^0$, on the one hand and $K_{\mu 2} \rightarrow \mu+\nu$ on the other. However, several cases suggest strongly the θ particle and yield an average mass $953\pm18m_e$. Several other special decay events are reported. After classification by p^*, lifetime measurements are made on groups consistent with two-body heavy meson decay. The nine positive events in this class give a lifetime $3.7\times10^{-10}<\tau<8.5\times10^{-10}$ sec with 50% confidence limits, and 7% probability that $\tau>5\times10^{-9}$ sec. The six negative events in this class give a lifetime $3.0\times10^{-10}<\tau<8.0\times10^{-10}$ sec with 50% confidence limits and 11% probability that $\tau>5\times10^{-9}$ sec. Effects of possible biases are discussed and it is concluded that these lifetimes characterize the charged θ meson. No unambiguous examples of the $K_{\mu 3}$ or Ke_3 heavy mesons were observed.

I. APPARATUS AND METHOD

THE results to be described were obtained by means of a double cloud-chamber arrangement located at the Echo Lake Laboratories of the Inter-University High Altitude Laboratories situated in Colorado at an altitude of 10 600 ft.

Double cloud chambers have been used first by the Paris group[1] in the analysis of heavy unstable particles. In this arrangement, a cloud chamber in a magnetic field is placed above another cloud chamber containing plates of dense material. The upper chamber is referred to as the momentum chamber, the lower as the plate chamber. The momentum chamber in the present disposition has been described previously,[2] being approximately 16 in.$\times$16 in.$\times$6 in. illuminated volume, in a magnetic field averaging 5500 gauss. The plate chamber is approximately 20 in.$\times$20 in.$\times$7 in. illuminated volume. This chamber has contained seven lead plates, 0.5 in. thick (through run 176); and seven copper plates of the same thickness (runs 177 through 241). More recently 11 tungsten plates each 0.6 in. thick have been installed. The results reported here are mainly from the momentum chamber data.

The chambers are triggered simultaneously by means of a penetrating shower detector consisting of lead and geiger counters above the top chamber, proportional counters between the chambers, and proportional counters and lead below the chambers. The general disposition is shown in Fig. 1. The counting rate of the detector is 20 per hour. The recycling time of the chambers is three minutes.

The quantities that can be measured are indicated in Fig. 2. P is the momentum of a primary track, p the momentum of a secondary track, θ the laboratory angle between the direction of the primary and secondary. The range R of a particle is measured in the plate chamber. Measurement techniques for P, p and θ have been described previously.[2] The errors in the measured momenta are made up essentially of three parts: measurement errors, including errors in reconstruction, curve plotting and magnetic field measurement; mul-

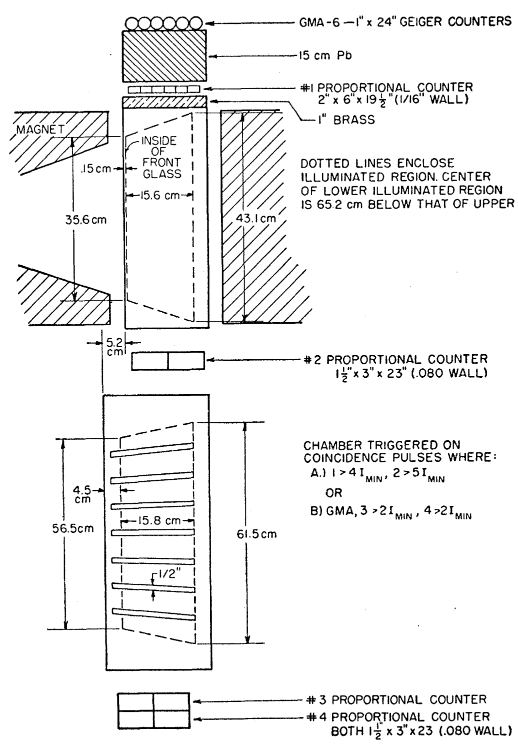

FIG. 1. Experimental arrangement for dual cloud chambers. This is presented as a typical arrangement. However, the counter disposition and depth of illumination has been varied during the course of the experiment.

* Supported by the Office of Naval Research and the U. S. Atomic Energy Commission.

[1] Gregory, Lagarrigue, Leprince-Ringuet, Muller, and Peyrou, Nuovo cimento **11**, 292 (1954).

[2] Hodson, Ballam, Arnold, Harris, Rau, Reynolds, and Treiman, Phys. Rev. **96**, 1089 (1954).

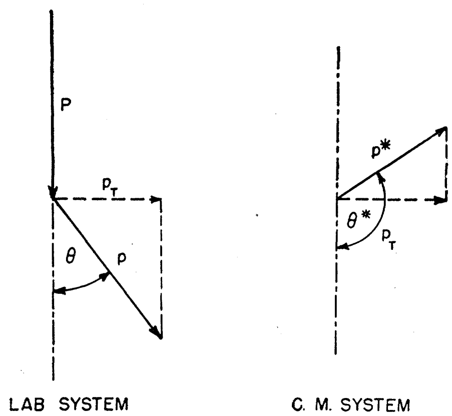

FIG. 2. Representation of a charged V decay in the laboratory and center-of-mass systems. In the laboratory system P and p are the momenta of the primary and secondary particles respectively and θ is the angle of emission of the secondary with respect to the primary. In the c.m. system p^* is the momentum of the secondary and θ^* is the angle of emission of the secondary with respect to the direction of motion of the center of mass. Pt is the transverse component of the momentum of the charged secondary and is the same in both systems.

tiple gas scattering; and random distortion due to gas motion. For all particles except the slow ones the random distortion error predominates. This was estimated by a direct measurement of proton masses by the momentum-range method. For these cases the range error could be neglected. From 17 proton mass measurements on runs 143–176 we found a systematic distortion curvature of -0.020 meter^{-1} and a random curvature of ± 0.012 meter^{-1} for tracks 40 cm long. After these runs, improvements in temperature conditions were made and measurements on 13 protons in runs 183–225 gave values of -0.01 ± 0.01 meter^{-1}. It was found experimentally that the random curvature error increased inversely with the length of the track and, from no-field measurements, that the systematic error disappeared for horizontally moving particles. The momentum errors quoted in this article are probable errors determined by combining as independent errors the three main components described above.

