ejection of neutrons and protons. They obtained $1/e$ values of 9.0 ± 1.0 Mev and 19.7 ± 1.5 Mev for Li and C respectively, indicating the same general trend among the light nuclei as observed in this experiment.

Wilcox and Moyer[14] find by bombarding light nuclei with 340-Mev protons and detecting two emerging protons in coincidence, that the protons in beryllium have a larger momentum than the protons in lithium. Beryllium and boron were seen to be rather similar.

V. ACKNOWLEDGMENTS

Sincere thanks are given to Professor A. C. Helmholz for his encouragement and advice throughout the course of this experiment. The theoretical discussions we had with Dr. Stephen Gasiorowicz and Dr. Warren Heckrotte were very helpful.

The assistance of Mr. Edward Knapp in taking some of the data is greatly appreciated. Finally we would like to thank Mr. James Vale and other members of the cyclotron crew for their help and cooperation during the runs.

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[14] J. M. Wilcox and B. J. Moyer, Phys. Rev. 99, 875 (1955).

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Cloud Chamber Investigation of Anomalous θ^0 Particles*

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Eighteen anomalous θ^0, ($\theta^0_{\rm anom}$), decay events observed in the California Institute of Technology magnet cloud chambers have been analyzed. Many of these decays are dynamically inconsistent with the $\tau^0\rightarrow\pi^++\pi^-+\pi^0$ scheme, but most are consistent with the decay processes: $\theta^0_{\rm anom}\rightarrow\pi^++\pi^-+\gamma$, $\pi^\pm+\mu^\mp+\nu$, and $\pi^\pm+e^\mp+\nu$. However, at least one event is inconsistent with each decay scheme. From the locations of the decays in the cloud chamber, the lifetime is found to be significantly longer than that of the normal θ^0 particle, called here the $\theta^0_{\pi2}$ particle. Other differences in the behavior of the $\theta^0_{\rm anom}$ and $\theta^0_{\pi2}$ particles were also observed in the (a) momentum distributions, (b) origin locations, (c) relative numbers of $\theta^0_{\rm anom}$ and $\theta^0_{\pi2}$ particles traveling upward, and (d) the types of V particles produced in association with the $\theta^0_{\rm anom}$ and $\theta^0_{\pi2}$. It is concluded that not all the $\theta^0_{\rm anom}$ decays can result from alternate decay modes of the $\theta^0_{\pi2}$. Moreover, many decays can be neither τ^0 decays nor alternate decays of the $\theta^0_{\pi2}$.

The characteristics of the θ^0_2 particle proposed by Gell-Mann and Pais are consistent with those of the $\theta^0_{\rm anom}$ particle, with the possible exception of the observed types of associations. An estimate was made of the relative number of $\theta^0_{\rm anom}$ to $\theta^0_{\pi2}$ particles observed to decay in the cloud chamber. If all $\theta^0_{\rm anom}$ decays are assumed to arise from decays of the θ^0_2 particle, then a lower limit for the θ^0_2 lifetime is found to be about 10^{-9} sec.

I. INTRODUCTION

Within the past few years, several groups have reported neutral V-particle decay events incompatible with either the Λ^0 or the $\theta^0_{\pi2}$ decay[1] schemes.[2–5] The general characteristics of these events which will be referred to as anomalous θ^0 decays ($\theta^0_{\rm anom}$) are as follows:

1. The positive secondaries of most of the events are observed to be lighter than a proton, and in no case is the mass of either secondary required to be greater than that of a π meson.
2. The Q values calculated on the basis of $\pi^++\pi^-$ secondaries are incompatible with the accepted $\theta^0_{\pi2}$ Q-value of 214 Mev,[5] and as a group are inconsistent with any unique Q value.
3. For many of the events, particularly those having the lowest Q values, the line of flight of the primary as determined by the vector sum of the secondary momenta does not pass through any of the visible interactions above the cloud chamber.

The characteristics listed in the foregoing strongly suggest that the $\theta^0_{\rm anom}$ decays involve at least one neutral secondary. A variety of decay schemes which have been suggested to account for these observations will be discussed later.

The events discussed in the present paper were obtained with the California Institute of Technology 21-in. and 48-in. magnetic cloud chambers triggered by cosmic-ray penetrating showers. The apparatus[6]

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* Assisted by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

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[1] The term $\theta^0_{\pi2}$ will be used to describe either the observed $\pi^++\pi^-$ decay or the neutral K particle from which this decay arises.

[2] Van Lint, Anderson, Cowan, Leighton, and York, Phys. Rev. 94, 1732 (1954).

[3] R. W. Thompson *et al.*, Phys. Rev. 90, 329 (1953); Huggett, Burwell, and Thompson, Phys. Rev. 98, 248 (1955); *Fourth Annual Rochester Conference on High-Energy Physics, 1954* (University of Rochester Press, Rochester, 1954).

[4] Arnold, Martin, and Wyld, Phys. Rev. 100, 1545 (1955); Ballam, Grisaru, and Treiman, Phys. Rev. 101, 1438 (1956).

[5] See Vol. 3 of Progress in Cosmic-Ray Physics (North Holland Publishing Company, Amsterdam, 1956).

[6] V. A. J. van Lint, Ph.D. thesis, California Institute of Technology. 1954 (unpublished).

and measuring techniques[7] have been described previously. Over a period of $3\frac{1}{2}$ years, about 80 000 photographs have been taken which have yielded 18 θ^0_{anom} decay events. These events have been analyzed to determine whether or not they exhibit the characteristics described above. The properties of the θ^0_{anom} particle itself were investigated as well as its possible decay schemes, and we find[8] that the θ^0_{anom} is not the same particle as that which gives rise to the $\theta^0_{\pi 2}$ decays.

List of Symbols

In the discussion of the data, the following symbols are used:

$\mathbf{P}_{\pm}$, $I_{\pm}$, $M_{\pm}$ = the momentum, ionization, and mass, respectively, of the positive or negative secondary,

$\mathbf{P}$ = the vector sum of the momenta of the charged secondaries,

$P_{\perp}$ = the component of $\mathbf{P}$ perpendicular to the line of flight of the θ^0_{anom} particle. $P_{\perp}$ is also equal to the component of momentum transverse to this line of flight of any neutral secondary or secondaries and is the same in both the laboratory and the center-of-mass systems,

$\mathbf{P}_0$, M_0 = the momentum and mass of the primary particle,

$Q(1,2)$ = the Q value computed on the assumption of a two-body decay into the charged secondaries 1 and 2,

θ = the included angle between the V^0 secondaries,

δ = the angle between the assumed line of flight of the θ^0_{anom} particle and the plane determined by the tracks of the charged secondaries,

$\alpha = (P_+^2 - P_-^2)/P^2$,

$\gamma\beta = P_0/M_0$.

Momenta and mass are expressed in energy units of Mev/c and Mev, respectively.

II. DATA

A group of neutral V events were selected from all observed decay events using one or more of the following criteria:

1. The ionization and momentum of the positive secondary restricted its mass to be less than the proton mass.
2. The quantity $P_- \sin\theta$ exceeded 118 Mev/c by an amount outside experimental error.[9]
3. $\alpha < 0$ for an event for which $P > 300$ Mev/c.[10]

No ordinary Λ^0 decay event can satisfy any of these criteria. In addition, it was required that no event could be interpreted as a charged V, $\pi-\mu$, or $\mu-e$ decay,[11] or a scattering. There are 256 events satisfying these criteria.

