D. Titanium

The titanium was in the form of a powder and came to us marked 98 to 99 percent pure. No marked resonances were shown to exist in the data (Fig. 5), but it did not correlate Aoki's results. Aoki has reported the following three points: 1.83 barns at 2.23 Mev, 2.15 barns at 2.55 Mev, and 2.05 barns at 2.85 Mev. The experimental accuracy of the final results was ± 1.7 percent.

E. Bromine

The element bromine in its liquid form was used, and it met the ACS specifications for purity. An indication of a peak was recorded at about 2.42 Mev. (Fig. 6). The experimental accuracy of the cross-section data was ± 1.7 percent.

F. Angular Correlation of Number of Neutrons

The data recorded afforded an experimental check with respect to the angular correlation of number of neutrons in the laboratory system.[20,21] The heavy line in Fig. 7 is the angular distribution of numbers of neutrons with respect to the forward direction of the beam with no corrections. The heavy dotted line is our data corrected for the $n-p$ cross section[3] in the energy region used. This gives an indication that the counter being used at present has an energy sensitivity variation depending principally on the $n-p$ cross section. Plans are being made to do more work to find out more about the properties of this particular counter.

The sudden dip in the curve at 89° was found to be caused by the fact that the neutrons produced at the inside surface of the copper sphere had to pass through a relatively long section of copper to get to the outisde of the sphere. This geometrical consideration was found to exist for our particular apparatus up to about 120° with respect to the forward direction of the beam, and it is seen from the Fig. 7 that the correlation is relatively good on either side of the above-mentioned region. This should not affect the total cross-section data, since it was a constant effect for all readings taken at any given position.

The authors wish to express their gratitude to the following men for assisting them continuously in this work: Mr. N. M. Schaeffer for building the counter; Mr. P. C. Cadenhead for assisting in operation of the accelerator, as well as taking data; Mr. B. P. Leonard, Jr., for assistance in the operation of the accelerator, as well as the calculations; and Mr. G. H. Olewin for assistance in building the apparatus.

[20] C. E. Mandeville, J. Franklin Inst. **244**, 391 (1947).
[21] Bretscher, French, and Seidl, Phys. Rev. **73**, 815 (1948).

PHYSICAL REVIEW VOLUME 90, NUMBER 4 MAY 15, 1953

Mean Lifetimes of V-Particles and Heavy Mesons*

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(Received February 2, 1953)

A maximum-likelihood procedure for determining mean lifetimes of V-particles from cloud-chamber data is 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 π-meson, a lifetime of $(2.5\pm0.7)\times10^{-10}$ 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 $\tau_L=(2.9\pm0.8)\times10^{-10}$ sec is found for those cases with $0\leqslant Q\leqslant 50$ Mev and a value of $\tau_H=(1.6\pm0.5)\times10^{-10}$ sec is found for those cases with $50<Q\leqslant150$ 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 that κ- and/or χ-mesons make up a part of these decays is considered.

I. INTRODUCTION

SINCE the first report of the discovery of neutral and charged V-particles by Rochester and Butler[1] and the subsequent confirmation of the discovery by Seriff *et al.*[2] 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

* Supported in part by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.
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[1] G. D. Rochester and C. C. Butler, Nature **160**, 855 (1947).
[2] Seriff, Leighton, Hsiao, Cowan, and Anderson, Phys. Rev. **78**, 290 (1950).
[3] Armenteros, Barker, Butler, Cachon, and Chapman, Nature **167**, 501 (1951).
[4] Thompson, Cohn, and Flum, Phys. Rev. **83**, 175 (1951).
[5] W. B. Fretter, Phys. Rev. **82**, 294 (1951).
[6] Leighton, Wanlass, and Alford, Phys. Rev. **83**, 843 (1951).
[7] Armenteros, Barker, Butler, and Cachon, Phil. Mag. **42**, 1113 (1951).
[8] Leighton, Wanlass, and Anderson, Phys. Rev. **89**, 148 (1953).

point to the existence of two or more different types of neutral V-particles and one or more types of charged V-particles. This paper 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

$$V^0 \rightarrow P^+ + \pi^- + Q.$$

While there is no assurance that additional neutral particles as light as the π-meson are not among the decay products, the above decay scheme will be assumed to hold for those cases in which the visible decay products are consistent with a proton and a negative π-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 π-meson into a μ-meson are included in the group of charged V-particles.