From the measurements of P, p, and θ, one can calculate the momentum (p^*) of the charged secondary particle in the center-of-mass system of the primary particle if the mass of the primary and the charged secondary are assumed. Alternatively on the basis of a two-body decay the Q value (i.e., Mass (primary) $-$ Mass (secondaries) $= Q$) can be obtained if a two-body decay and the nature of both secondaries are assumed.

A survey of the data can be attempted on the basis of the p^* or Q values. If one deals with two-body decays, the p^*'s and Q's should group (within experimental uncertainties) around the appropriate central values. Evidence for three-body decays should appear in distributed values of p^* and Q when these quantities have been calculated on an assumed two-body decay scheme. There is a limit to the usefulness of the p^* method

TABLE I. Decay constants of K mesons and charged hyperons.

Particle	Mass (electron masses)	Decay scheme	Q (Mev)	p^* (Mev/c)
$\tau^\pm$	965.5	$\pi^\pm+\pi^++\pi^-$	74.7	<125
		$\pi^\pm+2\pi^0$	84.1	<133
θ^0	966	$\pi^++\pi^-$	214	204
$\theta^\pm$	953	$\pi^\pm+\pi^0$	213	202
$K_{\mu 2}$	930	$\mu^++\nu$	371	226
κ	$\sim$1000	$\mu^\pm+2?$		$\lesssim$250
K_e	$\sim$1000	$e^\pm+2?$		$\lesssim$250
$\Sigma^\pm$	2329	$p+\pi^0$	117	196
		$n+\pi^\pm$	111	190
Ξ^-	2583	$\Lambda^0+\pi^-$	66	138

beyond the survey stage unless one resorts to selections that yield statistically significant averages. This limitation is due to the fact that from measurements of P, p, and θ one must assume a primary mass in order to calculate p^*. If then an individual p^* is not consistent with the assumed decay scheme, then there is no quantitative deduction immediately possible from this particular p^*. However, both p^* and Q values are useful in ruling out specific decay schemes as possibilities in particular events.

The decay schemes and their resultant p^* and Q values which were used for comparison purposes in this paper are listed in Table I for certain K mesons and hyperons. These are in all cases in close agreement with those presented by Rossi[3] at the Fifth Rochester Conference on Nuclear Physics held in February, 1955. One of the outstanding questions in this field has been that concerning the possibility that the $K_{\mu 2}$, θ^+, and τ^+ might be alternate decay schemes of the same particle. This possibility suggested itself because the measured masses were not clearly different, and has remained because there has been no compelling evidence for differences in lifetimes. The important work of Dalitz[4] has indicated strongly that the θ^+ and τ^+ are not alternate decay modes of the same particle, but there is no similar argument with respect to $K_{\mu 2}$. Evidence has been presented recently[5,6] indicating that the mass of the $K_{\mu 2}$ may be less than that of the τ. The results to be described in the present paper indicate that the lifetime of the θ^+ particle is shorter than that of the $K_{\mu 2}$.

II. EXPERIMENTAL DATA

The methods described above have been applied to a study of 46 charged decays of which 44 could be determined as to sign. One of the positive decays was that

[3] See summary by B. Rossi, Proceedings of the Rochester Conference, February, 1955 (Interscience Publishers, Inc., New York, 1955).
[4] R. H. Dalitz, Proceedings of the Rochester Conference, February, 1955 (Interscience Publishers, Inc., New York, 1955).
[5] Ballam, Hodson, and Reynolds, Phys. Rev. **99**, 1038 (1955); Armenteros, Gregory, Hendel, Lagarrigue, Leprince-Ringuet, Muller, and Peyrou, Nuovo cimento **I**, 915 (1955); Bridge, De-Staebler, Rossi, and Sreekantan, Nuovo cimento, **I**, 874 (1955).
[6] G. T. Reynolds and W. Aron, Phys. Rev. **99**, 1038 (1955).

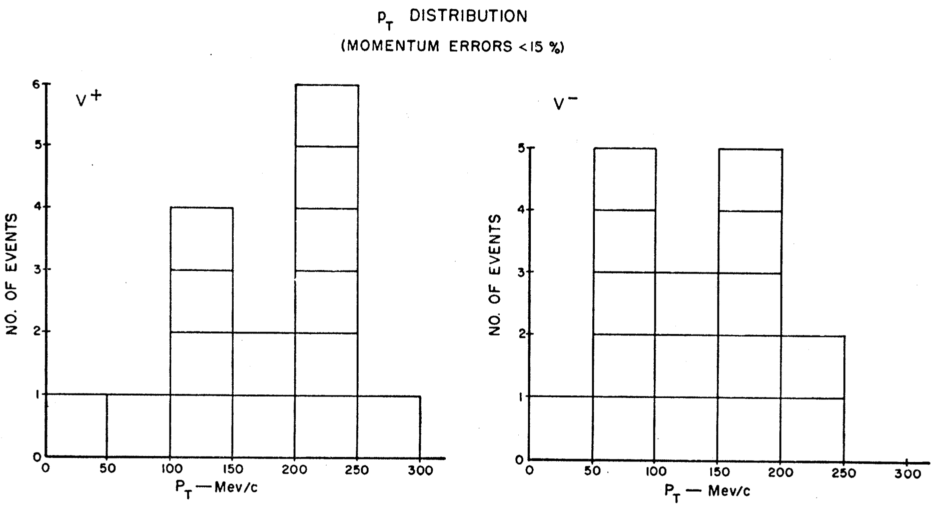

FIG. 3. Transverse momentum distribution of the charged secondary for both V^+ and V^- events.

