THE MEAN LIFETIME OF V-PARTICLES

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ABSTRACT

A maximum-likelihood procedure for determining mean lifetimes of V-particles from cloud chamber data is discussed and applied to samples taken from a group of 134 neutral V-particle decays. For 74 events which were consistent with a decay into a proton and a negative pi meson, a lifetime of $(2.5 \pm 0.7) \times 10^{-10}$ sec is obtained. Dividing the data into "low-Q" and "high-Q" groups on the basis of the calculated energy release in the decay, a value of $\tau_L = (2.9 \pm 0.8) \times 10^{-10}$ sec is found for those cases with $0 < Q \leq 50$ mev and a value of $\tau_H = (1.6 \pm 0.5) \times 10^{-10}$ sec is found for those cases with $50 < Q < 150$ mev. While no significant difference exists between these two values, the difference is greater than for other plausible division schemes which are considered.

A qualitative discussion of lifetimes is given for the case of 23 charged V-particle decays. For the charged V-particles these data suggest either a lifetime less than that of the neutral V-particles, provided the sample is homogeneous, or more likely an apparent average lifetime less than that of the neutral V-particles, if the sample is a mixture of two or more types of particles. The possibility of kappa mesons making up a part of these decays is considered and data indicating lifetimes approximately equal to or longer than 10^{-9} sec for both the kappa and tau mesons are briefly discussed.

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I. INTRODUCTION

Since the first report of the discovery of neutral and charged V-particles by Rochester and Butler[1] in 1947 and the subsequent confirmation of the discovery by Seriff *et al.*[2] in 1950, a number of cloud chamber experiments[3-8] have been performed to make further studies of these particles. Although the findings have been more complex than one might have expected and the need for a great deal more work has become apparent, certain definite conclusions have been reached and other possible results have been suggested.[7,8] All of these experiments point to the existence of two or more different types of neutral V-particles and one or more types of charged V-particles. This thesis will be concerned principally with that type of neutral V-particle which decays with an energy release, Q, in a manner consistent with the scheme

$$V^{o} \longrightarrow P^{+} + \pi^{-} + Q.$$

There is no assurance that additional neutral particles as light as the pi meson are not among the decay products. Nevertheless, for the purpose of the lifetime determinations to which this thesis is devoted, this decay scheme will be assumed to hold for those cases in which the visible decay products are consistent with a proton and a negative pi meson. This procedure is justified by the fact that the numerical results are not greatly changed if other decay schemes, consistent with the observed data, are assumed. Those events which are discussed as charged V-particle decays are cases in which a charged particle decays into a single charged particle plus one or more neutral particles. Only those events which can be shown to be inconsistent with known processes such as the decay of a pi meson into a mu meson are included in the group of charged V's.

The average lifetime of V-particles is one characteristic quantity for which estimates have been made from the above experiments.[2,9] Although the cloud chamber can be used for lifetime determinations in principle, the difficulty of obtaining a large unbiased sample of V-particle decays of a single type has prohibited accurate results. This difficulty is still apparent in the present work, which treats the decay of 134 neutral V-particles and 23 charged V-particles.* However, the information now available on the decay of neutral V-particles is more extensive than in the previously reported experiments. Thus an attempt is made here to determine the best value of the mean lifetime obtainable from this still rather meager set of data.

The method used is a maximum-likelihood procedure, which essentially involves finding that value of the mean lifetime

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* A rather complete analysis of these same events has been made by other workers whose findings are given in references 8, 10 and 11. These reports describe the experimental techniques and discuss the experimental errors in more detail than will be done here. When information such as the mass of the neutral V-particle, decay schemes, etc. is needed for the purpose of a lifetime determination, the results given by these workers will be used.

which maximizes the probability of obtaining the observed distribution of decay points in the chamber.* This procedure is applied to the case of the neutral V-particle decays. Since it is apparent from the data that no significant treatment of the charged decays can be made, only a qualitative discussion of the mean lifetime is given in this case.

* The maximum-likelihood procedure was used at the suggestion of Professor Leverett Davis, Jr.

II. THE APPARATUS AND FIDUCIAL SURFACES

The apparatus used in this experiment(8,10) was a counter-controlled double cloud chamber operated in a magnetic field of approximately 5,000 gauss. The experimental arrangement is shown in figure 1. The lead blocks above and between the two chambers served to filter out the soft radiation and provided a region in which the production of V-particles could take place near the tops of the chambers. The trays of counters above and below the double chamber were used to select penetrating showers. The chambers, lead and counters were inclosed in a thermostatically controlled copper box placed between the pole pieces of an electromagnet. Upon each expansion, stereoscopic photographs were taken of the chambers, which were illuminated by the discharge of a condenser bank through a gas-filled flash tube. Additional information on the apparatus and its operation is given in reference 10.

Also shown in figure 1 are fiducial surfaces which are used in the measurement of certain geometrical quantities needed for the lifetime determination. These surfaces were drawn to include only well-illuminated regions of the cloud chamber within which all V-particle decays would be almost equally likely to be detected. They were located at distances ranging from $\frac{1}{2}$ cm to 5 cm from each of the inner walls of the chambers. One might wish to make this separation of the fiducial surfaces from the inner walls much greater so