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 sufficiently large unbiased sample of V-particle decays of a single type has prohibited accurate results. Although the information now available on the decay of neutral V-particles is considerably more extensive than in the previously reported experiments, this difficulty is still apparent in the present work, which treats the decay of 134 neutral V-particles and 23 charged V-particles.[10]

The method used is a maximum-likelihood procedure, which essentially involves finding the value of the mean lifetime which maximizes the probability of obtaining the observed distribution of decay points in the chamber.[11] 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.

II. THE APPARATUS AND FIDUCIAL SURFACES

The apparatus used in this experiment[8] is shown schematically in Fig. 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.

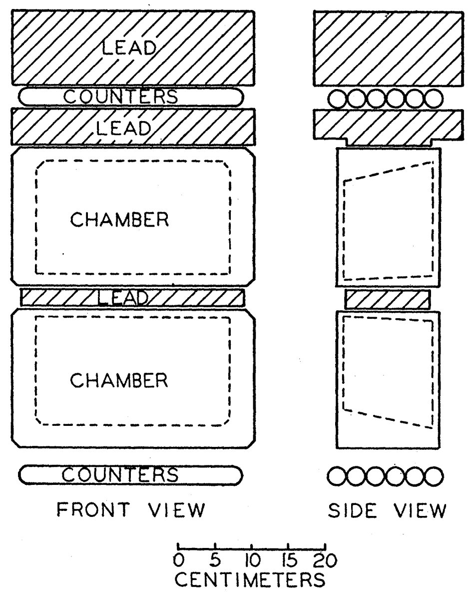

FIG. 1. The arrangement of the lead, counters, and cloud chambers. The dashed lines represent the fiducial surfaces.

Also shown in Fig. 1 are fiducial surfaces which are used in the measurement of certain geometrical quantities needed for the lifetime determination. These surfaces are 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 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 quantities which were used in the determination of the lifetime of the neutral V-particle are listed as follows: x_i is the distance between the point of entrance of the ith V-particle into the visible region of the chamber and the point of decay. d_i is the distance between the point of entrance of this 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

[9] Barker, Butler, Sowerby, and York, Phil. Mag. 43, 1201 (1952).

[10] A rather extensive analysis of these same events has been made by other workers whose findings are given in reference 8. 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.

[11] The maximum-likelihood procedure was used at the suggestion of Professor Leverett Davis, Jr. An independent treatment of the lifetime problem, also based upon the maximum-likelihood procedure, has recently been reported by J. G. Wilson and C. C. Butler, Phil. Mag. 43, 993 (1952).

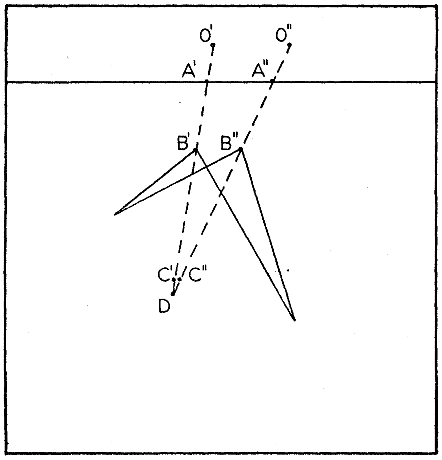

FIG. 2. A schematic diagram showing the superposition of the two stereoscopic views of a neutral V-particle decay.

to refer to this quantity. P_i is the momentum of the V-particle. t_i is the time taken to traverse the distance x_i. This time is given in the rest system of the V-particle. T_i is the time, measured in the rest system of the V-particle, taken to traverse the distance d_i. θ_i is the angle between the paths of the two charged decay products of the neutral V-particle. Q_i is the calculated energy release as given in reference 8. 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 π-meson was assumed.

The distances, x_i and d_i, were measured from the predetermined fiducial surfaces which were shown in Fig. 1 and discussed in Sec. II. The values of x_i and d_i 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 $0'$ and $0''$, 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_i, the momentum of the V-particle, was determined in one of two ways depending on the available information. If the momenta of the two decay products could be determined, P_i was calculated as the vector sum of these momenta. If the momenta of the decay products could not be determined, P_i was found from θ_i 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 c.m. system of the V-particle, the second of these 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_i 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_i and T_i, are given in the rest systems of the V-particles and are related to the distances, x_i and d_i, by the equations

$$t_i=(x_i/c)(M/P_ic) \quad \text{and} \quad T_i=(d_i/c)(M/P_ic).$$

M and P_ic are given in Mev so that P_ic^2/M is the product of the velocity of the V-particle and the time dilation factor. The mass of the neutral V-particle was taken to be 1120 Mev.[8]