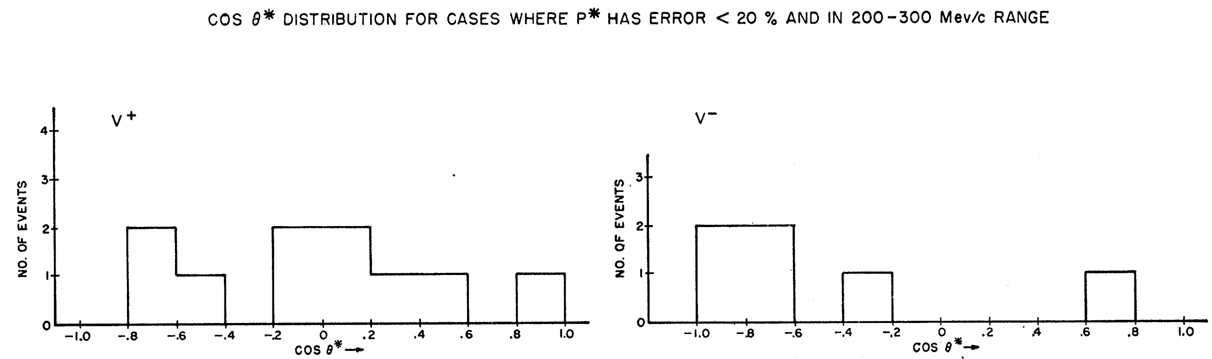

FIG. 4. Distribution of the cosine of the angle of emission of the charged secondary in the c.m. system for both V^+ and V^- events.

of a $\tau^+\rightarrow\pi^++\pi^++\pi^-$ and will not be discussed further. Of the remaining 43 events, all of the charged V type, 21 were positive and 22 were negative. These events were obtained in runs during which about 48 000 pictures were taken, including approximately 300 V^0. The measurements on these events are shown in Table II.

Of the 21 positive events, one appears to have mass greater than $1000m_e$ on the basis of a primary momentum of 510±40 Mev/c and ionization 2–5 times minimum. The p^* on the assumption of $\Sigma^+\rightarrow\pi^++n$ is 170±75 Mev/c.

One other event had a p^* consistent with that of a hyperon and not with a K meson. Of the remaining 19 V^+ events, 16 allowed a measurement of the transverse momentum p_T (15 of these have smaller than 15% probable error), 13 have p^* determined to better than 20% probable error.

The distribution of the p_T values is shown in Fig. 3. Figure 4 shows the distribution of $\cos\theta^*$ for these events, where θ^* is the angle of emission of the charged secondary in the c.m. system. The distribution of p_T is consistent with that expected for a two-body decay process, and the $\cos\theta^*$ distribution is consistent with isotropic decay, within the limitations of the statistics due to the number of events. Figure 5 shows the p^* values obtained. Of the 13 p^*'s two could be due to hyperons, in the sense that when they were analyzed as hyperons, the value obtained for p^* was within $1\frac{1}{2}$ probable errors of the accepted value. Thus 11 of the events can be K mesons, but not hyperons. One low p^* value was found, which was consistent with the decay $\tau^+\rightarrow\pi^++\pi^0+\pi^0$. One high value, 271±20 was found. These two values have been omitted from subsequent analysis. Of the 11 events that could be K mesons and are not consistent with hyperons, two show evidence for π secondaries. One of these, shown in Fig. 6, shows a star in the gas made by the charged secondary particle. Consideration of the laboratory momentum of the secondary, as well as the visible energy in the star indicates that this decay is not that of $\tau^+\rightarrow\pi^++\pi^0+\pi^0$. Thus it has been analyzed as the decay $\theta^+\rightarrow\pi^++\pi^0$. On this basis the mass obtained is 947_{-55}^{+75}. A second event previously reported[2] yields evidence for a π^0 secondary. On the basis of this θ^+ decay mode, the mass of the primary in this event was found to be 954_{-20}^{+30}. The p^* distribution is seen to be consistent with either θ^+ or $K_{\mu2}$ decay, or a mixture of the two.

TABLE II(A). Data on V^+ events.[a]