FIG. 1. Event No. 31855. The θ^0_{anom} event occurs in the midst of a shower, and is visibly out of line with the origin, indicating a relatively large momentum of the neutral secondary. Coming from the same origin is a probable K^+ meson, identified by its life in the chamber, 5.5×10^{-10} sec, which is much longer than the Σ^+ lifetime. The K^+ and θ^0_{anom} are probably associated.

The group of θ^0_{anom} particles which are described in this paper were selected from the above 256 events on the basis of the calculated $Q(\pi^+,\pi^-)$ value of the decay. A θ^0_{anom} decay was required to have a $Q(\pi^+,\pi^-)$ value differing by at least two standard deviations from the Q value (214 Mev) of the $\theta^0_{\pi 2}$ decay. Eighteen θ^0_{anom} decays were identified in this way. Some of the more striking examples of these events are shown in Fig. 1 through Fig. 4.

The results of measurements made upon the tracks of the secondaries are listed in Table I, and Table II gives some of the principal features of the events. Values of δ and P_T were obtained only for those events in which the existence of a clearly defined interaction above the chamber permitted an unambiguous choice of origin.

It is clear from examination of these tables that the present sample of events exhibit the same characteristics as those set forth in the introduction. In particular, the existence of a decay scheme in which two

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[7] Leighton, Wanlass, and Anderson, Phys. Rev. **89**, 148 (1953).

[8] Kadyk, Trilling, Leighton, and Anderson, Bull. Am. Phys. Soc. Ser. II, **1**, 251 (1956).

[9] J. P. Astbury, Nuovo cimento **12**, 387 (1954).

[10] Armenteros, Barker, Butler, and Cachon, Phil. Mag. **42**, 1113 (1951).

[11] One event (69328) could be a decay in flight of a μ^+ meson traveling upwards, but this interpretation seems very unlikely on the basis of the long lifetime of the μ^+ meson.

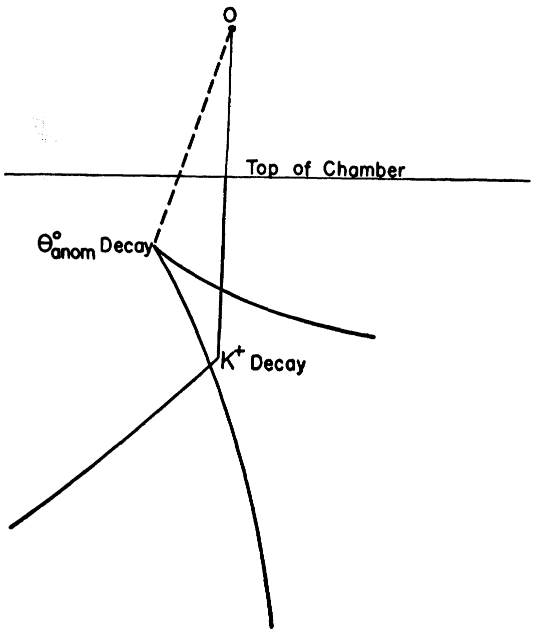

FIG. 2. Drawing of Event No. 31855. The origin of the θ^0_{anom} and K^+ particles are indicated by point 0. The line of flight of the θ^0_{anom} particle is indicated by the dashed line.

charged secondaries no heavier than a π meson and at least one neutral secondary are produced appears to be strongly indicated.

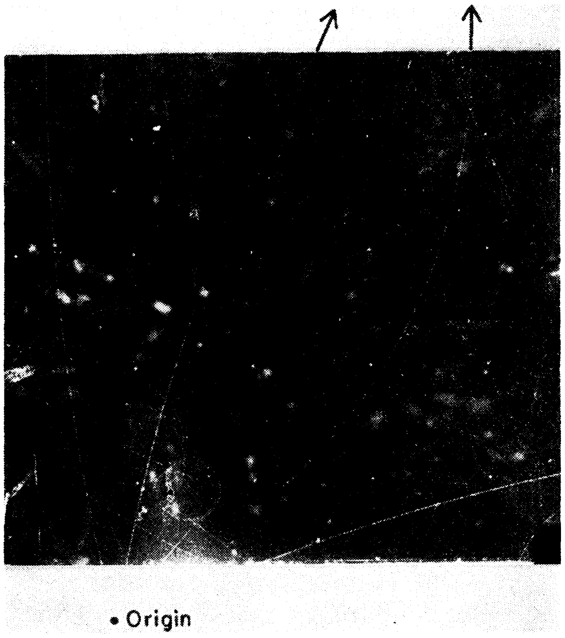

FIG. 3. Event No. 47202. This event is the only known example of a θ^0_{anom} decay wherein both secondaries can be identified with certainty as L mesons. Unfortunately, neither secondary can be identified as a π or μ meson. This is one of the few θ^0_{anom} events which could be a $\tau^0 \rightarrow \pi^+ + \pi^- + \pi^0$ decay. Also, this event is one of four θ^0_{anom} events in which the primary travels upward.

III. DECAY SCHEMES

In order to discuss the compatibility of the data with certain specific decay schemes, a mass for the primary particle must be assumed. In the following analysis, the primary mass has been chosen to be equal to the mass of all currently known K particles, $965m_e$;[12] a justification of this choice will be made later. Four specific decay schemes will now be discussed in detail.

(1) $\theta^0_{anom} \equiv \tau^0 \rightarrow \pi^+ + \pi^0 + 80$ Mev

Scheme (1) was an early suggestion to account for the θ^0_{anom} decay mode as the neutral counterpart of the well-known τ^+ and τ^- decays. Event 47202 may be evidence for the τ^0 decay, since this event is best interpreted as an example of decay (1) on the basis of dynamics and the identification of both secondaries as L mesons. However, evidence that not *all* of the

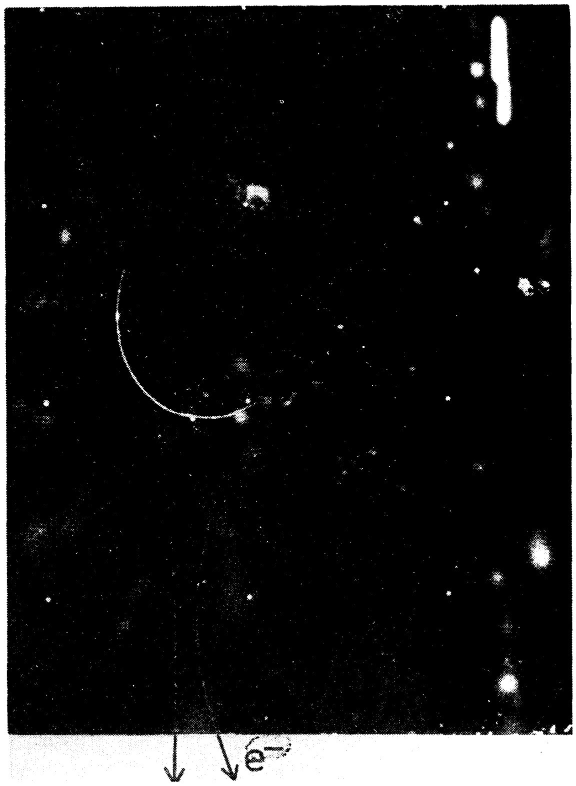

FIG. 4. Event No. 45766. In this unusual θ^0_{anom} event the negative secondary which is identified as an L meson is emitted very slowly and appears to stop in the front glass. An electron of momentum 49 ± 6 Mev/c appears to come from the end of the negative secondary track indicating that a $\mu^- - e^-$ decay occurs in the front glass. Since a π^- would almost certainly be absorbed in glass, this suggests that the θ^0_{anom} negative secondary is a μ^-. Unfortunately, it is impossible to prove that the secondary could not have undergone a $\pi^- - \mu^-$ decay inside the poorly illuminated region of about 1 cm width near the front glass; it is even possible for the secondary to have stopped in this region. Although no origin is present for this event, a lower limit on its life in the chamber was found to be 4.3×10^{-10} sec.