In addition to the quantities mentioned above, one may feel that a knowledge of the time interval between the 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

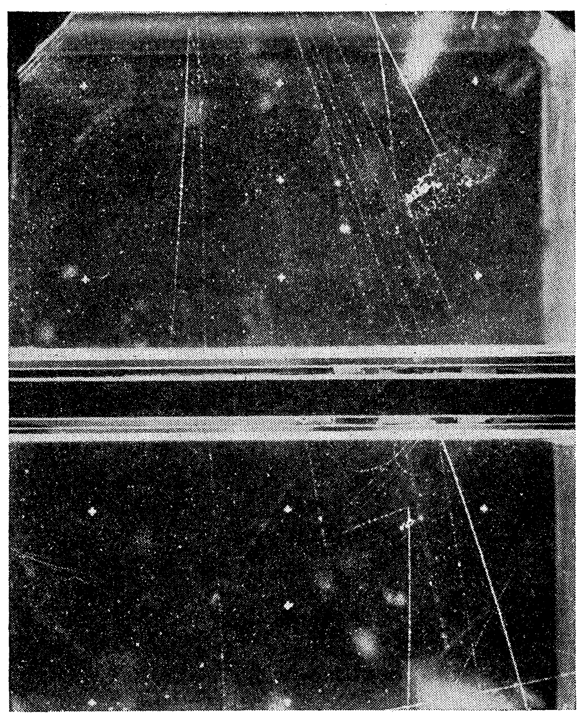

FIG. 3. Two examples of the decay of a neutral V-particle. The decay products are consistent with a proton and a negative pi meson. The trajectory of the V-particle in the lower chamber is described in part III.

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_i and T_i 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 or after passing through it. The only use which was made of the origins that were identified was in the determination of the direction along which to measure x_i and d_i. For those V-particles which had no identifiable origin, x_i and d_i were measured along the line determined by the vector sum of the momenta of the two decay particles. For fifteen percent 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_i, d_i, and x_i/d_i 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.

IV. METHOD OF CALCULATING THE MEAN LIFETIME

In treating methods of determining the mean lifetime of the radioactive substances, Peierls[12] in 1935, Bartlett[13] in 1936, and Hole[14] in 1947, have discussed the application of the maximum-likelihood procedure[15] 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_i's which vary over a rather wide range. The range in values of T_i is due to a difference in both the potential path lengths and the velocities of the V^0-particles. In spite of this difference the procedure with constant T_i is readily extended to cover the case in which T_i 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

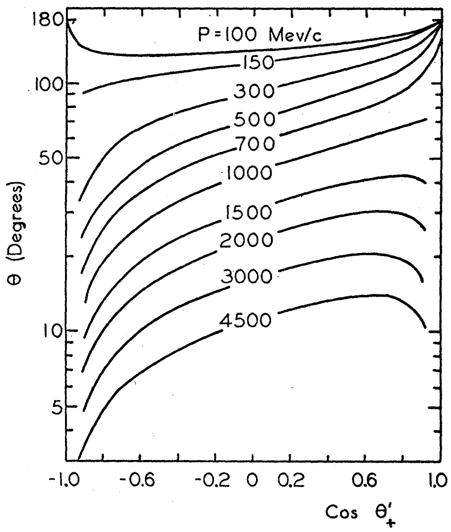

FIG. 4. Graph of θ vs θ_+' for various V-particle momenta. A two-body decay of a neutral V-particle into a proton and a negative pi meson with an energy release of 50 Mev is assumed. θ_+' is the angle, measured in the c.m. system of the V-particle, which the proton makes with the line of flight of the V-particle. P and θ are defined in Part III.

be "alive" at time $t=0$, has the probability

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

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[16] to unity so that

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

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

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

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 the value of τ for which L, or more conveniently $\ln L$, is maximum:

$$\partial \ln L/\partial\tau=0. \tag{4}$$

Carrying out the differentiation of $\ln L$ one obtains for

[12] R. Peierls, Proc. Roy. Soc. (London) **149**, 467 (1935).
[13] M. S. Bartlett, Proc. Roy. Soc. (London) **154**, 124 (1936).
[14] N. Hole, Arkiv Mat., Astron. Fysik **34B**, No. 12 (1947).
[15] R. A. Fisher, Trans. Roy. Soc. (London) **222**, 309 (1922).