Event	P	p	θ	p^* $965\to\pi$	p^* $912\to\mu$	Q $\Sigma^+\to n+\pi^+$	Q $\Sigma^+\to p+\pi^0$	$M(\pi,\pi^0)$	$M(\mu,\nu)$	Remarks
137–629	(0.8)	153 ± 8	55.7 ± 0.7	201^{+9}_{-6}		NO	NO	954^{+30}_{-20}		$\theta^+\to\pi^++\pi^0$ (See reference 2)
164–818	658^{+125}_{-100}	373^{+95}_{-70}	32.3 ± 0.5	200^{+50}_{-45}		NO	NO	947^{+75}_{-55}		Secondary forms star in gas
176–213										$\tau^+\to\pi^++\pi^-+\pi^+$
136–315	374 ± 64	146 ± 9	86.5 ± 0.5	202 ± 21	198 ± 21	NO	NO	958 ± 50	843 ± 50	
137–834	1065 ± 160	(1000 ± 400)	5.0 ± 0.7							
146–599	3.8^{+2*}_{-1}	346 ± 30	24.3 ± 0.5	450^{+235}_{-120}	390^{+200}_{-100}	109^{+95}_{-30}	NO			Possibly $a\Sigma^+\to n+\pi^+$
150–149	1130^{+560}_{-460}	842 ± 95	13.5 ± 1	210^{+85}_{-30}	209^{+85}_{-30}	430^{+225}_{-190}	142 ± 35			Possibly $\Sigma^+\to p+\pi^0$
151–616	794 ± 140	816 ± 125	18.3 ± 0.5	289 ± 50	285 ± 50	511 ± 140	224 ± 100			Possibly $\Sigma^+\to p+\pi^0$
157–566	671^{+85}_{-75}	680^{+80}_{-65}	7.6 ± 0.5	210^{+35}_{-30}	205^{+35}_{-30}	NO	NO	1047 ± 300	787 ± 280	
170–157	600 ± 300	245 ± 9	9.5 ± 1	55^{+60}_{-10}	68^{+60}_{-10}	32 ± 30	NO			V^0 in same picture. Possibly 3-body
178–888	$2^{+1*}_{-0.6}$		20.0 ± 1.5							
179–446	104 ± 12	139 ± 14	63.0 ± 1	126 ± 13	127 ± 13	NO	NO			Possibly 3-body $I=6$–10
180–899	392 ± 30	317 ± 62	50.7 ± 1	245 ± 48	245 ± 48	NO	NO	1100 ± 150	980 ± 140	$I=2.5$–4.5
183–883	$4^{+2.5*}_{-1.5}$	>300	23.8 ± 1							
191–672	515 ± 40	(200 ± 80)	58.0 ± 1			89 ± 65	NO			$I=2$–5 more than 2 probable errors from K mass
192–289	820 ± 300	524 ± 50	23.5 ± 1	211 ± 25	211 ± 25	299 ± 60	NO	993 ± 65	886 ± 60	
195–815	480 ± 55	371 ± 17	36.4 ± 0.5	225 ± 11	225 ± 11	NO	NO	1029 ± 35	917 ± 35	
198–745	437 ± 70	250 ± 15	69.5 ± 0.5	271 ± 20	271 ± 20	NO	NO	1140 ± 50	1049 ± 55	High mass ?
201–564	$>4*$	916 ± 100	8.5 ± 0.3	>150	>162					Probably not τ'
201–663	481 ± 55	382 ± 20	33.8 ± 0.5	217 ± 13	217 ± 13	NO	NO	1014 ± 50	882 ± 50	
204–042	100 ± 14	220 ± 18	66.1 ± 0.7	205 ± 18	205 ± 18	NO	NO	980 ± 55	850 ± 50	$I=5$–10
214–928	885^{+135}_{-85}	239^{+75}_{-65}	66.8 ± 0.3	373^{+100}_{-85}	367^{+100}_{-85}	175^{+75}_{-65}	NO			Possibly Σ^+; V^0 in same picture

[a] Masses are in electron masses; $M(\pi\pi^0)$ means the mass of K obtained by assuming scheme $K\to\pi+\pi^0$. Momenta are in Mev/c, except for * values which are in Bev/c. Lower limits on P were obtained by using MDM, or setting upper limit of 2 on relative ionization. Lower limits on p^* were obtained by using lower limit on P and one probable error down on p. A NO has been placed in the hyperon columns where the momenta had to be changed more than $1\frac{1}{2}$ probable errors to accord with ionization. Parentheses have been used in the hyperon column either because of a NO or because the calculated Q is more than $1\frac{1}{2}$ probable errors from the accepted value. Where the secondary was heavily ionizing, the remarks column has "L-meson." Ionization is given in multiples of $I_{\min}$.

In a similar way it is not possible to distinguish between the two possibilities on the basis of Q values. The weighted mean of the p^* values on the basis of a θ decay is 208 ± 5 Mev/c. The mean of the basis of a $K_{\mu2}$ decay omitting the two cases of known π secondaries is 216 ± 8 Mev/c.

Of the 22 negative decay events, one is the cascade type $\Xi^-\to\Lambda^0+\pi^-$, already reported,[7] giving a Q value of 63 ± 9 Mev. Of the remaining 21 negative decay events, 17 have measurements of the transverse momentum to better than 15%. The distribution is shown in Fig. 3, and is seen to be consistent with a three-body distribution. However, the distribution of $\cos\theta^*$ for this particular sample, shown in Fig. 4, indicates an anisotropic distribution in the center of mass.

[7] Arnold, Ballam, Lindeberg, and van Lint, Phys. Rev. **98**, 838 (1955).

As will be discussed below, the p^* values for the negative K's appear to be consistent with a two-body decay process. The consistency of the p_T distribution with a three-body process is due in this case to the anisotropic decay in the center-of-mass system for our particular sample of particles. It is thus apparent that the use of p^* in the investigation of decay schemes offers a distinct advantage over the use of p_T, and that in fact the p_T plots may in particular cases be misleading. In the present analysis, classification of decay events has been on the basis of p^* values.

Of the 21 negative V decays, 10 allow measurement of p^* to within 35%. Of these 10, only two could be known hyperons within $1\frac{1}{2}$ probable errors. Of the remaining eight, only one has a value of p^* below 150 Mev/c. Thus an appreciable component of V^- observed in our apparatus are neither hyperons nor alternate τ decays. It is quite unlikely that all seven p^* values

TABLE II(*B*). Data on V^- events.