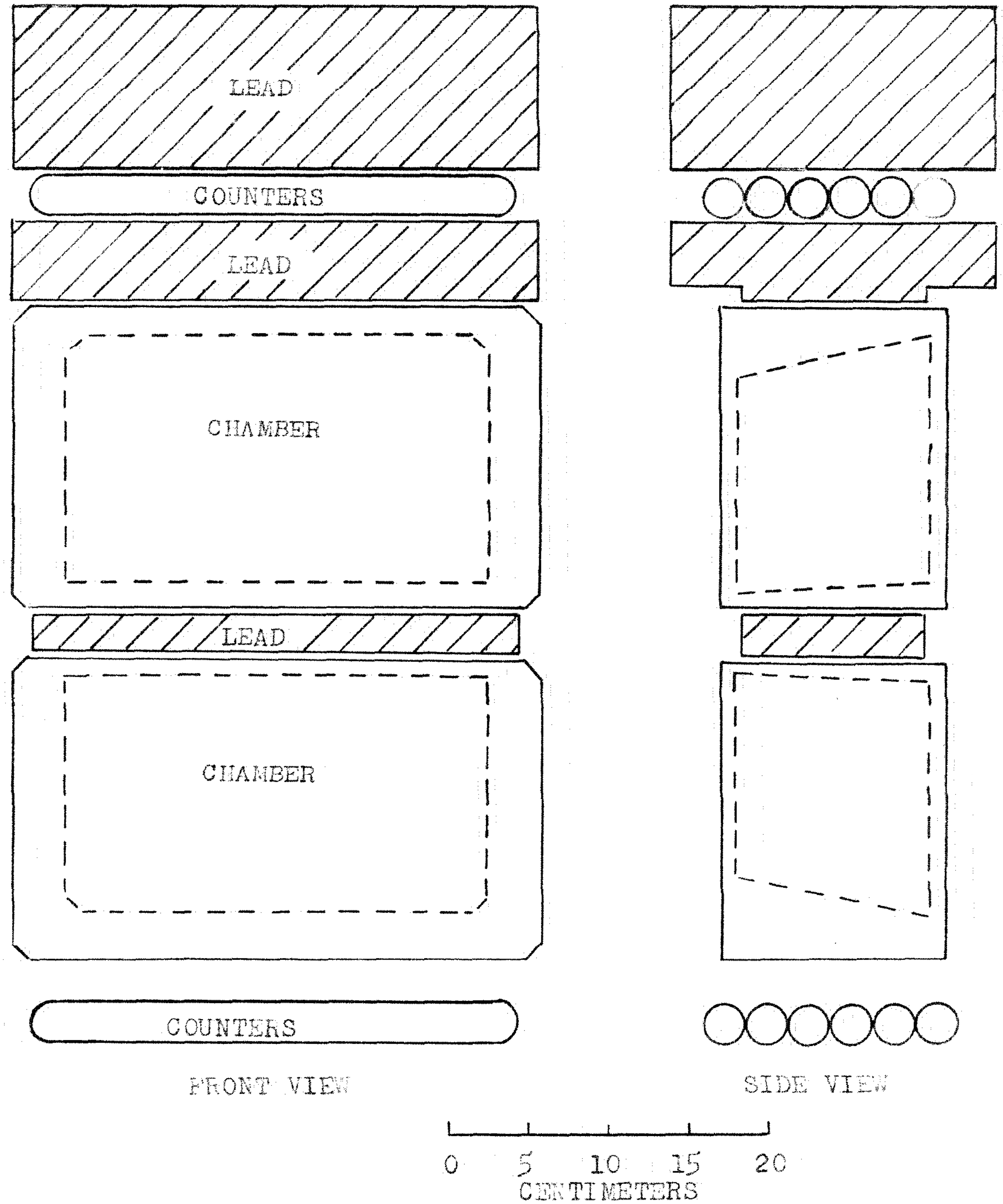

Figure 1. The arrangement of the lead, counters and cloud chambers. The dashed lines represent the fiducial surfaces.

that any track originating within these surfaces would have sufficient visible length within the chamber to allow all necessary measurements to be made; however, the already critically small size of the chambers prohibits such a restriction on the usable volume. Although tracks and V-particle decays were often clearly visible in much of the region between the fiducial surfaces and the walls of the chambers, the terms "visible" or "illuminated" region will be used to refer to the volume within the fiducial surfaces.

III. THE DATA

The experimental data which were used in the determination of the lifetime of the neutral V-particle are given in table I. The quantities tabulated are described briefly below with a more detailed description immediately following the table. When a knowledge of the decay scheme of the neutral V-particle was required in order to determine some of the quantities given, a two-body decay into a proton plus a negative pi meson was assumed.

x is the distance between the point of entrance of the V-particle into the visible region of the chamber and the point of decay.

d is the distance between the point of entrance of the V-particle into the visible region and the point at which it would have left this region if it had not decayed. The term "gate length" or "potential path length" will be used to refer to this quantity.

P is the momentum of the V-particle.

t is the time taken to traverse the distance x. This time is given in the rest system of the V-particle.

T is the time, measured in the rest system of the V-particle, taken to traverse the distance d.

θ is the angle between the paths of the two charged decay products of the neutral V-particle.

Q is the calculated energy release as given in reference 10.

No. serves to identify the photograph on which the decay was recorded.

TABLE I

No.	Q (Mev)	θ (Deg)	P* (Mev/c)	x (cm)	d (cm)	t (10^{-10} sec)	T (10^{-10} sec)
6724	65	152.0	712	8.1	14.1	4.2	7.4
9200	--	22.0	(2200)	10.3	15.6	1.8	2.7
9285	--	21.5	(2300)	0.2	15.0	0	2.4
9489	44	54.5	467	0.6	15.4	0.5	12.3
10876	28	72.0	455	1.2	13.7	1.0	11.2
11326	76	24.0	1600	0.8	9.1	0.2	2.1
11373	37	132.0	310	1.4	17.8	1.7	21.6
12717	63	71.0	850	0.1	16.1	0	7.1
13231	33	41.6	868	6.4	13.8	2.8	5.9
14228	145	55.0	850	2.7	11.4	1.2	5.0
14345	86	28.0	700	3.8	20.3	2.0	10.9
14539	33	45.0	508	1.8	19.2	1.3	14.1
15011	35	49.0	1080	9.7	14.0	3.3	4.8
15181	20	15.0	1250	6.0	13.2	1.8	3.9
15543	91	28.0	922	2.1	10.5	0.9	4.3
16631	--	49.0	(900)	13.5	14.8	5.6	6.1
17078	--	15.0	(3200)	11.1	14.4	1.3	1.7
17407	31	39.0	938	0.1	10.7	0	4.3
17582	26	26.0	878	9.5	12.2	4.0	5.2
17596	80	2.5	1390	0.1	17.0	0	4.6

* The values of P shown in parenthesis were estimated from a knowledge of θ as described in the next section.

TABLE I

(Continued)

No.	Q (Mev)	θ (Deg)	P* (Mev/c)	x (cm)	d (cm)	t (10^{-10} sec)	T (10^{-10} sec)
17685	14	22.0	900	10.5	14.2	4.4	5.9
18675	--	44.0	(1000)	0.7	14.0	0.3	5.2
19063R	34	34.0	1460	4.7	14.4	1.2	3.7
19063C	41	151.0	348	9.0	23.0	9.7	24.9
19063L	51	51.0	972	5.3	22.2	2.0	8.5
19286	18	16.0	1240	2.7	13.3	0.8	4.0
19287	79	39.0	1570	1.1	16.4	0.3	3.9
19955	72	19.0	830	0.2	16.3	0.1	7.3
19960	--	34.0	(1400)	2.4	10.6	0.6	2.8
20019	--	31.0	(1500)	5.3	14.8	1.3	3.7
21301	--	47.0	(900)	1.9	4.5	0.8	1.9
21428	--	15.0	(2800)	6.8	16.4	0.9	2.2
21910	10	19.0	1590	6.3	14.5	1.5	3.4
22578	25	42.0	608	1.6	8.1	1.0	5.0
22895	57	32.0	880	3.6	11.0	1.5	4.7
23159	42	37.2	880	5.2	16.2	2.2	6.9
23865	33	32.9	1180	4.0	13.3	1.3	4.2
23942T	--	35.0	(1300)	0.1	14.2	0	4.1
23942B	37	65.0	291	3.5	9.8	4.5	12.6
24026	34	45.0	862	0.7	4.8	0.3	2.1
24141	35	72.0	411	1.8	3.4	1.6	3.1
24358	73	31.4	1300	3.1	11.2	0.9	3.2

TABLE I

(Continued)

No.	Q (Mev)	θ (Deg)	P* (Mev/c)	x (cm)	d (cm)	t (10^{-10} sec)	T (10^{-10} sec)
24390	22	28.0	1072	5.4	13.0	1.9	4.5
25504	32	41.8	816	5.1	14.6	2.3	6.7
25587	31	42.6	853	1.9	8.5	0.8	3.7
25686	10	52.7	402	5.1	13.4	4.7	12.5
26585	32	37.1	1040	5.3	18.5	1.9	6.7
26655	75	65.0	1074	11.2	15.7	3.9	5.5
26769	50	24.0	624	3.6	15.3	2.2	9.2
26867	32	52.4	488	3.7	5.5	2.8	4.2
26912	29	10.4	5580	4.5	14.3	0.3	1.0
27529	60	62.0	693	0.1	14.0	0	7.5
27875	97	78.5	1030	2.7	13.2	1.0	4.8
28167	79	114.0	770	0.4	13.3	0.2	6.4
28225	--	16.0	(3000)	6.3	10.1	0.8	1.3
28569	37	27.8	1970	3.2	18.1	0.6	3.4
29141B	--	32.4	(970)	0.8	14.6	0.3	5.6
29637	97	42.8	750	4.1	15.9	2.0	7.9
30045	59	30.3	1160	2.8	12.7	0.9	4.1
30047	33	41.8	790	1.4	15.3	0.7	7.2
30095	49	44.6	1250	5.1	15.8	1.5	4.7
30117	--	12.3	(3500)	3.2	11.8	0.3	1.3
30129	34	67.0	552	0.7	17.0	0.5	11.5
30334	67	13.5	1900	12.8	14.6	2.5	2.9