[16] This normalization to unity essentially corrects for those particles which passed through the chamber and decayed after time T_i. Peierls 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.

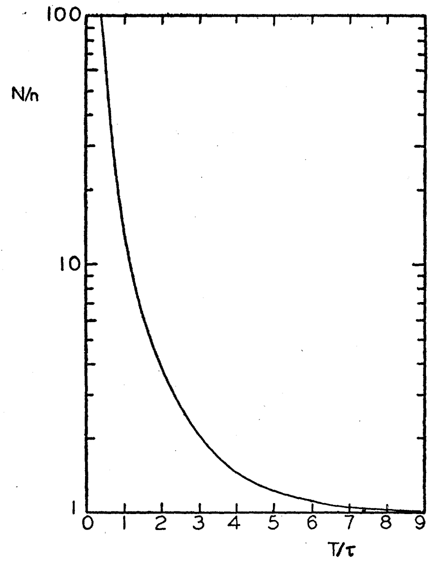

FIG. 5. The ratio N/n, as defined in Eq. (8), is plotted *versus* the ratio of the gate time to the mean lifetime.

the best value of the mean lifetime

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

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 for the V^0 particle, Eq. (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

$$\Delta\tau=1/\sqrt{I}, \tag{6}$$

in which I is defined by the equation

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

Equation (6) is derived on the assumption that the estimates of the parameter, τ, are normally distributed as the variance of $\partial \ln L/\partial\tau$.[12] 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_i are the same and to consider the quantity, n, which is given by

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

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 Fig. 5.[17] 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 average value of 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 $\langle(t_i/T_i)\rangle_{\text{Av}}$ would be equal to one-half. Thus, one can hope to use the cloud chamber to measure mean lifetimes only if $\langle(t_i/T_i)\rangle_{\text{Av}}=\langle(x_i/d_i)\rangle_{\text{Av}}$ is significantly less than one-half.

Further uncertainty in the lifetime is due to the limitations of the experimental technique and to a lack of exact knowledge of the decay process or processes which are taking place. In each of the lifetime determinations which are given here, 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_i, x_i, and d_i do not contribute very large errors to the mean life, τ. For most cases x_i and d_i 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 percent, the resulting error in the mean lifetime should be small compared with the statistical error given by Eq. (6).[18]

V. THE MEAN LIFETIME OF NEUTRAL V-PARTICLES

In a series of 23 000 cloud-chamber photographs taken at Pasadena and on Mt. Wilson, 134 examples of the decay of neutral V-particles have been obtained. The distribution of the decays is shown in Fig. 6. Data on 74 of these examples which were consistent with the

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

[18] 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 thus introduced into the sample.

decay scheme

$$V^0 \rightarrow P^+ + \pi^- + Q, \quad (9)$$

were used in the present calculation. The remaining 60 decays were 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 $\leqslant 10°$, or
(3) the decay did not seem to fit the proton plus negative π-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 nonuniform 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 are independent 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 was not directly measureable could have been eliminated by throwing out those cases with $\theta \leqslant 20°$; 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 Eq. (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.

A mean lifetime was calculated for the remaining 74 examples from the t_i and T_i, assuming that these decays follow the two-body decay scheme given above. 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. Substitution of the numerical data into Eq. (5), gave 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 Eq. (5), one obtains for τ the value

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

The statistical error has been computed by use of Eqs. (6) and (7). Although the effect of additional errors in the experimental quantities is difficult to determine, an

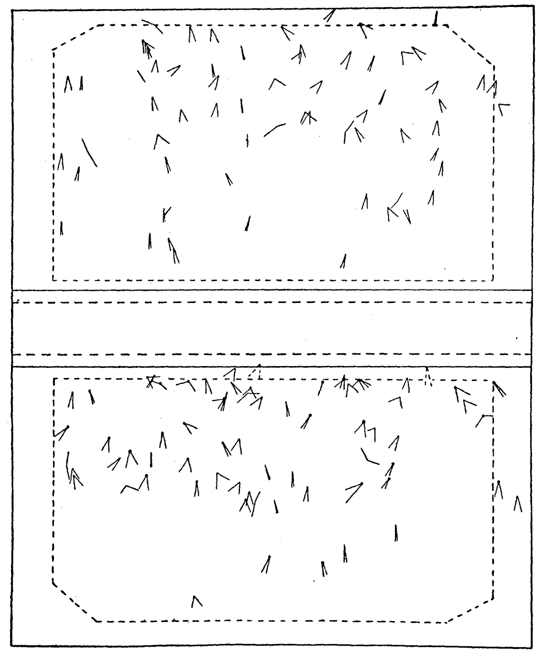

FIG. 6. The distribution of the neutral V-particle decay points. A dot at the apex indicates production in the lead plate between the two chambers. A dashed track signifies a hidden apex.

attempt has been made to estimate 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 percent or less, while for the remaining cases, whose momenta were determined solely from the value of θ_i, there was an appreciable probability of errors as large as one hundred percent. The errors in x_i and d_i were small compared with these errors in P_i. 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 days 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 lifetime calculated for the remaining cases with Q either less than 30 Mev or greater than 40 Mev.