Event	P	p	θ	p^* $965\rightarrow\pi$	p^* $912\rightarrow\mu$	Q $\Sigma^-\rightarrow n+\pi^-$	Q $\Xi^-\rightarrow\Lambda^0+\pi^-$	$M(\pi,\pi^0)$	$M(\mu,\nu)$	Remarks
122–267	1180^{+420}_{-230}	22 ± 5	62.2 ± 1	312^{+110}_{-60}	245^{+85}_{-45}	128^{+45}_{-20}	115^{+42}_{-25}			*L* meson sec.; possibly Σ
124–681	>1.2*	480 ± 40	15.3 ± 0.7	>116	>116					
126–637	355 ± 35	110 ± 9	143 ± 1	243 ± 20	243 ± 20	NO	NO	1045 ± 45	941 ± 50	
128–690	>300	51 ± 6	132.4 ± 1	>135	>120					*L* meson sec.
132–197	>2.5*	585 ± 45	8.2 ± 0.5	>98	>83					
146–745	>300	90 ± 8	84.7 ± 1	>121	>113					
148–972	>2.5*	1250 ± 175	6.6 ± 0.5	>130	>130					V^0 in same picture
151–544	740^{+180}_{-160}	630^{+95}_{-75}	13.7 ± 0.5	201^{+45}_{-40}	211^{+45}_{-40}	279^{+90}_{-75}	356^{+90}_{-75}	942^{+250}_{-200}	767^{+225}_{-190}	
163–068	>1.2*		21.0 ± 1							
164–496	>1.2*	470 ± 75	21.1 ± 0.5	>163	>145					Probably not τ'
168–758	390^{+80}_{-75}	187 ± 9	83.9 ± 1	245 ± 25	241 ± 25	NO	NO	1065 ± 55	986^{+60}_{-55}	$I=2$–4
169–212	1360^{+400}_{-300}	560^{+100}_{-75}	21.3 ± 1	213^{+40}_{-30}	208^{+40}_{-30}	180^{+70}_{-60}	192 ± 70			Possibly Σ^-
170–837	498 ± 75	126 ± 20	29.7 ± 1	69 ± 10	63 ± 10	NO	NO			Sec. *L* meson; 3-body
173–480	>400	531 ± 75	15.5 ± 0.7	>122	>122					Secondary has deflection with $p_T=18$ Mev/c $(\pi-\mu)$?
173–885	746 ± 65	184 ± 13	60.3 ± 0.7	244 ± 18	231 ± 16	NO	NO	1049 ± 40	936 ± 30	V^0 in same picture
176–200	>2.5*		9.8 ± 0.5							
190–080	>2*	354 ± 16	20.0 ± 0.7	>165	>195					Probably not τ'
195–488	620^{+190}_{-140}	700 ± 50	18.5 ± 1	278^{+100}_{-75}	275^{+100}_{-75}	450 ± 120	NO	1350^{+350}_{-320}	1210^{+330}_{-280}	
198–149		114 ± 6	41.3 ± 0.3				63 ± 9			Ξ^-. (See reference 7.)
222–873	1000 ± 160	824^{+240}_{-180}	18.6 ± 0.5	270^{+80}_{-65}	266^{+80}_{-65}	454^{+220}_{-180}	477^{+220}_{-180}	1154^{+320}_{-220}	1158^{+320}_{-220}	
223–284	759 ± 55	78.2 ± 4	60.0 ± 0.5	200 ± 18	166 ± 18	NO 35 ± 4	NO	954 ± 30	790 ± 25	
223–890	>1.4*	637^{+60}_{-45}	17.5 ± 0.5	>180	>180					Probably not τ'

which are neither hyperons nor below 150 Mev/c are due to a three-body decay because of the strongly peaked distribution, although of course some could represent three-body decays. Some could be of the type $\theta^-\rightarrow\pi^-+\pi^0$, although no strong evidence exists for this particle. In fact, the average of the p^* values is high, being 231 ± 10 Mev/c.

The uncertainty with regard to the identification of the negative decays is consistent with the observations of some other workers.[8] However, one event is of interest in this regard. Event 223–284 is not consistent with known hyperon decay. It yields a mass $954_{-30}^{+30}\ m_e$ when interpreted as a $\theta^-\rightarrow\pi^-+\pi^0$ and a mass of $790_{-25}^{+25}\ m_e$ when interpreted as a $K_{\mu2}^-\rightarrow\mu^-+\nu$. Although the possibility of $K_{\mu3}^-\rightarrow\mu+?+?$ cannot be rules out, we have assumed the event as θ^- in analogy with observed θ^+. When this mass is averaged with the two θ^+ events described above, the resulting mass is $953\pm18\ m_e$. This may be compared with the value $952\pm11\ m_e$ obtained by the M.I.T. group[9] by means of range measurements of the charged secondaries.

In comparing the two groups, K^+ and K^-, it can be noted that the average primary momentum of the K^+ events whose p^*'s were determined was 575 Mev/c, and that of the K^-'s whose p^*'s were determined was 750 Mev/c. The total number of K^+ was about equal to the total number of K^-. However, the number of slow K^+ was about twice that of slow K^-. This is also consistent with the experience of other groups.[10] The secondaries of the K^+ events have traversed 225 g/cm² of lead in the lower chamber without observed interactions. (Recall, however, that one K^+ secondary produced a star in the gas of the upper chamber.) No similar information exists for the secondaries of the K^- events, although one such secondary shows a $\pi-\mu$ decay.

III. LIFETIME ANALYSIS

Lifetime measurements were undertaken on the groups of decay events described below. For this purpose it was necessary to establish in advance fiducial planes limiting the volume of observation in the chamber.

[8] B. Gregory (private communication).

[9] H. De Staebler, Jr., and B. V. Sreekantan, Phys. Rev. 98, 1520 (1955).

[10] Proceedings of the Rochester Conference, 1955 (Interscience Publishers, Inc., New York, 1955).