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[12] A. M. Shapiro, Revs. Modern Phys. 28, 164 (1956).

TABLE I. Main features of θ^0_{anom} secondaries.

Event No.	P_+ (Mev/c)	I_+ (I_{min})	M_+ (m_e)	P_- (Mev/c)	I_- (I_{min})	M_- (m_e)	θ (deg)
			48-in. chamber				
04480	105_{-23}^{+40}	<2.0	<320	120_{-12}^{+15}	<1.7	<280	118
19143[a]	250 ± 23	<1.5	<500	88 ± 5	1.6–3.2	170–320	40.7
31855	156 ± 6	<2.0	<400	88 ± 5	1.5–2.5	160–260	21.5
35045	132_{-22}^{+34}	<2.1	<330	330_{-110}^{+330}	<2.0	<1500	25.3
36537	...	<1.5	...	206 ± 12	<1.5	<400	92.9
36894	233 ± 19	<1.2	<310	75_{-14}^{+22}	1.5–3.0	110–330	118
37663	655_{-100}^{+145}	<2.0	<1800	360 ± 35	<2.0	<900	30.7
39522	562_{-150}^{+320}	<2.0	<1800	547_{-110}^{+180}	<2.0	<1700	17.2
45766	192 ± 12	<1.5	<350	30 ± 4	6.5–10.0	150–250	46.2
47202	101 ± 6	1.5–3.0	185–350	94 ± 6	1.5–3.0	170–320	61.8
56500	51_{-7}^{+10}	3.0–6.0	150–340	89_{-14}^{+20}	<2.6	<380	65.2
56791	355_{-55}^{+80}	<1.5	<800	120_{-30}^{+54}	2.0–4.0	150–500	77.6
57680	107 ± 11	<1.5	<300	610_{-150}^{+250}	<1.5	<1000	19.9
60134	226 ± 9	<2.0	<550	389_{-55}^{+76}	<1.5	<900	65.8
69328	$11.9\pm.9$	<1.5	<12	200_{-27}^{+36}	<1.5	<380	46.1
			21-in. chamber				
10475	594 ± 57	<2.0	<1500	1247_{-330}^{+460}	<2.0	<3000	16.0
12590[a]	595_{-110}^{+170}	<2.0	<1500	243_{-36}^{+50}	<2.0	<600	34.2
20923	554 ± 34	<2.0	<1400	198_{-33}^{+50}	<1.6	<400	52.2

[a] Given are the results of remeasurement of Events 19143 and 12590 which were published in reference 2. Event 15329 upon remeasurement seems to be somewhat dubious and has been omitted from this sample.

θ^0_{anom} decay events could be accounted for in this way has already been reported,[2,4] and further evidence on this point can be obtained from the present data.[8] One event, 69328, has an electron secondary, and cannot be a τ^0 decay. Four of the events listed in Table II have $Q(\pi^+,\pi^-)$ values greater than 100 Mev, and are quite unlikely to be τ^0 decays.

Additional proof that not all θ^0_{anom} decays are of the τ^0 decay scheme can be obtained from a study of Fig. 5. Curve A shows the relationship between $Q(\pi^+,\pi^-)$ and the momentum, $P^*(Q)$, of the neutral secondary in the c.m. system of the θ^0_{anom} particle, calculated for the τ^0 decay scheme. P^* is the upper limit to $P_\perp$; but, since in the center-of-mass system the neutral secondary is most likely to be emitted nearly at right angles to the line of flight, the measured values of $P_\perp$ should cluster close to the values of P^*. Out of the 10 points plotted, which represent the 10 θ^0_{anom} decay events having an origin and a measurable Q value, 9 fall outside curve A, and 4 lie outside by 2 or more standard deviations. In summary, we find 8 events clearly inconsistent with scheme (1), which may be taken as strong evidence that most of the θ^0_{anom} decay events are not of this type.

(2) $\theta^0_{\text{anom}} \rightarrow \pi^+ + \pi^- + \gamma + 214$ Mev

This decay scheme suggests a radiative decay of the $\theta^0_{\pi 2}$ particle. However, it has been shown[13] that it is exceedingly unlikely that a radiative correction to the $\theta^0_{\pi 2}$ decay could give rise to the low $Q(\pi^+,\pi^-)$ values observed. Perhaps, however, the γ ray may play a more fundamental role in this decay process and may be on an equal status with the other secondary particles.

Curve B in Fig. 5 shows P^* as a function of $Q(\pi^+,\pi^-)$ as calculated for the decay scheme (2). Although there are three points outside the curve B, none of these lies as much as two standard deviations from the curve. Except for one event with an identified electron secondary, the θ^0_{anom} decay events *could* all be of the decay scheme (2).

(3) $\theta^0_{\text{anom}} \rightarrow \mu^\pm + \pi^\mp + \nu + 238$ Mev

Recent work with emulsions has brought forth evidence[14] for the $K_{\mu 3}^+$ decay scheme as: $K_{\mu 3}^+ \rightarrow \mu^+$

TABLE II. Decay dynamics of θ^0_{anom} events.

Event No.	$Q(\pi^+,\pi^-)$ (Mev)	δ (deg)	$P_\perp$ (Mev/c)	Comments
		48-in. chamber		
04480	60_{-12}^{+21}	...	...	
19143	35 ± 2.5	29.5 ± 4	181 ± 30	Probable θ^0 association
31855	10.3 ± 1	33.5 ± 4	175 ± 18	Probable K^+ association
35045	32_{-20}^{+58}	11.7 ± 2	107_{-34}^{+100}	
36537	...	19.4 ± 9	~150	Travels upward
36894	96 ± 12	...	...	Travels upward
37663	112_{-18}^{+26}	2.4 ± 4	46_{-46}^{+70}	Probable V^+ association
39522	45_{-12}^{+16}	1.6 ± 2	90_{-47}^{+80}	
45766	34 ± 4	...	...	
47202	17 ± 5	16.4 ± 1	108 ± 5	Travels upward
56500	10_{-3}^{+4}	...	...	
56791	123_{-24}^{+37}	12.7 ± 3	89_{-24}^{+34}	Travels upward
57680	90_{-30}^{+48}	4.4 ± 2	73_{-26}^{+35}	
60134	152_{-21}^{+28}	...	...	
69328	8.3 ± 0.7[a]	3.3 ± 2	21 ± 14	Λ^0 decay also present; probably not associated.
		21-in. chamber		
10475	98_{-25}^{+42}	0.6 ± 5	49_{-47}^{+22}	
12590	92_{-21}^{+33}	3.5 ± 4	58 ± 50	
20923	147_{-14}^{+18}	...	...	

[a] The value given is $Q(\pi^-,e^+)$, since the positive secondary is identified as an electron.

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[13] S. B. Treiman, Phys. Rev. **95**, 1360 (1954).

[14] Yekutieli, Kaplon, and Hoang, Phys. Rev. **101**, 506 (1956); **101**, 1834 (1956).