TABLE I

(Continued)

No.	Q (Mev)	θ (Deg)	P* (Mev/c)	x (cm)	d (cm)	t (10^{-10} sec)	T (10^{-10} sec)
30770	28	28.0	882	0.8	11.7	0.3	5.0
30803	46	39.0	1350	5.9	14.0	1.6	3.9
30844	81	40.0	990	0.2	15.7	0.1	5.9
30925	--	90.0	(340)	6.5	11.7	7.1	12.8
30964	41	31.0	1600	8.1	14.8	1.9	3.5
30986	--	22.0	(2200)	5.0	16.1	0.8	2.7
31044	36	32.0	842	1.0	10.0	0.4	4.4
31200	44	29.0	1240	0.8	16.1	0.2	4.8
31216	--	13.0	(3800)	7.3	14.6	0.7	1.4
31337	--	14.0	(3600)	7.6	11.3	0.9	1.2

IV. DISCUSSION OF THE DATA*

x and d were measured from the predetermined fiducial surfaces which were shown in figure 1 and discussed in part II. The values of x and d were obtained from the two stereoscopic photographs of the chamber. The two views were projected through a lens system identical to that of the camera onto a single screen following the procedure described in reference 8. The projection was such that points lying on the back plate of the chamber were superimposed upon the screen, while points which were forward in the chamber were separated by an amount dependent on their distance from the back plate. Figure 2 illustrates this for a V-particle which was produced in the lead plate between the two chambers. The particle had an origin determined from O' and O", a point of entrance through the top fiducial surface determined from A' and A", a decay point determined from B' and B", and a "potential point of exit" from the illuminated region at the back fiducial surface determined from C' and C". The point D, at which the separation becomes zero, lies in the back plate. Figure 3 is a photograph showing one view of a decay in which the V-particle was following a trajectory of this kind.

P, the momentum of the V-particle, was determined in

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* Much of the procedure used in collecting data and in making lifetime determinations is due to Professor Robert Leighton. Although developed independently, the general procedure is similar to that suggested by J. G. Wilson and C. C. Butler.[12]

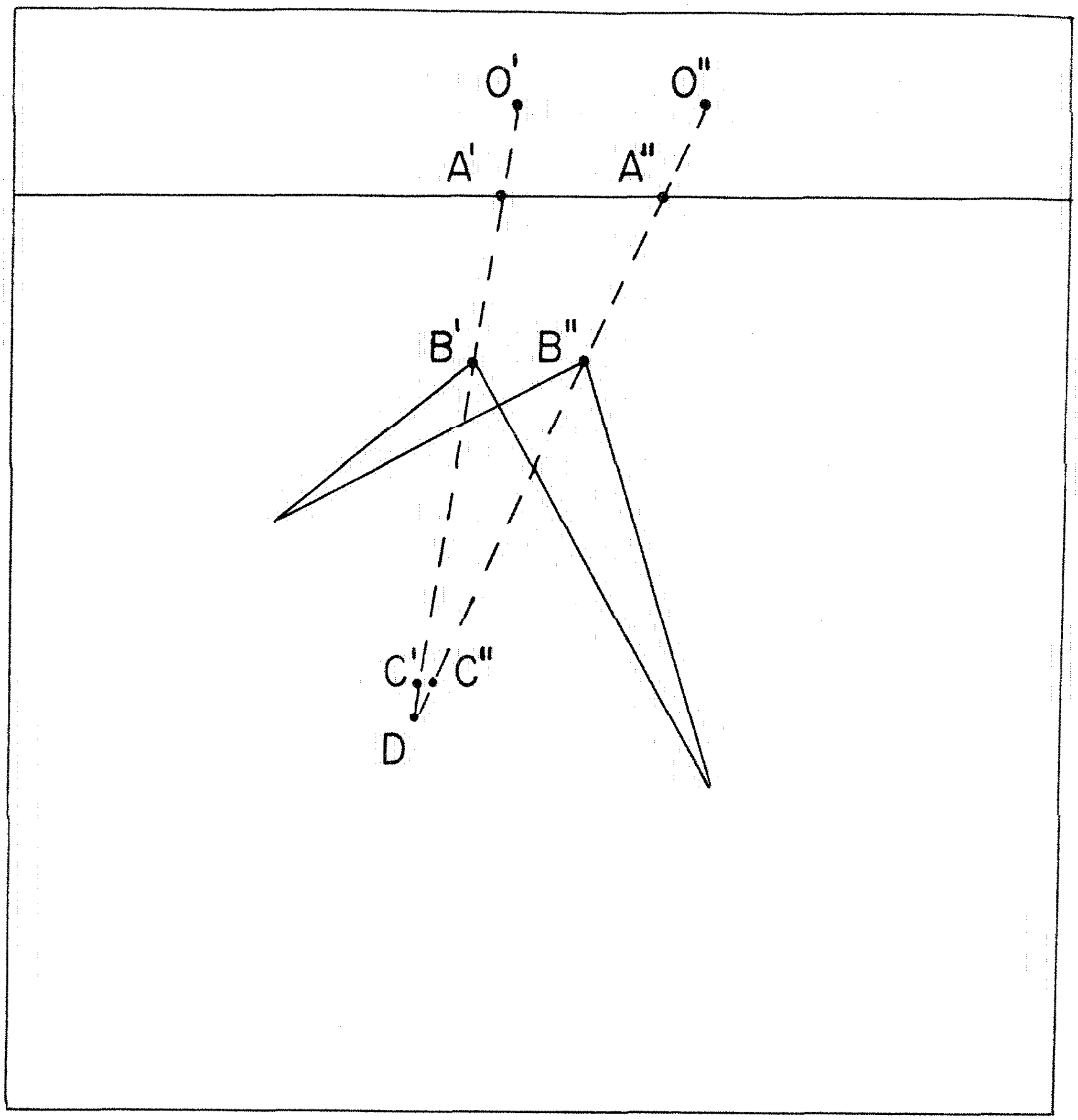

Figure 2. A schematic diagram showing the superposition of the two stereoscopic views of a neutral V-particle decay.