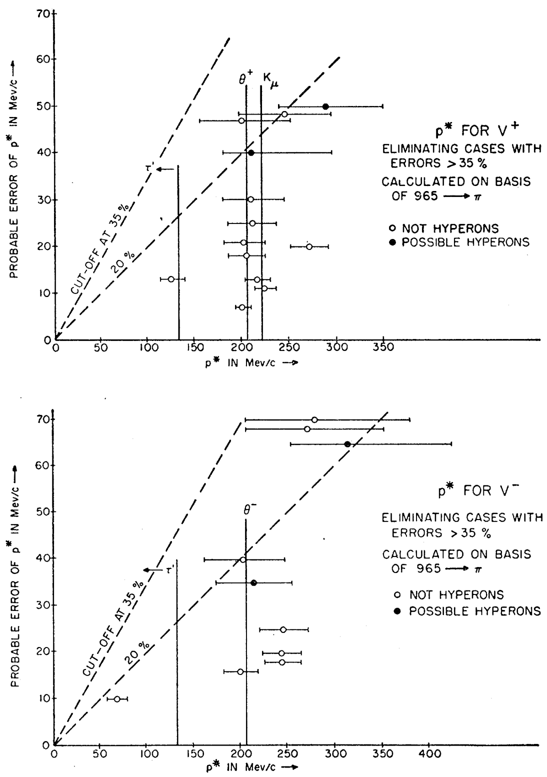

FIG. 5. Momenta of the charged secondaries in the c.m. system for V^+ and V^- events. These are plotted in order of increasing probable error in the momenta. The cut-off lines determine quickly how many events are eliminated by making the percentage error requirements more stringent.

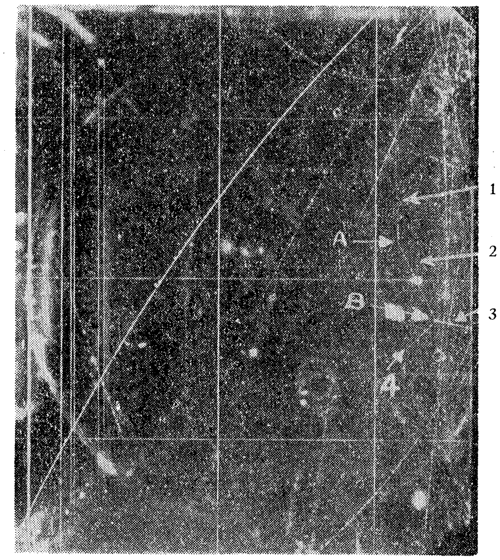

FIG. 6. Cloud-chamber photograph of a V^+ event in which the secondary creates a star in the argon gas of the chamber. The primary, track 1, decays at point A into the secondary, track 2, which forms a star at point B having a proton, track 3, and an L meson, track 4. There is also a blob due to a heavy recoil. The analysis is given in Table II under event 164–818.

These planes were chosen in such a way that within them there was no dependence of detection efficiency upon the point of decay. The planes chosen in the present experiment are shown in Fig. 7. This figure also includes the projection of each decay on the plane of the front glass. Also for the purpose of lifetime analysis, it is best to deal with homogeneous groups. It is therefore necessary to classify events according to the nature of the decay schemes indicated and thus to be able to make a statement as to the possible identities of the particles. With two exceptions all V^+ events within the planes allowed some measurements of p^* and therefore some statement as to possible identity. In the case of the V^- events, seven decays within the planes did not yield p^* values. Lowering the upper fiducial plane to a distance 12.5 cm above the center plane eliminated five of these. This procedure does not introduce bias, being only analogous to a shift in the zero of time in more conventional lifetime measurements; it allows a better identification of the nature of the sample.

The lifetime planes then contained 20 V^+ and 12 V^-, which were divided into three groups:

Group A: Particles which could not be two-body K decays, but could be $K_{\mu 3}$'s, τ's, or hyperons. These include the cascade event; a particle whose ionization and momentum indicate a mass >965 by more than two probable errors; and low and high p^*'s more than $1\frac{1}{2}$ probable errors from accepted θ^+ and K_μ p^* values. In this group were 7 V^+, 2 V^-.

Group B: Particles which could be two-body decays but which also could be hyperons, due either to the calculated p^*'s, or due to inability to measure p^*. In this group were 4 V^+ and 4 V^-.

Group C: Particles which could be two-body K decays and could not be hyperons or low p^* (i.e., three-body decays). In this group were 9 V^+ and 6 V^-, which are interpreted on the basis of known particles, as a possible mixture of θ and $K_{\mu 2}$.

The events in group A are obviously not a homogeneous group and are disregarded in further analysis.

The lifetime of groups B and C have been calculated using the method of maximum likelihood described by Bartlett.[11] For this purpose actual and potential path lengths X and D are measured and converted into corresponding proper times t and T according to

$$t=(x/v)(1-\beta^2)^{\frac{1}{2}}=x/\eta c, \quad \text{where} \quad \eta=P/M.$$

On the assumption of a single lifetime, τ, for a given group, it is possible to develop a function:

$$S=\frac{\displaystyle\sum_{i=1}^{M}\left[\frac{t_i}{\tau}-1+\frac{T_i}{\tau}\frac{\exp(-T_i/\tau)}{1-\exp(-T_i/\tau)}\right]}{\displaystyle\frac{1}{\tau}\left\{\sum_{i=1}^{M}\left[1-\frac{T_i^2}{\tau^2}\frac{\exp(-T_i/\tau)}{[1-\exp(T_i/\tau)]^2}\right]\right\}^{\frac{1}{2}}}.$$

[11] M. S. Bartlett, Phil. Mag. 44, 249 (1953).