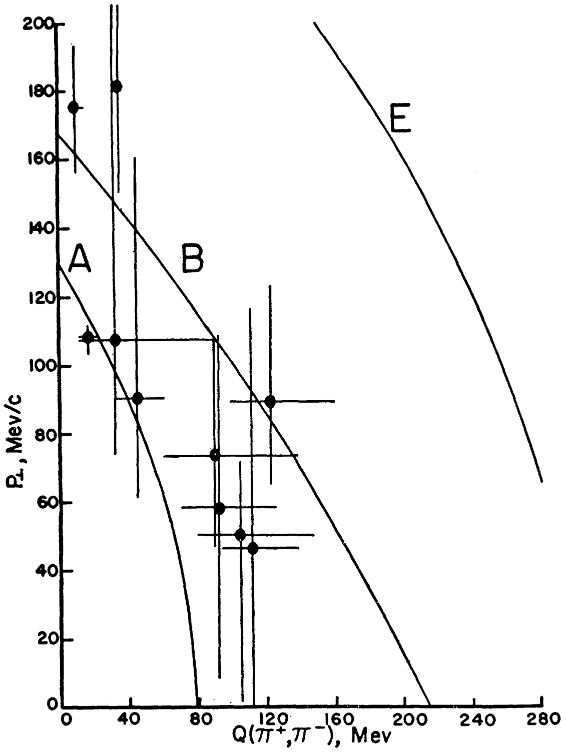

FIG. 5. $P_\perp$ and $Q(\pi^+,\pi^-)$ plotted for 10 θ^0_{anom} events. Each plotted point is shown as a small circle, and the errors in Q value and $P_\perp$ are indicated by horizontal and vertical lines, respectively, passing through the circle. Curve A shows the relationship between P^* and $Q(\pi^+,\pi^-)$ for the τ^0 decay scheme (1). Curve B is a similar curve for the decay scheme (2). Curve E is calculated for decay scheme (1), but assuming a primary mass of $1400m_e$ instead of $965m_e$.

$+\pi^0+\nu$. The scheme (3) is the neutral counterpart of this decay scheme.

The graph in Fig. 6 is similar to that of Fig. 5, except that the decay scheme (3) has been assumed. Since $Q(\pi,\mu)$ depends only slightly on which charged secondary is the π and which is the μ, the average of the two possible values of $Q(\pi,\mu)$ was plotted in Fig. 6. The agreement between the experimental points and the curve C is entirely satisfactory, and somewhat better than for scheme (2).

(4) $\theta^0_{\text{anom}}\rightarrow\pi^\pm+e^\mp+\nu+354$ Mev

This decay scheme may be the neutral counterpart of the well-known $K_{e3}{}^+$ decay scheme. Event No. 69328, which has an identified electron secondary, may be an example of scheme (4). There is also recent evidence[15] from work at Brookhaven for the existence of a V^0 particle decaying in this way. However, it appears that not all of the events presented here can be explained in this way, since in one event, 47202, *both* secondaries are clearly L mesons from momentum and ionization.

Figure 7 shows a graph similar to the previous ones, constructed by assuming scheme (4). For the five events in which either secondary could have been an electron, the $Q(\pi,e)$ value lying closest to the P^* curve was chosen. Again, the events are evidently compatible with scheme (4) on a dynamical basis.

The conclusion which is drawn from the foregoing analysis is that most of the present events cannot be explained by the τ^0 decay scheme (1), but that most, but not all, of the data are consistent with each of the decay schemes (2), (3), and (4).

If the θ^0_{anom} particle is assumed to be a K meson, the choice of its mass as $965m_e$ is reasonable in view of the close agreement between all currently established K-particle masses. However, some additional justification of this mass for the θ^0_{anom} particle can be made on the basis of the previously discussed graphs. The curves A through D in the graphs are rather sensitive to the value assumed for the primary mass. Furthermore, as previously noted, most of the experimental points should cluster close to but below these curves. Thus, if the mass is assumed too small or too large, the data become incompatible with the curves. For example, curve E in Fig. 5 based upon decay scheme (1) with an assumed primary mass of $1400m_e$ is clearly incompatible with the experimental points.

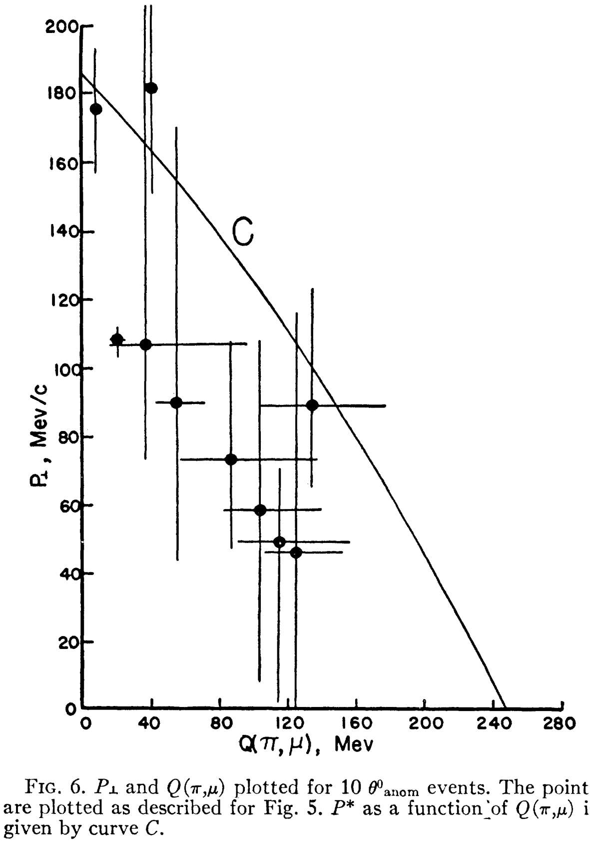

FIG. 6. $P_\perp$ and $Q(\pi,\mu)$ plotted for 10 θ^0_{anom} events. The points are plotted as described for Fig. 5. P^* as a function of $Q(\pi,\mu)$ is given by curve C.

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[15] Lande, Booth, Impeduglia, and Lederman, Brookhaven National Laboratory Report, BNL 2857 (unpublished).

The interpretation of the θ^0_{anom} decays as some form of hyperon decay into a neutron secondary is a possibility that should not be overlooked. However, if the present data are to be explained in this way, one would expect to find a comparable number of corresponding events with a proton secondary, which would be observed as anomalous Λ^0 decays. Few if any such anomalous Λ^0 events have ever been detected.

A π^0 internal conversion into a wide-angle electron pair may have the general appearance of a θ^0_{anom} decay if both electrons are too fast to be identified. The π^0 might, for example, be produced in the neutral decay mode of a Λ^0. However, it is found that $\frac{2}{3}$ of the present events cannot have originated from π^0 conversion, by an argument based upon the π^0-decay dynamics and mass estimates of the secondaries.

IV. θ^0_{anom} PARTICLE

In the previous discussion, it was shown that the θ^0_{anom} decay dynamics are consistent with a primary mass equal to the usual K-particle mass of $965m_e$, which suggests that θ^0_{anom} decays may arise from alternate decay modes of $\theta^0_{\pi 2}$ particles. This possibility has been investigated in a number of ways.

A. Lifetime Analysis

Fifteen of the θ^0_{anom} decay events were found to be suitable for a lifetime analysis, which was made according to the maximum likelihood procedure of Bartlett.[16] In making the lifetime calculations it was necessary (a) to assume a particular decay scheme for each event, and (b) to calculate a value of $\gamma\beta$ for each θ^0_{anom} particle:

(a) The decay scheme (3) was assumed as the basis for the lifetime calculations. Although none of the schemes (2), (3), and (4) has been firmly established, it was found that the result of the lifetime calculation would not have differed significantly if either scheme (2) or (4) had been assumed instead.

(b) Since the momentum of the neutral secondary is unknown, $\gamma\beta$ cannot be determined directly. For each event, $\gamma\beta$ can have any value within certain limits, or if an origin is present so that $P_\perp$ can be found, $\gamma\beta$ is double-valued. This difficulty was resolved by performing two lifetime calculations—assuming first the maximum $\gamma\beta$ for each event, giving the smaller lifetime value, and then the minimum $\gamma\beta$ for each particle, which yields a somewhat larger value for the lifetime.