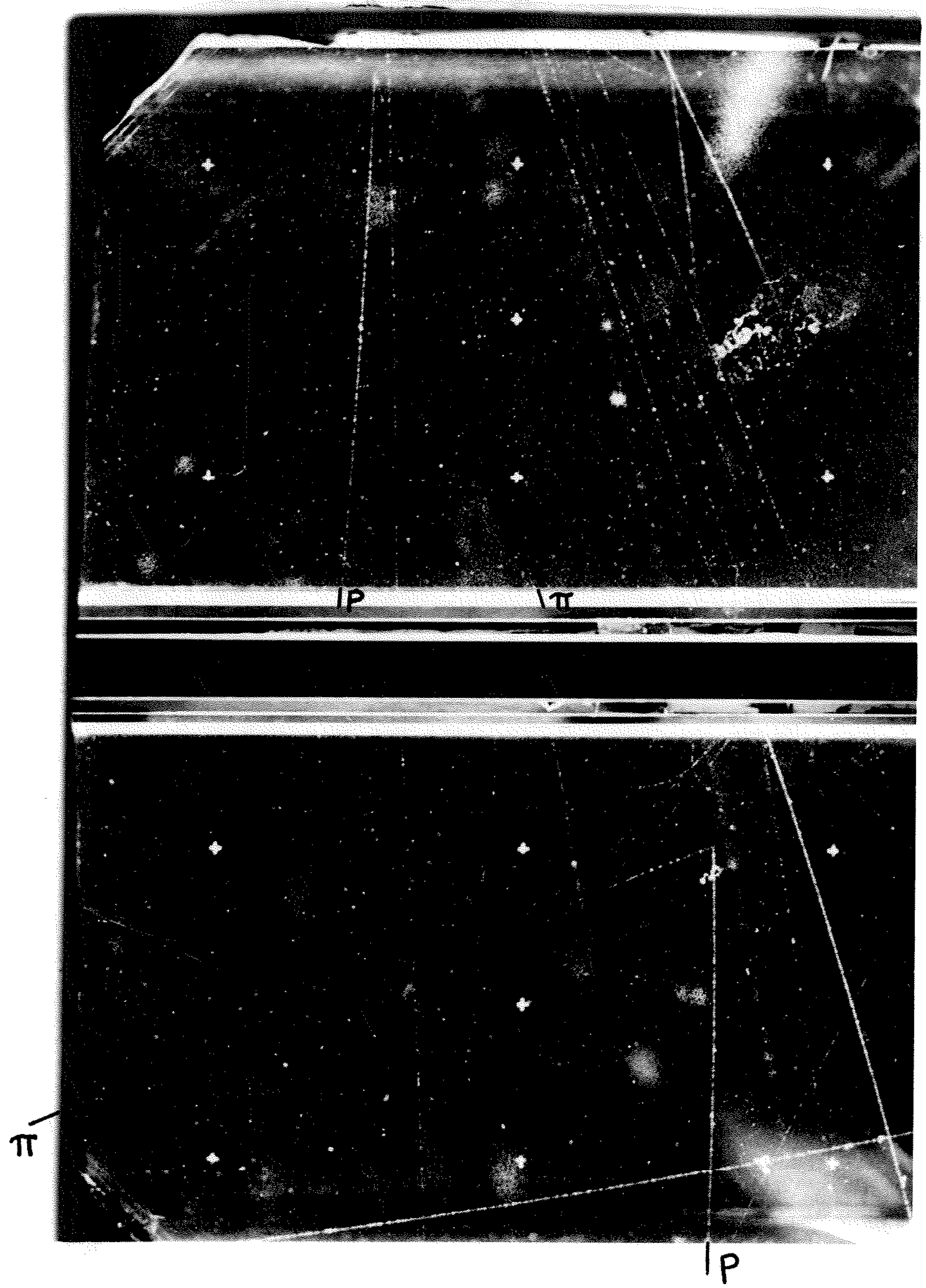

Figure 3. Two examples of the decay of a neutral V-particle. The decay products are consistent with a proton and a negative pi meson. The trajectory of the V-particle in the lower chamber is described in part IV.

one of two ways depending on the information which was available. If the momenta of the two decay products could be determined, P was calculated as the vector sum of these momenta. If the momenta of the decay products could not be determined, P was found from θ under the assumptions: (1) that the energy release in the assumed two body decay was 50 Mev and (2) that the decay products were emitted at right angles to the line of flight of the V-particle, in the center-of-mass system. Figure 4 shows that, if the decay products have a random angular distribution in the CM system of the V-particle, the second of the above assumptions could lead to a considerable error in any one case but statistically should be a fair procedure. Also, it might be noted that P was quite large for most of the cases for which this procedure was used and, as shown later, such cases have very little weight in the determination of the lifetime.

The times, t and T, are given in the rest systems of the V-particles and are related to the distances, x and d, by the equations

$$t = (x/c)\,(M/Pc) \text{ and } T = (d/c)\,(M/Pc).$$

M* and Pc are given in Mev so that Pc^2/M is the product of the velocity of the V-particle and the time dilation factor.

In addition to the quantities given in table I, one may feel that a knowledge of the time interval between the

* The value of the mass of the neutral V-particle used in forming table I was taken to be 1120 Mev[10].

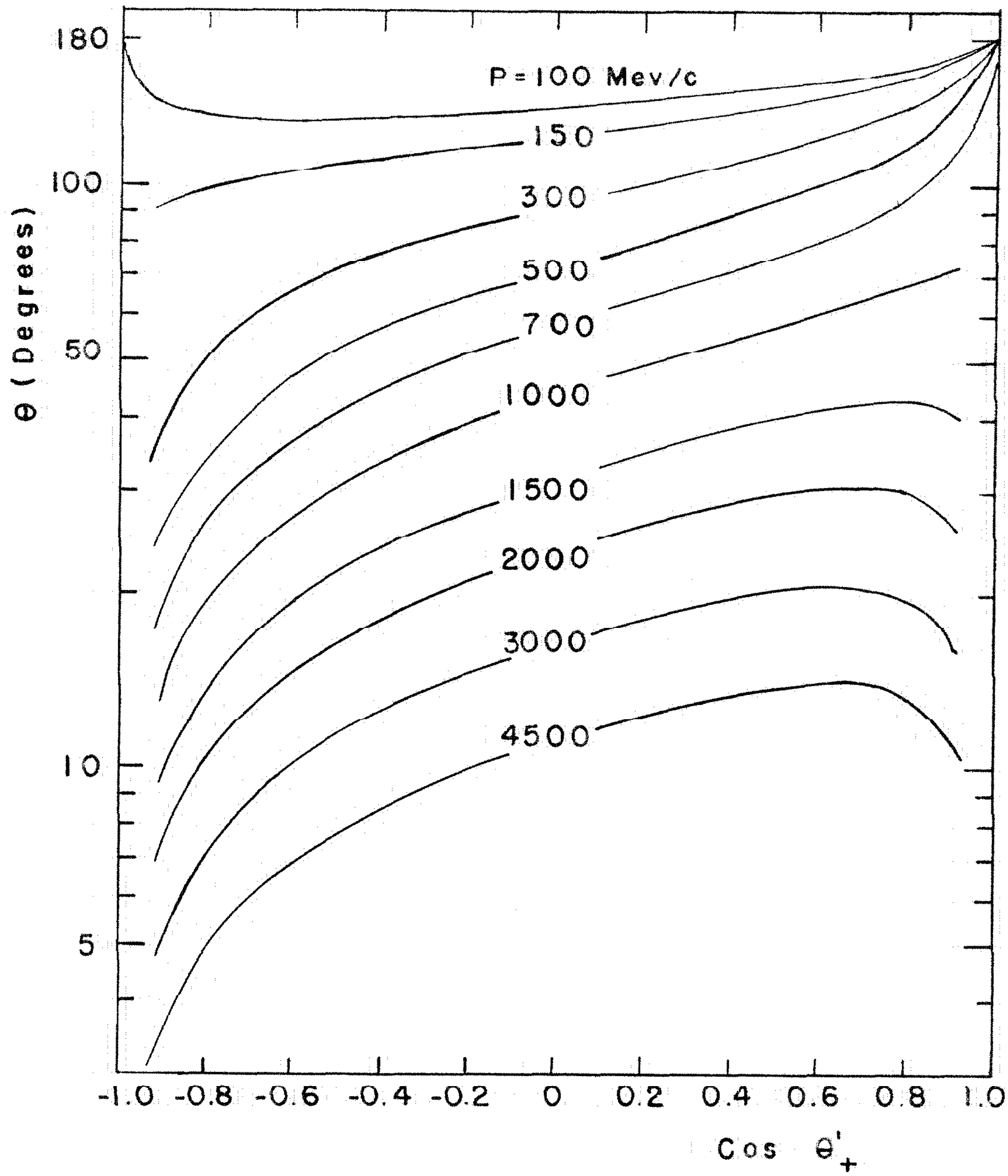

Figure 4. A two-body decay of a neutral V-particle into a proton and a negative pi meson with an energy release of 50 Mev is assumed. θ'_+ is the angle, measured in the CM system of the V-particle, which the proton makes with the line of flight of the V-particle. P and θ are defined in part III .