This function has zero value for the most probable lifetime and unit standard deviation. For a given set of M decay events. S is evaluated for various values of $1/\tau$. If S is then plotted against $1/\tau$ the maximum likelihood value of τ is given by the point at which S is zero, and the value of S at any other value of $1/\tau'$, is the probability, in standard deviations, that τ is farther from the central value than τ'.

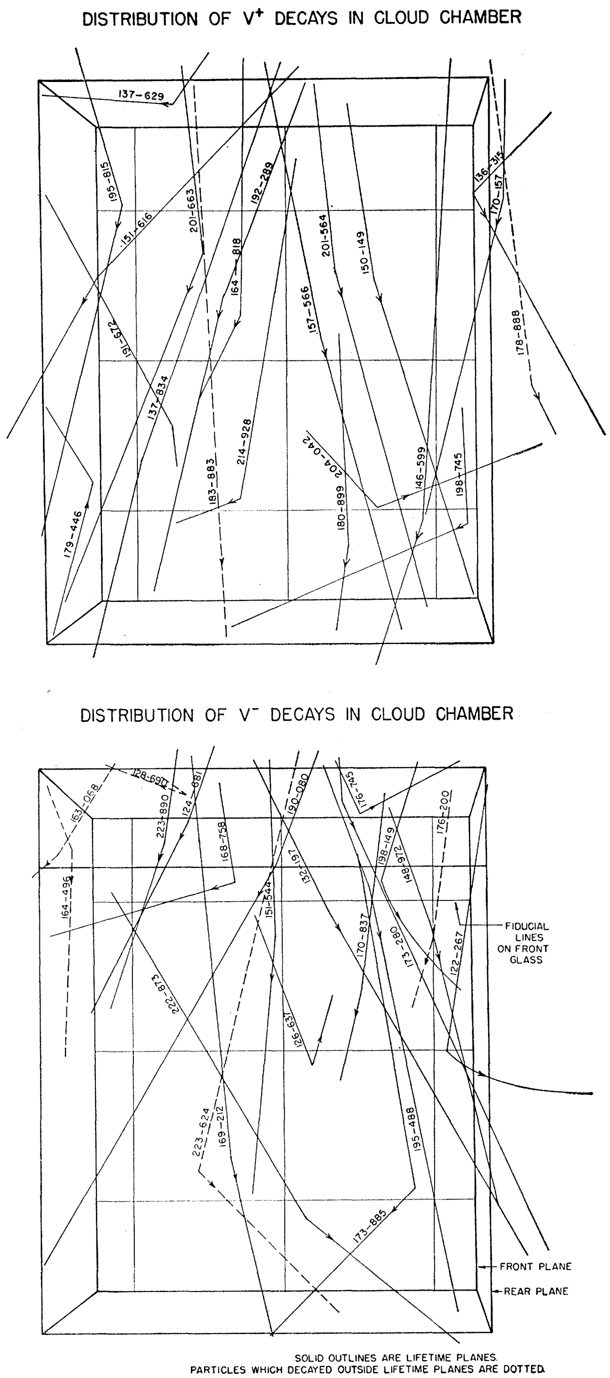

FIG. 7. Fiducial planes used for lifetime measurements.

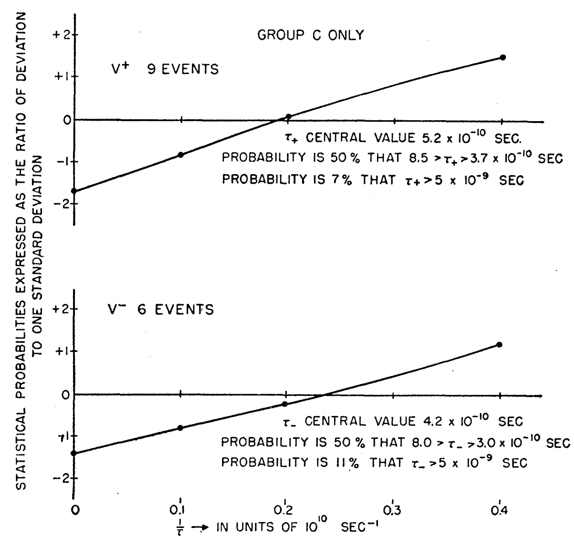

FIG. 8. The function S plotted against the reciprocal of the assumed lifetime for group C events. These events are those in which possible hyperons have been excluded.

The results of these measurements are shown in Figs. 8 and 9. From Fig. 8, the indicated lifetime of group C of the positive sample is 5.2×10^{-10} second with 50% probability for the interval $3.7<\tau<8.5\times10^{-10}$ second. The probability that τ is greater than 10^{-9} second is 20% and that τ is greater than 5×10^{-9} second is 7%. For the negative sample, the maximum likelihood value is 4.2×10^{-10} second with 50% probability limits for the interval $3.0<\tau<8.0\times10^{-10}$ second. The probability that τ is greater than 10^{-9} second is 20% and that τ is greater than 5×10^{-9} second is 11%.