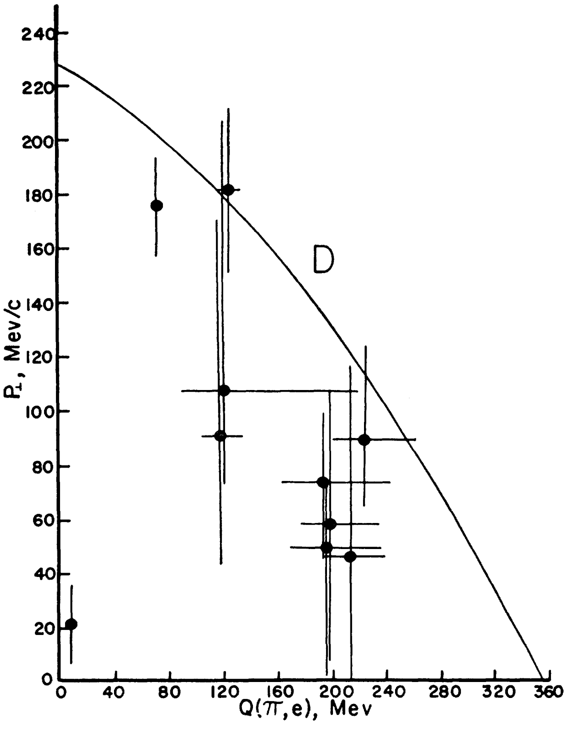

FIG. 7. $P_\perp$ and $Q(\pi,e)$ plotted for 10 θ^0_{anom} events. The points are plotted as described for Fig. 5. P^* as a function of $Q(\pi,e)$ is given by curve D.

The θ^0_{anom} decay events were selected not by requiring a specific decay scheme, but rather by requiring them to be incompatible with the $\theta^0_{\pi 2}$ and Λ^0 decay schemes. For this reason, it is quite possible that the present data represent a mixture of different particles having different lifetimes (see Sec. VI). Accordingly, the calculated mean lifetime value is called τ_{Av}, and is some "average" of the lifetimes of the particles present. If a mixture of particles is involved, not all lifetimes can be greater than the upper limit on τ_{Av}, and not all lifetimes can be smaller than the lower limit on τ_{Av}. Figure 8 shows the resulting likelihood and S functions[16] plotted against reciprocal mean lifetime. The result obtained is:

$$\underset{(\max \gamma\beta)}{(2.9_{-1.0}{}^{+3.0})\times 10^{-10}\ \text{sec}} < \tau_{\text{Av}} < \underset{(\min \gamma\beta)}{(4.4_{-1.6}{}^{+5.3})\times 10^{-10}\ \text{sec.}}$$

Standard deviations reflecting the statistical uncertainty are quoted on each lifetime limit. It should be emphasized that the above result does not necessarily preclude the presence of long-lived particles, because (a) this sample probably does contain a mixture of particles of different lifetimes, and (b) even if the sample consists of particles of a unique lifetime, the statistics are insufficient to rule out a relatively long lifetime.

The curves G and I in Fig. 8 provide a quantitative measure of the agreement of the data with any assumed value for the lifetime. When the Caltech value for the $\theta^0_{\pi 2}$ mean lifetime, 1.3×10^{-10} sec, is chosen, then curve G for $\gamma\beta$ max gives $S=2.5$ standard deviations. Consequently, the observed lifetime data are incompatible with the hypothesis that this lifetime sample consist entirely of particles having the $\theta^0_{\pi 2}$ lifetime, to a 98% significance level. Moreover, this significance level

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

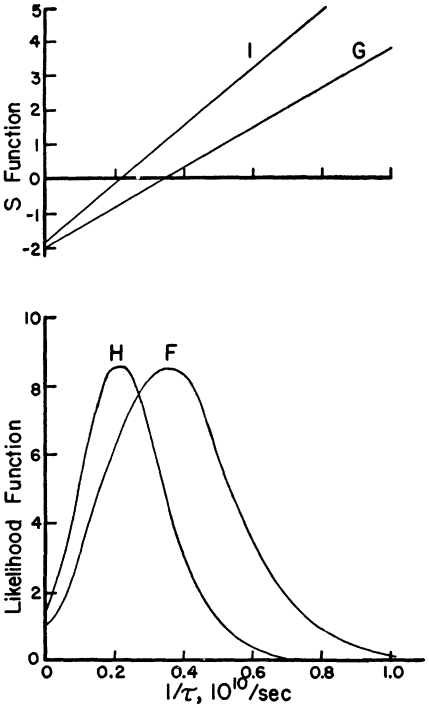

FIG. 8. Likelihood functions and S functions for 15 θ^0_{anom} events. Curves F and G are calculated assuming $\gamma\beta_{\max}$ for each event, while curves H and I are based on $\gamma\beta_{\min}$ for each event.

is raised if the $\theta^0_{\pi 2}$ lifetime is actually less than 1.3×10^{-10} sec; this is likely to be the case if the sample of $\theta^0_{\pi 2}$ decays previously used for the lifetime determination was contaminated with a number of high-Q θ^0_{anom} decays, which are experimentally indistinguishable. The above results are taken as evidence for the existence of a θ^0_{anom} particle having a lifetime substantially greater than the $\theta^0_{\pi 2}$ lifetime and for the conclusion that not all θ^0_{anom} decays can be alternate decays of the $\theta^0_{\pi 2}$ particle.

B. Other Evidence

The conclusion drawn from the lifetime analysis is also supported by a comparison of other features of the $\theta^0_{\pi 2}$ and θ^0_{anom} decays.

1. *Momentum Distributions of $\theta^0_{\pi 2}$ vs θ^0_{anom} Particles*

In order to test the hypothesis that the $\theta^0_{\pi 2}$ and θ^0_{anom} decays arise from the same particle, a comparison was made of the momentum distributions in the two cases. Care was taken to avoid bias due to the three-body nature of the θ^0_{anom} decay. The resulting distributions are shown in Fig. 9 from which it is clear that the θ^0_{anom} particles possess a lower average momentum than do the $\theta^0_{\pi 2}$ particles. A statistical test based on the numbers of primary particles of each type having P_0 above and below 800 Mev/c shows with 99% confidence that the data are inconsistent with the assumption that the momentum distributions are actually the same.

2. *Origin Distributions*

A comparison of the origin locations for $\theta^0_{\pi 2}$ and θ^0_{anom} decay events was also made. The origins of low-momenta θ^0_{anom} particles were situated, on the average, higher up in the producing layer of lead above the cloud chamber than were the origins of $\theta^0_{\pi 2}$ particles in the same momentum range. Again, care was taken in making the comparison to allow for the three-body nature of the decay, and to be sure of correct origin identification. Assuming the $\theta^0_{\pi 2}$ lifetime, a calculation was made of $\pi(\theta^0_{\pi 2})$ for each event found to be suitable for the analysis, where $\pi(\theta^0_{\pi 2})$ is the probability of decay within the chamber. For nine out of the ten $\theta^0_{\pi 2}$ events, $\pi(\theta^0_{\pi 2})$ was greater than 30 percent, while in only three out of the eight θ^0_{anom} events was $\pi(\theta^0_{\pi 2})$ greater than 30 percent. There is less than one chance in fifty that the values of $\pi(\theta^0_{\pi 2})$ should be divided as asymmetrically as this if the $\theta^0_{\pi 2}$ and θ^0_{anom} decays arise from the same parent particle.