production of the V-particle and its entrance into the visible region of the chamber is necessary for a lifetime determination. However, it is assumed that the probability of decay follows an exponential law, and this assumption implies that the decay is spontaneous and is independent of the past history of the V-particle. Thus one is justified in treating each particle as if it were created at its point of entrance into the visible region and in measuring t and T from the time at which the particle passed this point. This procedure has advantages in that: (1) it allows the use of many cases for which approximate points of entry into the chamber can be obtained, but for which no clearly identifiable origin can be found in the lead above the chamber, and (2) it eliminates the necessity for considering the unknown number of particles which decay before reaching the visible region. The only use which was made of the origins that were identified was in the determination of the direction along which to measure x and d. For those V-particles which had no identifiable origin, x and d were measured along the line determined by the vector sum of the momenta of the two decay particles. For fifteen per cent of the events, for which neither an origin could be identified nor a momentum measurement made, the direction of flight of the neutral V-particle was taken to be along the line bisecting the angle between the paths of the two decay products. For most of the cases included in this last category the general direction of travel of the V-particle was clearly from the top of the chamber toward the bottom, and the angle between the paths of the decay products was small. These two conditions made the resulting error in x, d, and x/d quite small. Such would not be the case if the V-particle were traveling obliquely across the chamber or if the angle between the paths of the decay products were large.

V. METHOD OF CALCULATING THE MEAN LIFETIME

In treating methods of determining the mean lifetime of radioactive substances, Peierls[13] in 1935, Bartlett[14] in 1936 and Hole[15] in 1947 have discussed the application of the maximum-likelihood procedure[16] to counter experiments. The results given by these workers are almost immediately applicable to the present situation with the principal exception that each of these has treated the problem in which the gate time, T, is a constant, whereas the data obtained by use of the cloud chamber contain T's which vary over a rather wide range. From table I it is seen that the range in values of T is due to a difference in both the potential path lengths and the velocities of the V^o-particles. In spite of this difference the procedure with constant T is readily extended to cover the case in which T varies over a range of values.

A. The Maximum-Likelihood Procedure

An unstable particle, which follows an exponential decay law with mean lifetime τ and which is known to be alive at time t = 0, has the probability

$$(dp)_i = (1/\tau) \ e^{-t_i/\tau} dt \qquad (1)$$

of decaying at time t_i in the time interval dt. If the decay is known to have taken place within the time T_i, the probability of decay in that time can be normalized* to unity so that

$$(dP)_i = (1/\tau)\,\frac{e^{-t_i/\tau}}{(1-e^{-T_i/\tau})}\,dt. \qquad (2)$$

For a set of N independent decays which follow the probability law of equation (2), the probability of having obtained the particular set of experimental data is proportional to

$$L = \prod_{i=1}^{N} (1/\tau)\frac{e^{-t_i/\tau}}{(1-e^{-T_i/\tau})}\;. \qquad (3)$$

L will be referred to as the likelihood function. The maximum-likelihood procedure is based upon the assumption, much used in statistical methods, that the best value of a parameter on which the likelihood function depends is that value of the parameter which makes this function a maximum. Hence one wishes to find that value of τ for which L, or more conveniently lnL, is a maximum:

$$\frac{\partial \ln L}{\partial \tau} = 0. \qquad (4)$$

Carrying out the differentiation of lnL one obtains for the best value of the mean lifetime

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* This normalization to unity essentially corrects for those particles which passed through the chamber and decayed after time T_i. Peierls[13] does not proceed in this way but rather uses a procedure which requires assumptions as to the a priori probability of having had a given total number of decays for each particle which decayed in time T_i.

$$\tau = \frac{1}{N} \sum_{i=1}^{N} \left(t_i + \frac{T_i}{e^{T_i/\tau} - 1}\right). \qquad (5)$$

Hence, in principle, the mean lifetime can be determined from data obtained in cloud chamber experiments. Given a set of t_i and T_i such as table I contains for the V^o-particle, equation (5) can be solved by iteration to find the best value of τ. The actual worth of such a determination will depend of course on the statistical and systematic errors involved. The next section will be devoted to a discussion of these errors.

B. Errors

Following Bartlett's discussion of the maximum-likelihood procedure, one is led to the statistical error in τ given by

$$\Delta\tau = 1/\sqrt{I} \qquad (6)$$

in which I is defined by the equation

$$I = -\frac{\partial^2 \ln L}{\partial \tau^2} = \frac{1}{\tau^2} \sum_{i=1}^{N} \left[1 - \frac{T_i^{\,2}}{\tau^2} \frac{e^{T_i/\tau}}{(e^{T_i/\tau} - 1)^2} \right]. \qquad (7)$$

Equation (6) is derived on the assumption that the estimates of the parameter, τ, are normally distributed as the variance of $\frac{\partial \ln L}{\partial \tau}$(14). Although this condition is only approximately met in the present experiment because of the small sample available, this equation probably furnishes the best means of arriving at some estimate of the statistical error.

To gain some feeling for the effect of the finite gate time, it is interesting to consider the case for which all of the T_1 are the same and to look at the quantity, n, which is given by

$$n = I\tau^2 = N\left[1 - (T/\tau)^2 \frac{e^{T/\tau}}{(e^{T/\tau}-1)^2}\right] \qquad (8)$$

and which is the number of decays with an infinite gate required to produce the same statistical accuracy as N cases with a given finite gate, T. The quantity N/n is plotted versus T/τ in figure 5.* As an example, if T/τ is equal to unity, N/n is found to be 12.5; so that 10 decays observed with T infinite would yield a lifetime with the same statistical accuracy as 125 decays for which T/τ was unity.

Since one assumes a knowledge of τ in using the quantity T/τ discussed above, the ratio t/T, which can be found directly from the experimental data, is more readily given as a measure of significance. For gate times which are small compared with τ one expects the decay points to be uniformly distributed throughout the chamber so that t/T would be equal to one-half. Thus, one can hope to use the cloud chamber to measure mean lifetimes only if the ratio t/T = x/d is significantly less than one-half.

* This graph was also quite useful in evaluating the terms in equation (7) to find the statistical error when T was allowed to take on many different values.