These results are to be compared with emulsion[12] and other cloud-chamber work[13–15] that indicates

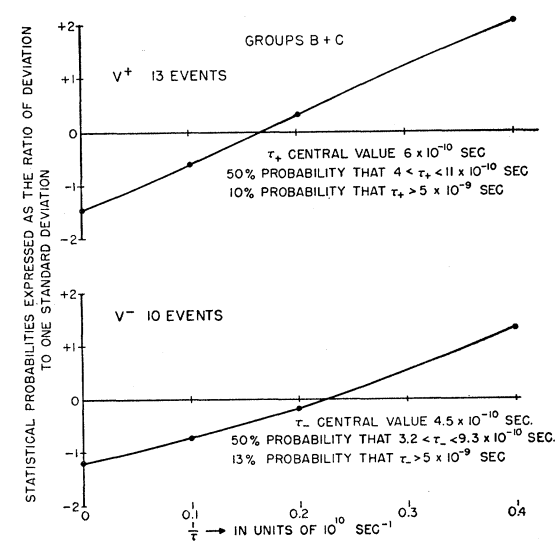

FIG. 9. The function S plotted against the reciprocal of the assumed lifetime for group $B+C$ events. These include possible hyperons.

generally longer lifetimes for K meson decays. The strong indications of the Paris group[13] for K lifetimes of the order of $>5\times10^{-9}$ sec and the results of Robinson[16] and Hyams[17] from direct timing experiments indicate that the $K_{\mu2}$ lifetime is the order of 10^{-8} second. The emulsion work indicates the τ lifetime to be the order of 5×10^{-9} second or longer.

The question arises as to whether there is a bias in the sampling of the present work that leads to an apparent short lifetime, or whether the lifetime obtained is the result of averaging a group with a long life such as that of the $K_{\mu2}$ with a group with a short lifetime, such as that suggested for the hyperon (5×10^{-11} second),[12] although there should be no hyperons in group C. The first of these questions concerns the bias of the chamber geometry and the selection criterion. Although the geometry of the chamber and generating layer of lead favors the detection of a lifetime of 5×10^{-10} over that of a lifetime of 10^{-8}, this fact in itself would not simulate a short lifetime. The p^* selection criterion should favor longer lifetime, since, if biased at all in application, it tends to select slower, longer living particles. We can investigate the effects of the p^* criterion by mixing the groups referred to above. In the first place, group A is obviously not homogeneous and in fact gives a negative value of $\Sigma_i(T_i/2-t_i)$. The effect of mixing groups B and C is shown in Fig. 9, where essentially the same results as before are obtained. In fact group B alone gives no indication of a shorter lifetime, and this group contains our "possible" hyperons.

The possibility that the lifetime found could result from an average of a group with a short lifetime and a group with a long lifetime can be investigated by calculating a lifetime for each event. Although each event has a very small statistical weight in itself, nevertheless such a procedure in our sample shows good grouping around the median result on a $1/\tau$ scale. There is thus no evidence that the value found for τ is due to such an average of widely separated groups.

We conclude therefore that among charged K mesons, there is a group with a lifetime which has about 90% probability of being shorter than 5×10^{-9} second. In view of the results of our group and other groups mentioned above, which indicate the $K_{\mu2}$ lifetime to be 10^{-8} second, and in view of the p^* results of the present sample, we conclude that the shorter lifetime is to be attributed to the $\theta^{\pm}$ particle.

It is of course possible that our particular small sample has not been representative of the mixtures of $K_{\mu2}$ and θ particles to be expected in cloud-chamber samples. If we take seriously the difference in lifetimes of the positive and negative samples, and attribute the difference to a mixture of $K_{\mu2}$ and θ's in the positive sample; calculate the geometrical bias of the chamber for the different lifetimes; and assume a momentum distribution at production $p\eta d\eta=(K/\eta^2)d\eta$, then we find about 90% probability that the ratio of θ^+/K_μ at production is greater than 1/6, and that our results are consistent with a production ratio of 1/1.

ACKNOWLEDGMENTS

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Note added in proof.—Since the writing of this paper several groups working with the Bevatron at the University of California Radiation Laboratory have reported examples of well-identified θ^+ mesons which have lived 10^{-8} second before decaying (see Preliminary Report of Pisa Conference on Elementary Particles, August, 1955). This is a factor of 15–20 longer than the value reported here. In this connection we might consider an interesting proposal made by T. D. Lee and Jay Orear (to be published). They suggest that only two K-mesons of somewhat different mass need be postulated to explain all our present information. They suppose that the heavier particle (e.g. the τ) can decay radiatively into the lighter one (e.g. the θ), with a lifetime of $\sim10^{-8}$ second. If the lighter particle has a lifetime short compared to this, it would *appear* to have the lifetime of the parent particle. We might then imagine that the θ particle has a natural lifetime ($\sim5\times10^{-10}$ second as reported here) and that it can also be produced directly in nuclear collisions. The θ's which are directly produced would then decay with their natural lifetime; those which arise from the radiative τ decay would then have an apparent lifetime equal to the τ. We wish to thank Dr. Lee and Dr. Orear for a preprint of their paper.

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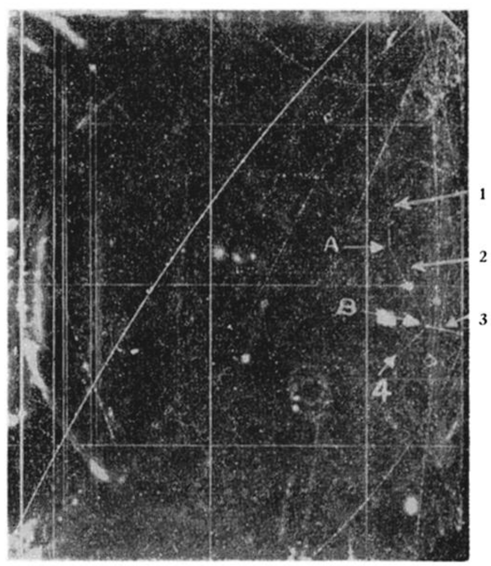

FIG. 6. Cloud-chamber photograph of a V^+ event in which the secondary creates a star in the argon gas of the chamber. The primary, track 1, decays at point A into the secondary, track 2, which forms a star at point B having a proton, track 3, and an L meson, track 4. There is also a blob due to a heavy recoil. The analysis is given in Table II under event 164–818.