3. *Upward Moving θ^0_{anom} Particles*

One interesting feature of the θ^0_{anom} decays is that the θ^0_{anom} particle is often found to be traveling upward, while $\theta^0_{\pi 2}$ particles do not appear to share this feature. These upward-moving particles are readily detected with the three cloud chambers in the 48-in. magnet, since interactions frequently occur in the lead plates which separate the chambers. Particles resulting from such an interaction may therefore be seen in the chambers above and below the interaction. To determine the direction of travel of the θ^0_{anom} particle, it is, of course, necessary to make allowance for the neutral secondary in the three-body decay process. Of the 18 θ^0_{anom} decays, 4 travel upward, while out of 238 $\theta^0_{\pi 2}$ decays, only one appears to be going upward, and it is possible that this one event is really a high-Q θ^0_{anom} decay. If the θ^0_{anom} decay were merely an alternate decay of the $\theta^0_{\pi 2}$, then the direction of travel should be the same for both types of decay, and it is exceedingly unlikely that in such a great fraction of the events the θ^0_{anom} particle should go upward. In view of the fact that upward-moving particles would be expected to move relatively slowly, the absence of $\theta^0_{\pi 2}$ can be attributed to decay before entering the chamber because of their short lifetime, while if the θ^0_{anom}

TABLE III. Associations of θ^0 and θ^0_{anom}.

		θ^0	θ^0_{anom}
Group A	Λ^0	10	0
	V^0	9	0
	V^-	4	0
Group B	K^+	1	1
	V^+	1	1
	θ^0	0	1
	K^-	0	0
	$V^\pm$	1	0

lifetime were relatively long, the upward moving ones would have a large probability of decaying within the chamber.

4. *Associated Decay Events*

If the $\theta^0_{\pi2}$ and θ^0_{anom} decays arise from the same particle, then they should be associated with the same types of *V*-particle decays. Among the 18 θ^0_{anom} events, there are 3 in which another *V*-particle decay is seen in the same photograph. Although the nature of the three-body decay makes more uncertain the assignment of the correct origin for a θ^0_{anom} particle, each of these θ^0_{anom} events is consistent dynamically with the origin from which the other *V* particle comes. An investigation was made to determine the probability that the θ^0_{anom} and *V* particles in each of these events might not actually have been produced in association, but might have arisen instead from different origins which happened to be closely spaced. For this purpose, an examination was made of all other events where two or more *V*-particle decays are seen together. Only a small fraction of such events was found in which the particles were not actually associated, and from this it was deduced that probably all 3 of the $\theta^0_{\text{anom}}-V$ events are cases of genuine associated production.

Table III summarizes the observed types of associations for the $\theta^0_{\pi2}$ and θ^0_{anom} particles. Even though the statistics are somewhat limited, the differences in the associations are rather striking.

In order to express in more quantitative terms the apparent difference between the associations, a statistical test was made in the following way. Two groups of associated events were formed: group *A* consisted of the most prevalent associations of the $\theta^0_{\pi2}$, *viz.*, the Λ^0, V^0, and the V^-, while group *B* consisted of the remaining associations in Table III. While 23 out of the 26 $\theta^0_{\pi2}$ associated decay events occur in group *A*, none of the 3 θ^0_{anom} associations falls in group *A*. If we assume that the types of associations should be the same for the $\theta^0_{\pi2}$ and θ^0_{anom} events, then the probability that a disparity as great as this should exist between the observed associations is only 0.005. However, a preliminary study has shown that biases resulting from a large difference in lifetime of the θ^0_{anom} and $\theta^0_{\pi2}$ particles may account for the observed differences in the associations. Further experimental results on associations are required to clarify this situation.

In summary, from the foregoing analysis it is concluded that the θ^0_{anom} decays and $\theta^0_{\pi2}$ decays are not alternate decay modes of the same particle.

C. Mixture of τ^0 Decays and Alternate Decays of $\theta^0_{\pi2}$

The previous discussion does not rule out the possibility that the data may be explained partly by the τ^0 decay scheme, and partly as an alternate decay mode of the $\theta^0_{\pi2}$. However, some of the previous arguments may also be used to show that this explanation is not adequate, since a number of θ^0_{anom} decays do not fit either interpretation:

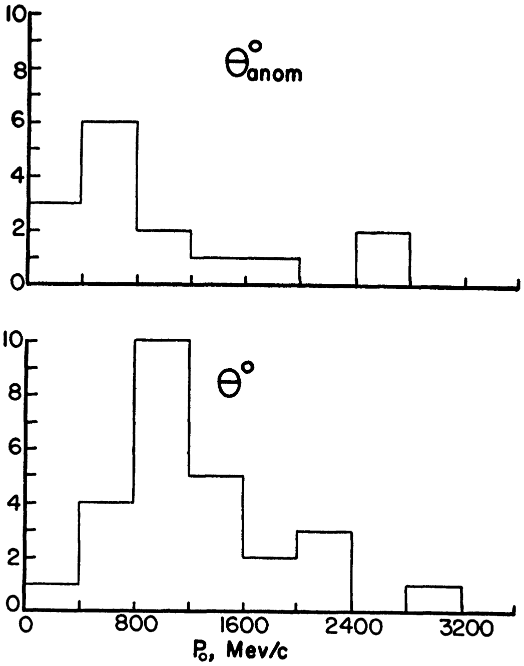

FIG. 9. Momentum distributions for 26 θ^0 and 15 θ^0_{anom} events. $\gamma\beta_{\text{max}}$ was assumed for each θ^0_{anom} event. The contrast between the distributions would be even more pronounced if $\gamma\beta_{\text{min}}$ is assumed for each event.

(1) The lifetime has been calculated from 10 θ^0_{anom} events which are inconsistent with the τ^0 decay scheme by at least one standard deviation in *Q* and $P_\perp$ from the values appropriate to the τ^0 decay scheme. The resulting likelihood function and *S* function are shown in Fig. 10. Even though the statistics are limited, it was found that with 94% significance, the lifetime data are inconsistent with the $\theta^0_{\pi2}$ lifetime of 1.3×10^{-10} second.

(2) As was pointed out in Sec. IV.3.3, the four events in which the θ^0_{anom} is traveling upward are quite unlikely to be alternate decays of a $\theta^0_{\pi2}$. However, two of these events are also dynamically inconsistent with the τ^0 decay scheme by more than two standard deviations, and a third has a $Q(\pi^+,\pi^-)$ value greater than 80 Mev by more than one standard deviation.

(3) In the previous section, it was shown that the observed associations are very unlikely if the θ^0_{anom} events with associations were alternate decays of the $\theta^0_{\pi2}$. Moreover, the decay dynamics are such that all three θ^0_{anom} events with associated decays are inconsistent with the τ^0 decay scheme by at least two standard deviations.

From these arguments, one concludes that all θ^0_{anom} events cannot be explained as simply a combination

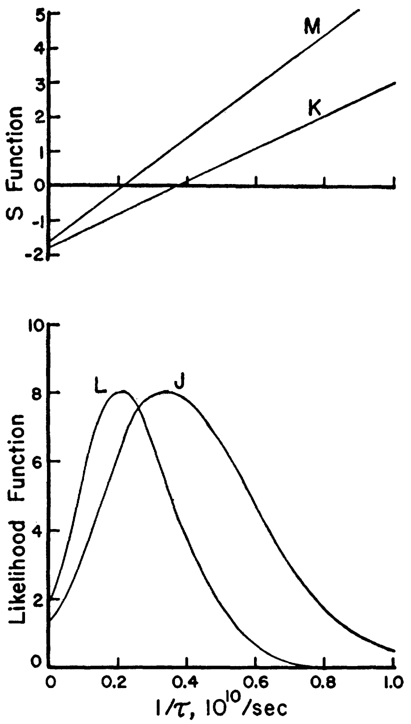

FIG. 10. Likelihood and S functions for 10 events which cannot be τ^0 decays of scheme (1). For curves J and K, $\gamma\beta_{\max}$ was assumed for each event, while for curves L and M, $\gamma\beta_{\min}$ was assumed for each event.

of the τ^0 decay scheme and the alternate decay modes of the normal $\theta^0_{\pi 2}$.