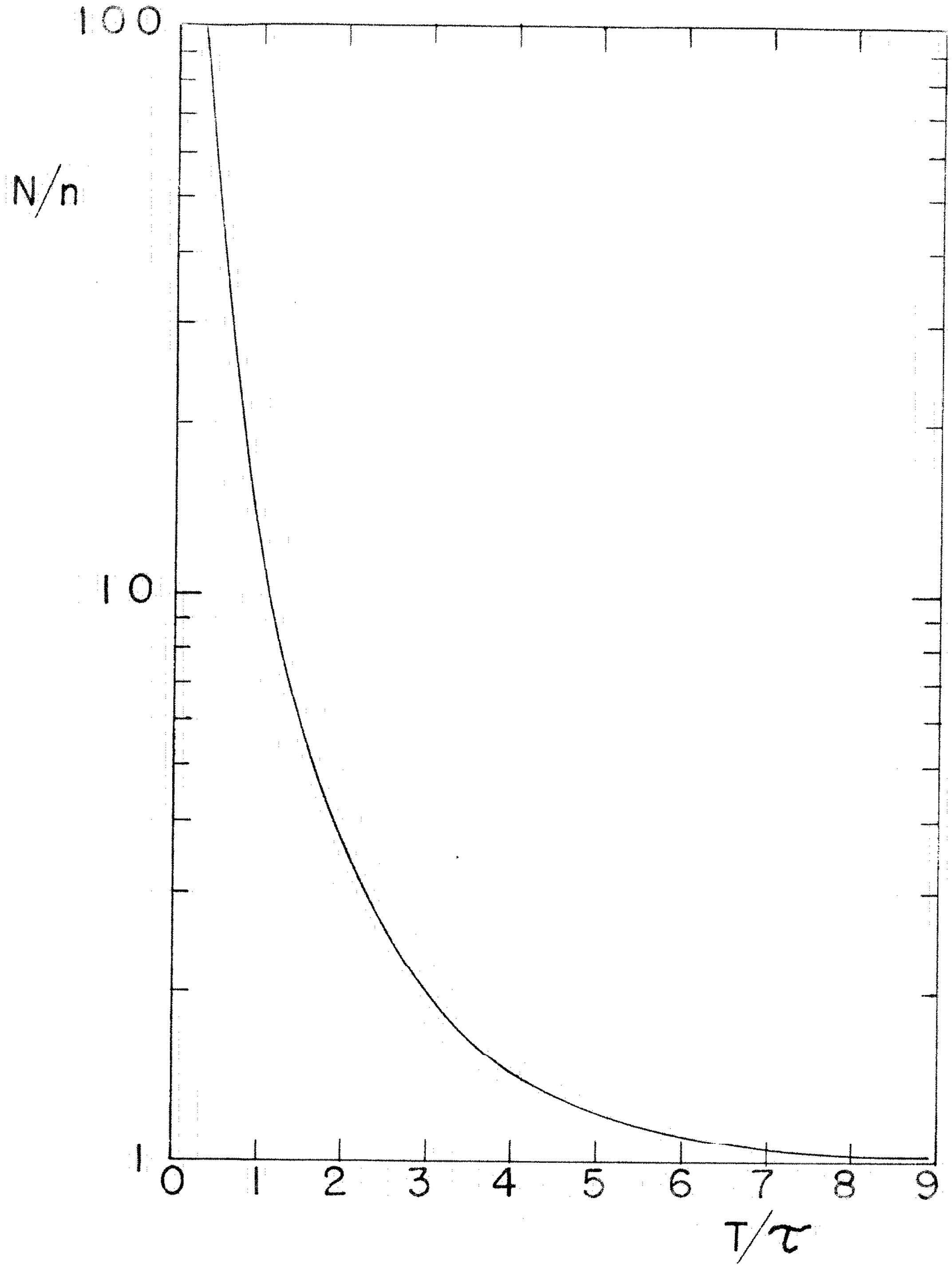

Figure 5. The ratio N/n, as defined in equation (8), is plotted versus the ratio of the gate time to the mean lifetime.

Further uncertainty in the lifetime is due to the limitations of the experimental technique and to a lack of knowledge of the decay process or processes which are taking place. In each of the lifetime determinations which are given later, it is quite possible that the samples contain a mixture of particles of different lifetimes so that the "lifetime" calculated is actually some sort of an average value of two or more characteristic lifetimes. Efforts which were made to separate such possible mixtures will be discussed. Apart from the fact that the errors in the measurements of momentum prevent an accurate classification of the V-particle decays into homogeneous groups and may thereby prevent us from making a proper calculation, the errors in the quantities P, x, and d do not contribute very large errors to the mean life, τ . For most cases x and d can be measured with sufficient accuracy that the error can be neglected, and if selection criteria are used such that the momentum of each V-particle in the sample is measurable to within twenty or thirty per cent, the resulting probable error in the mean lifetime should be small compared with the statistical error given by equation (6).*

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* Since such a selection might tend to discriminate against the decay of long lived particles near the walls of the chamber, care must be taken that bias is not introduced into the sample.

VI. THE MEAN LIFETIME OF NEUTRAL V-PARTICLES

In a series of 23,000 cloud chamber photographs taken at Pasadena and on Mount Wilson, 134 examples of the decay of neutral V-particles have been obtained. Data on 74 of these examples which were consistent with the decay scheme

$$V^{o} \longrightarrow P^{+} + \pi^{-} + Q \qquad (9)$$

were given in table I. The remaining 60 decays have been eliminated from consideration for at least one of the following reasons:

(1) the decay occurred outside the fiducial surfaces,

(2) the total angle between the paths of the two decay products was $\leqslant 10^{o}$,

(3) the decay did not seem to fit the proton plus negative pi meson decay scheme.

These criteria were established in an attempt to obtain an unbiased sample of events for which maximum information was available. Nineteen decays between the walls of the chambers and the fiducial surfaces were discarded because of the non-uniform illumination and the reflections which made it doubtful that all of the V-decays in this region were detected. The arbitrary restriction on the total angle eliminated twenty-three cases for which the V-particle momentum was unmeasurably high and eliminated no case for which the V-particle momentum was accurately known. This restriction was chosen since the angle measurements could be made almost irrespective of the track length available and of the position of the decay point in the chamber. Thus there was no apparent discrimination against decays occurring near the bottom of the chamber. Such would not be the case if momentum measurements were required in making the selection.

More of the cases for which the momentum had to be estimated could have been eliminated by throwing out those cases with $\theta \leqslant 20^{\circ}$; however, this much greater restriction would have caused the loss of several events with known V-particle momentum. The final group of eighteen decays was removed because of the apparent inconsistency with the decay scheme given by equation (9). This group included such cases as those in which the positive decay particle was definitely lighter than a proton or in which the calculated energy release was greater than 150 Mev.

Assuming that the remaining 74 examples follow the two-body decay scheme given above, a mean lifetime has been calculated from the set of t_i and T_i in table I. The average value of the ratio t_i/T_i was 0.30, with a statistical error of approximately 0.05, so that there was at least an indication of a result with some significance. Substituting from table I into equation (5), the first term gives a value of 1.6×10^{-10} sec. for the average value of t_i. Since the second or correction term is always additive, this places a lower limit on the mean lifetime, subject only to the ordinary statistical fluctuations. Following an iterative procedure to solve equation (5), one obtains for τ the value

$$\tau = (2.5 \pm 0.7) \times 10^{-10} \text{ sec.} \qquad (10)$$

The statistical error has been computed by use of equations (6) and (7). Although the effect of additional errors in the experimentally determined quantities is difficult to estimate, an attempt has been made to determine the magnitude of the resulting error in τ. For three-fourths of the 74 cases the error in the V-particle momentum was approximately twenty per cent or less, while for the remaining cases there was an appreciable probability of errors as large as one hundred per cent in the momenta determined solely from the value of θ. The errors in x and d were small compared with these errors in P. A consideration of these facts leads to an estimated probable error of about $\pm 0.2 \times 10^{-10}$ sec. in the value of the lifetime. If this error is assumed to be independent of the statistical error given above, the combined error is still given approximately as $\pm 0.7 \times 10^{-10}$ sec.

This leaves to be considered the uncertainty due to the possibilities that the sample of 74 cases is a mixture of two or more types of particles with different lifetimes and that sources of bias are present in the data. Although it is impossible to reach any definite conclusions as to the actuality of these possibilities, the following checks were made in an effort to detect any such sources of error.

(1) A procedure was used which in effect reduced the volume enclosed by the fiducial surfaces.

(2) A separate lifetime determination was made for 32 decays occurring in the upper chamber and for 42 decays occurring in the lower chamber.

(3) A separate lifetime determination was made for those V-particles with identifiable origins and for those without clearly identifiable origins.

(4) A comparison of the lifetime calculated for cases with an energy release between 30 Mev and 40 Mev was made with the lifetime calculated for the remaining cases with Q either less than 30 Mev or greater than 40 Mev.

(5) Lifetimes were calculated for the two groups formed by placing those cases with Q less than or equal to 50 Mev in one group and those cases with Q greater than 50 Mev in a second group.