V. INTERPRETATION AS θ^0_2 PARTICLES

Previous experiments performed on associated production[17] have suggested that the θ^0 is distinct from its antiparticle, $\bar{\theta}^0$, in the production process. Gell-Mann and Pais[18] have shown that if this is so, there may result some important consequences concerning the nature of the θ^0. One consequence is the prediction of a neutral K particle (called θ^0_2 here) having the same mass, spin, and parity as the $\theta^0_{\pi 2}$ but with a lifetime longer than that of the $\theta^0_{\pi 2}$.

According to this theory, in the decay process the θ^0 is regarded as a particle "mixture," consisting half of one type of particle called θ^0_1, whose predominant decay mode is into $\pi^+ + \pi^-$, and half of another particle type called θ^0_2, for which the $\pi^+ + \pi^-$ is forbidden. The θ^0_2 probably undergoes a three-body decay and has a lifetime much longer than that of the θ^0_1, whose lifetime is, of course, just that deduced from the observed $\theta^0_{\pi 2}$ decays. Except for the difference in decay modes and lifetimes, the θ^0_1 and θ^0_2 particles are supposed to be identical in mass, momentum distribution, angular distribution, and in all other such features not related to the decay process.

It is apparent that most of the features of the θ^0_{anom} events can be readily explained by interpreting the θ^0_{anom} as the θ^0_2, and the $\theta^0_{\pi 2}$ as θ^0_1: the θ^0_{anom} decays clearly have three or more secondary particles, and the lifetime is longer, perhaps much longer, than that of the $\theta^0_{\pi 2}$. Furthermore, a pronounced lifetime difference between the $\theta^0_{\pi 2}$ and θ^0_{anom} might well be sufficient to account for the observed differences in the momentum distributions and origin locations, the comparatively large fraction of θ^0_{anom} particles traveling upward, and perhaps even for the apparent differences in associations of the $\theta^0_{\pi 2}$ and θ^0_{anom}.

Special attention should be given to the data on associated decays, for there should be no difference between the associations for the θ^0_1 and θ^0_2. The considerable difference between the observed types of associations shown in Table III appears to be inconsistent with the assumption that the θ^0_1 is to be identified with the $\theta^0_{\pi 2}$ and the θ^0_2 with the θ^0_{anom}. As pointed out earlier, such a difference in associations may be the effect of a lifetime bias. Further experimental work is required to elucidate this matter.

VI. RELATIVE NUMBER OF θ^0_{anom}

The 18 θ^0_{anom} particles which have so far been discussed presumably constitute only a part—perhaps a small part—of the θ^0_{anom} which actually decayed inside the chamber. This is partly because θ^0_{anom} decays cannot be distinguished from ordinary $\theta^0_{\pi 2}$ decays unless their Q value, coplanarity, or momentum balance deviate markedly from the values expected for $\theta^0_{\pi 2}$ decay. Accordingly, it is of great interest to try to estimate the relative number of θ^0_{anom} and $\theta^0_{\pi 2}$ decays which actually occurred within the cloud chamber. Since certain decay modes are much more readily identified than others, it was necessary to consider the effects of various biases arising from such characteristics as lifetime and the three-body nature of the θ^0_{anom} decay. Because of the relatively short and long lifetimes of the $\theta^0_{\pi 2}$ and θ^0_{anom}, respectively, most of the $\theta^0_{\pi 2}$ particles tend to decay near the top of the chamber, whereas θ^0_{anom} decays are distributed more or less uniformly throughout the chamber. However, a particle which decays near the bottom of the chamber can seldom be classified because of the short secondary track lengths. Therefore, only particles which decayed in the upper half of the chamber were used for this analysis. The separation into θ^0_{anom} and $\theta^0_{\pi 2}$ decays was then made on the basis of the apparent Q value of each given event, using where necessary a statistical relationship between the momentum of the particle and the angle between the secondary tracks for $\theta^0_{\pi 2}$ decay. Correction for θ^0_{anom} decays whose Q value are indistinguishable from $\theta^0_{\pi 2}$ decays was made assuming that statistical factors alone determined the θ^0_{anom}

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[17] Walker, Preston, Fowler, and Kraybill, Phys. Rev. **97**, 1086 (1955). The absence of the reaction $n+n \rightarrow \Lambda^0 + \Lambda^0$, together with the observation of the reaction $\pi^- + p \rightarrow \Lambda^0 + \theta^0$, indicates that the θ^0 and $\bar{\theta}^0$ are distinct.

[18] M. Gell-Mann and A. Pais, Phys. Rev. **97**, 1387 (1955).

Q-value distribution. (With this assumption, one expects most θ^0_{anom} to exhibit a $Q(\pi^+,\pi^-)$ value of about 80 Mev, which is easily distinguished from that of the $\theta^0_{\pi 2}$.)

$\theta^0_{\pi 2}$ and θ^0_{anom} events were therefore selected according to criteria which eliminated most of the principal biases due to these effects. The result of this analysis is given below,

$$N(\theta^0_{\text{anom}})/N(\theta^0_{\pi 2})=0.1_{-0.04}^{+0.1},$$

where N represents the *true* number of decays of each type within the cloud chamber. Estimated probable errors are assigned to the result.

A lower limit on the θ^0_2 lifetime can now be found if it is assumed that (1) the θ^0_2 and θ^0_1 occur in equal numbers at production, (2) the lifetime of the θ^0_2 is at least somewhat longer than the average gate time of the θ^0_2 particles, and (3) all θ^0_1 decay by the $\pi^+ + \pi^-$ mode. The value obtained was

$$\tau(\theta^0_2) \gtrsim (0.6_{-0.3})\times 10^{-8}\text{ sec},$$

where a probable error has been assigned. This value has not been given an upper limit as this would require knowledge of how many θ^0_{anom} decays arise from particles other than the θ^0_2. If it is assumed that *all* θ^0_{anom} decays are θ^0_2 decays, an upper limit on $\tau(\theta^0_2)$ is $\sim 10^{-7}$ sec.

Because of the large statistical uncertainty, the lower limit on $\tau(\theta^0_2)$ is not completely inconsistent with τ_{Av}, but is sufficiently greater than τ_{Av} to indicate that some short-lived events may be present in our θ^0_{anom} lifetime sample. It is quite possible that the θ^0_1 may occasionally decay by a three-body mode (e.g., $\pi+\mu+\nu$ or $\pi+e+\nu$). Such decays would be observed as θ^0_{anom} events and would tend to make the measured lifetime shorter than the lifetime of the θ^0_2.

SUMMARY

The above analysis of 18 θ^0_{anom} decay events indicates that these involve 3 or more secondary particles, and probably arise from a K^0 meson having approximately the mass of presently established K particles. Most of the decays cannot be explained by the scheme $\tau^0 \rightarrow \pi^+ + \pi^- + \pi^0$. However, all are consistent with the schemes $\theta^0_{\text{anom}} \rightarrow \pi^+ + \pi^- + \gamma$ and $\theta^0_{\text{anom}} \rightarrow \pi^\pm + \mu^\mp + \nu$, with the exception of one decay having an identified electron secondary. All the decays are also consistent with the scheme $\theta^0_{\text{anom}} \rightarrow \pi^\pm + e^\mp + \nu$, with the exception of one which has two identified L-meson secondaries. The θ^0_{anom} events cannot be entirely explained by merely a combination of τ^0 decays and alternate decay modes of the $\theta^0_{\pi 2}$ particle.

The lifetime of the θ^0_{anom} particle is longer than that of the $\theta^0_{\pi 2}$ particle. There are also observed differences in momentum distributions and origin locations for the θ^0_{anom} and $\theta^0_{\pi 2}$ particles, and a large disparity exists in the fraction of each type of particle found traveling upward in the cloud chamber. However, a θ^0_{anom}-particle lifetime much longer than the lifetime of the $\theta^0_{\pi 2}$ particle can readily explain all these differences. The existence of the θ^0_1 and θ^0_2 particles proposed by Gell-Mann and Pais is in accord with these observed results. However, there is also found to be a considerable difference between the types of particles observed in association with the θ^0_{anom} and $\theta^0_{\pi 2}$ particles. This difference may be partly the effect of a lifetime bias. Since the validity of the theory of the θ^0_1 and θ^0_2 particles bears crucially upon the observed associations, it is important that further experimental work be done to clarify this matter.

The ratio of the numbers of θ^0_{anom} to $\theta^0_{\pi 2}$ decays observed in the cloud chamber is $0.1_{-0.04}^{+0.1}$, and is used to set a lower limit on the lifetime of the θ^0_2 as $(0.6_{-0.3})\times 10^{-8}$ sec.

ACKNOWLEDGMENTS

We wish to thank Dr. E. W. Cowan for his helpful comments and permission to use several θ^0_{anom} events from his chamber. We are also indebted to Dr. C. A. Rouse for the use of an excellent event obtained by him, and to Mr. Gerry Neugebauer and Mr. Robert Luttermoser for their generous assistance in numerous ways.

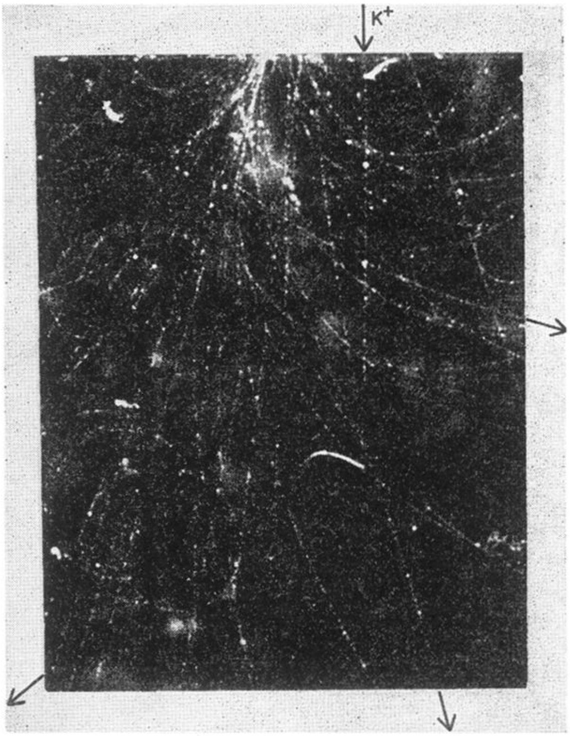

FIG. 1. Event No. 31855. The θ^0_{anom} event occurs in the midst of a shower, and is visibly out of line with the origin, indicating a relatively large momentum of the neutral secondary. Coming from the same origin is a probable K^+ meson, identified by its life in the chamber, 5.5×10^{-10} sec, which is much longer than the Σ^+ lifetime. The K^+ and θ^0_{anom} are probably associated.

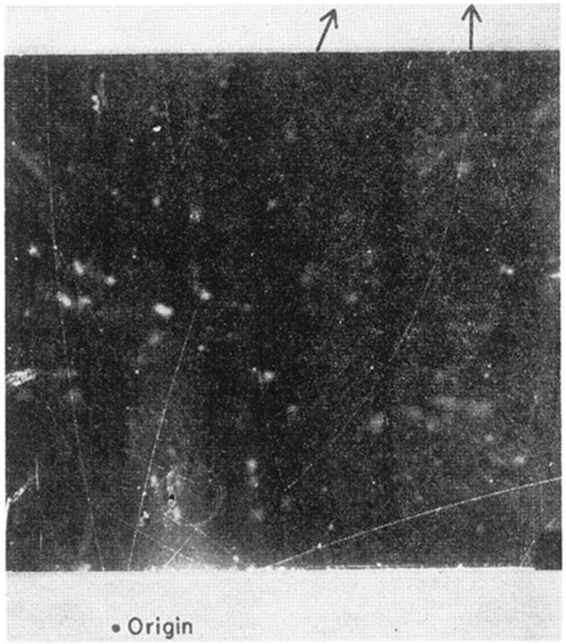

FIG. 3. Event No. 47202. This event is the only known example of a θ^0_{anom} decay wherein both secondaries can be identified with certainty as L mesons. Unfortunately, neither secondary can be identified as a π or μ meson. This is one of the few θ^0_{anom} events which could be a $\tau^0 \rightarrow \pi^+ + \pi^- + \pi^0$ decay. Also, this event is one of four θ^0_{anom} events in which the primary travels upward.

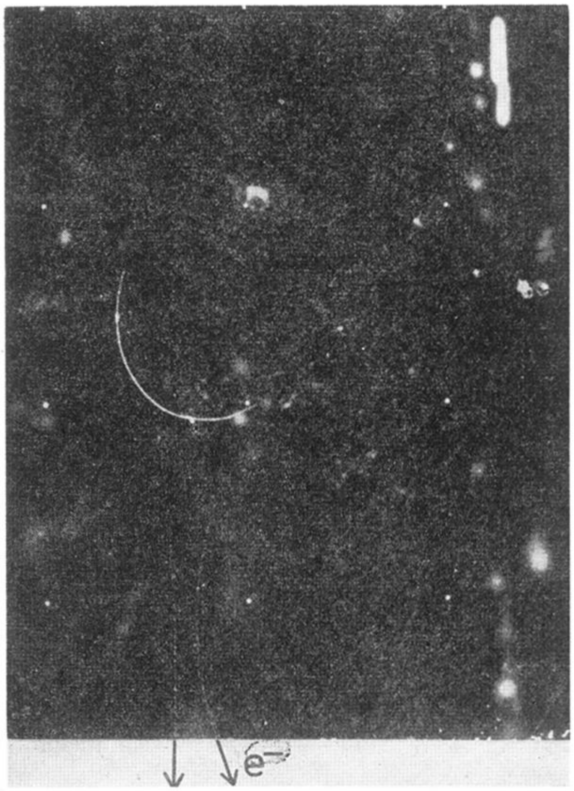

FIG. 4. Event No. 45766. In this unusual θ^0_{anom} event the negative secondary which is identified as an *L* meson is emitted very slowly and appears to stop in the front glass. An electron of momentum 49±6 Mev/*c* appears to come from the end of the negative secondary track indicating that a $\mu^- - e^-$ decay occurs in the front glass. Since a π^- would almost certainly be absorbed in glass, this suggests that the θ^0_{anom} negative secondary is a μ^-. Unfortunately, it is impossible to prove that the secondary could not have undergone a $\pi^- - \mu^-$ decay inside the poorly illuminated region of about 1 cm width near the front glass; it is even possible for the secondary to have stopped in this region. Although no origin is present for this event, a lower limit on its life in the chamber was found to be 4.3×10^{-10} sec.