The first of these checks was aimed at testing whether or not the fiducial surfaces really eliminated bias due to observational difficulties in the region near the walls of the chamber. The method used was approximately equivalent to moving in the fiducial surfaces by reducing each gate time by ten per cent.* The mean lifetime was then redetermined and found to agree within ten per cent with the above value. The same result was found when each gate time was reduced by thirty-three per cent.

The separate lifetime determinations for the 32 decays occurring in the upper chamber and for 42 decays occurring

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* Any event for which the decay time was then greater than the new gate time was removed from the sample.

in the lower chamber were compared. Since the illumination improved slightly from top to bottom for the upper chamber and conversely for the lower chamber, it was felt that this check might indicate bias in the data. However, the two values of the lifetime fell within ten per cent of the result given above for the combined data. Because of the distances of the principal source of V-particles in the lead above each chamber to the respective illuminated regions (fig. 1), it was thought that this test might also indicate the presence of a mixture of two different lifetime particles with the upper chamber favoring the detection of the longer-lived particles and the lower chamber favoring the detection of the shorter-lived ones. The negative result which was found could mean among many possibilities that the V's were all or almost all of one kind or that different kinds, if present in comparable numbers, were of very nearly the same lifetime.

There was no significant difference between the lifetime calculated for the decays with identifiable origins and that calculated for those without clearly identifiable origins.

The fourth point was checked because of the suggestion that part of the V's which were observed might follow the decay scheme of equation (9) with Q near 35 Mev while the remainder followed the scheme

$$V^{o} \longrightarrow P^{+} + \mu^{-} + \nu + Q \qquad (11)$$

with the apparent energy release calculated on the basis of the decay scheme of equations (9) varying over a range of values. Again the result was negative with no significant difference appearing in the two lifetimes.

The final division of the data arose from the analysis of the 134 neutral V-particle decays reported in references 8 and 10. This analysis suggests the possible existence of two groups of V-particles which follow the decay scheme of equation (9), but with different values of the energy release, Q, and with different lifetimes. There was a concentration of a number of decays with Q near 35 Mev and with Q near 75 Mev. This suggested a division of the data such that 37 cases with Q less than or equal to 50 Mev were placed in a low Q group and 20 cases with Q less than 150 Mev, but greater than 50 Mev, were placed in a high Q group. Substituting the data for the 37 low Q cases into equation (5), a lifetime of $\tau_L = (2.9 \pm 0.8) \times 10^{-10}$ was obtained. Again the error has been computed by using equations (6) and (7) and does not include an estimate of the bias due to the failure to consider the remaining 17 cases for which Q could not be determined. If the 17 cases were added to the low Q cases but weighted by the factor 37/57,* the resulting lifetime was found to be $\tau_L = (3.0 \pm 0.8) \times 10^{-10}$ sec. A similar treatment of the high Q cases yielded a mean lifetime of $\tau_H = (1.3 \pm 0.5) \times 10^{-10}$ sec. for the 20 cases of known Q value and a mean lifetime of $\tau_H = (1.6 \pm 0.5) \times 10^{-10}$ sec. when the 17 cases of unknown

* This weighting factor divides the cases in proportion to the number of cases of known Q value in each group.

Q value are added in but weighted by the factor 20/57. Other possible division schemes were tried in the treatment of the 17 cases to determine the range of lifetime values which resulted from various ways of adding in these cases. If those divisions which give the greatest possible range of values consistent with the data are included, the values found in units of 10^{-10} seconds were $1.3 \leq \tau_H \leq 2.3$ and $2.4 \leq \tau_L \leq 3.5$. Thus on the basis of these results and of the large statistical errors one would hesitate to place any real significance on the difference between the lifetimes of the low Q and high Q groups.(17)

VII. THE MEAN LIFETIME OF CHARGED V-PARTICLES

In the same series of 23,000 photographs which contained the 134 examples of neutral V-particles, 23 examples of charged V-particle decay were observed. For most of those cases, both the incident charged V-particle and the visible decay product had high momenta with the result that very few data could be obtained and no significant lifetime determination could be made. The distribution of decays as shown in figure 7 is suggestive of the existence of at least two different types of particles in the group. The events shown in the figure with a dot at the apex to indicate their production in the lead plate between the chambers were decays which occurred predominantly near the top of the lower chamber. A qualitative comparison of these events with the neutral V-decays shown in figure 6 indicates a somewhat shorter mean free path for the charged V-particle.* Since ionization estimates show that P/M is, on the average, greater for the charged V's than for the neutral V's, a mean lifetime of less than 2.5×10^{-10} sec, possibly by a factor of from 2 to 4, is indicated for this particular type of charged V-decay. Also in support of this short lifetime is a consideration of the ratio of the number of V-particles produced in the lead

* The arguments based on this overall comparison of neutral and charged V's are weakened somewhat because of the unequal efficiency of observing the two types of decay. A small deflection in the track left by a very fast particle is often the only indication of a charged V-decay. Such a deflection is much more difficult to detect than is the inverted V which characterizes the decays of the neutral variety. This is especially true of events near the walls of the chambers.

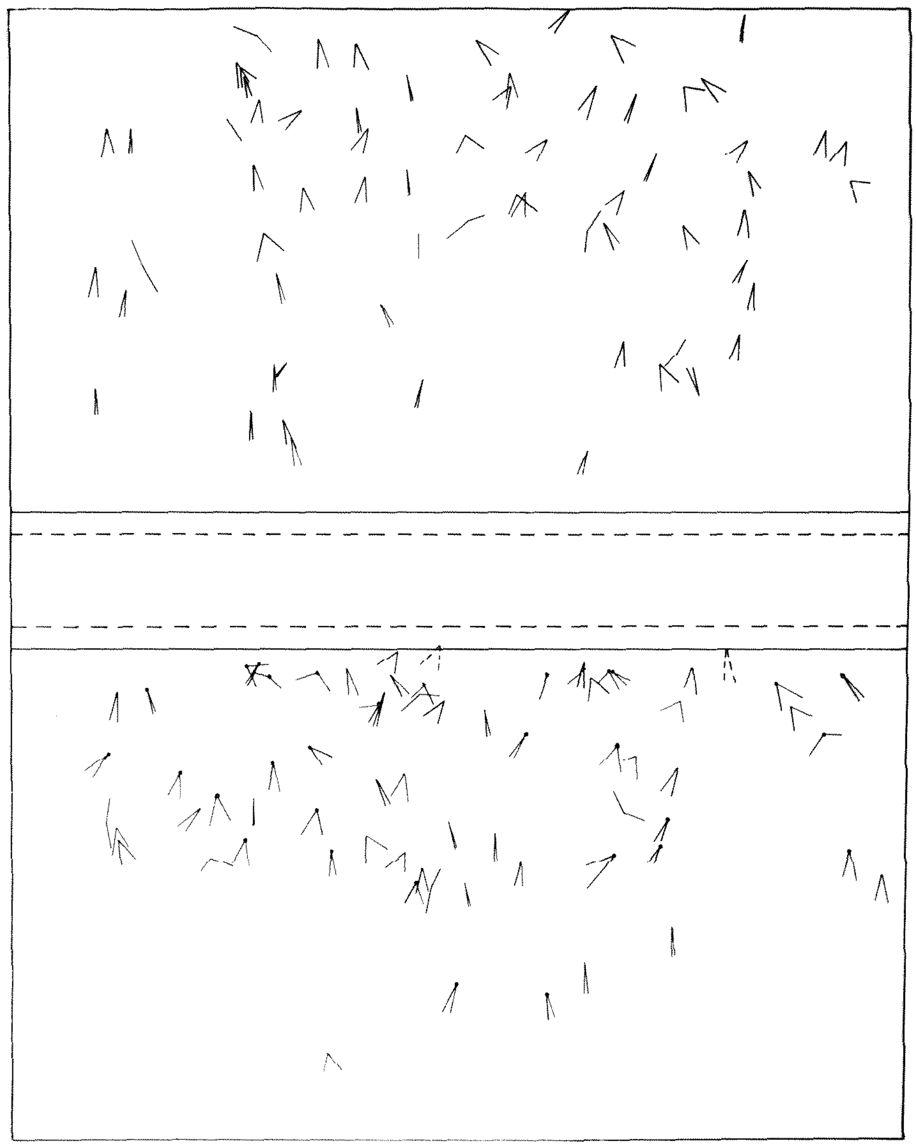

Figure 6. The distribution of the neutral V-particle decay points. A dot at the apex indicates production in the lead plate between the two chambers. A dashed track signifies a hidden apex.

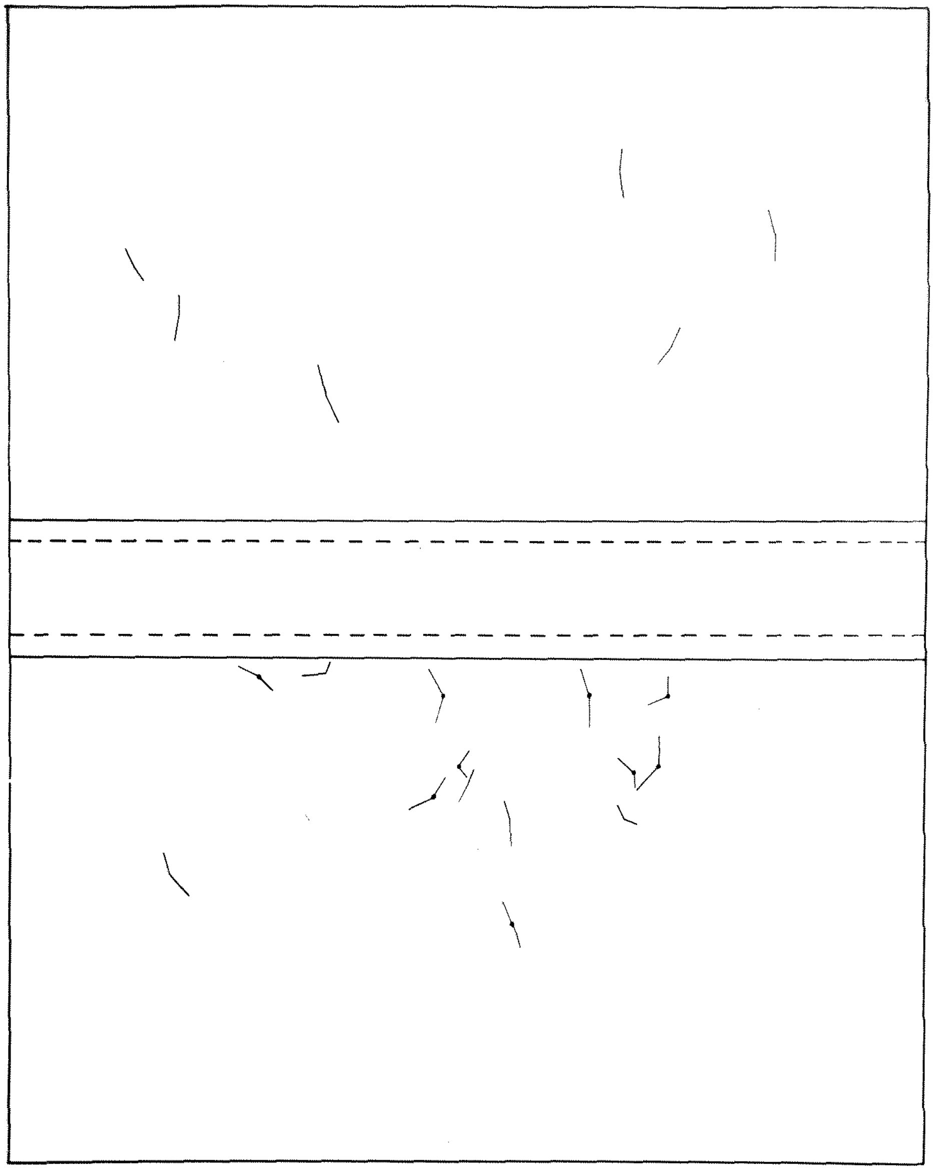

Figure 7. The distribution of the charged V-particle decay points. A dot at the apex indicates production in the lead plate between the two chambers.

between the two chambers to the number produced in the lead above the upper chamber. For the charged V-particles with identifiable origins this ratio is approximately 1 compared with 1/2 for the neutral V-particles. This comparison points to a shorter average lifetime for the combined cases of charged V's than for the neutral V's.

On the other hand, the decays shown in figure 7 without a dot at the apex were apparently produced in the lead above the upper chamber and were distributed more uniformly throughout the chambers. Several of the particles decaying in the lower chamber traversed completely the upper chamber indicating a long lifetime, provided P/M is not too much greater for these particles than for the neutral V's. In addition, two examples, in which a relatively slow particle of estimated mass between that of the proton and the pi meson has been observed to decay into a particle consistent with a pi or mu meson after a time greater than 10^{-9} sec, also suggest the presence of a comparatively long-lived particle of such mass accompanying penetrating showers. Thus it is felt that at least some of the charged V's are identical with these two examples and are probably kappa mesons[18,19] with a mean lifetime of 10^{-9} sec or greater.

In addition to those events which have been described as charged V-decays and which may in part be kappa mesons decaying into a mu meson plus one or more neutral particles, two examples have been obtained[18] of a charged particle decaying into three charged particles. Each of the three decay products in these two events had a mass consistent with that of a pi meson and the primary particle appeared to be identical with the tau mesons which had previously been observed in nuclear emulsions.[20] Although no good estimate of the lifetime of this particle can be made from only two cases, the relatively long paths of the tau's in the chamber before decay and the estimates of P/M indicate a mean lifetime greater than that of the neutral V-particle. Just as for those particles which were thought to be kappa's, this mean lifetime is probably 10^{-9} sec or longer.*

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* Approximately twice the amount of data discussed in this section is now available and these additional data lead to essentially the same conclusions as those given.

VIII. CONCLUSION

In the present attempt to determine the mean lifetime of V-particles, a worthwhile numerical analysis is permitted only for those cases in which the decay is consistent with equation (9). Although the accuracy of this analysis is somewhat limited because of the present state of knowledge concerning the exact type of decay involved, assuming any one of several alternative decay processes, which are consistent with the data, should not greatly alter the given results. For example, the results would be changed very little if a three-body decay proved to be the actual process rather than the assumed two-body decay.

Considering apparatus which is soon to be in operation, it is quite possible that many of the difficulties encountered here will be overcome because of the larger chambers which are to be used, the stronger magnetic field which is available, and other improvements which have been made in the apparatus and in the experimental techniques, It is likely that further investigation of lifetimes can be made, particularly for the neutral V treated here and for the short-lived charged V if additional evidence of its existence is found. There should also be an opportunity for investigation of the one or more additional types of neutral V's which have been proved to exist [7,8] but which have essentially been ignored in this thesis because of the small number of cases observed. For the apparently longer-lived tau and kappa mesons, the direct method here used in determining lifetimes is of doubtful value in obtaining good statistical accuracy since the gate times for useful events must be long and the frequency of observation of such decays has been quite low. Perhaps however, even this difficulty will be eliminated by the use of these larger chambers or by the use of techniques which will increase the frequency of observing slow particles.

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