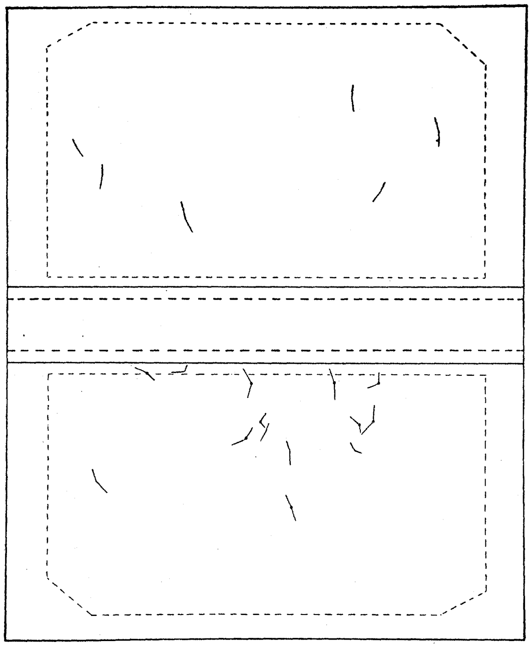

FIG. 7. The distribution of the charged V-particle decay points. A dot at the apex indicates production in the lead plate between the two chambers.

(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 percent.[19] The mean lifetime was then redetermined and found to agree within ten percent with the above value. The same result was found when each gate time was reduced by thirty-three percent.

The separate lifetime determinations for the 32 decays occurring in the upper chamber and for 42 decays occurring 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 percent 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-particles were all or almost all of one kind or that different kinds, if present in comparable numbers, were of 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-particles which were observed might follow the decay scheme of Eq. (9) with Q near 37 Mev, and the remainder the three-body scheme:

$$V^0 \rightarrow P^+ + \pi^- + \nu + Q, \tag{11}$$

with the apparent energy release calculated on the basis of the decay scheme of Eq. (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 reference 8. This analysis suggested the possible existence of two groups of V-particles which follow the decay scheme of Eq. (9), but with different values of the energy release, Q, and possibly 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 $Q \leqslant 50$ Mev were placed in a "low Q" group and 20 cases with 50 Mev $< Q \leqslant 150$ Mev, were placed in a "high Q" group. Substituting the data for the 37 low Q cases into Eq. (5), a lifetime of $\tau_L = (2.9 \pm 0.8) \times 10^{-10}$ was obtained. Again the error has been computed by using Eqs. (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,[20] 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 Q-value are added in but weighted by the factor 20/57. Other possible division schemes were tried in 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} sec were $1.3 < \tau_H < 2.3$ and $2.4 < \tau_L < 3.5$. 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.[21]

VI. 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.

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

[20] This weighting factor divides the cases in proportion to the number of known Q-values in each group.

[21] R. J. Finkelstein, Phys. Rev. 88, 555 (1952).

For most of these 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 Fig. 7 is suggestive of the existence of more than one type of particle 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 Fig. 6 indicates a somewhat shorter mean free path for the charged V-particle.[22] Since ionization estimates show that P/M is, on the average, greater for the charged V-particles than for the neutral V-particles, 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 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 unity, to be compared with one-half for neutral V-particles with identifiable origins. This comparison again points to a shorter average lifetime for the combined cases of charged V-particles than for the neutral V-particles.

On the other hand, the decays shown in Fig. 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-particles. In addition, two examples, in which a relatively slow particle of estimated mass between that of the proton and the π-meson has been observed to decay into a particle consistent with a π- or μ-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-particles are identical with these two examples and are probably κ- or χ-mesons[23,24] with a mean lifetime of 10^{-9} sec or greater.[25]

[22] The arguments based on this over-all comparison of neutral and charged V-particles are weakened somewhat because of the unequal efficiency of observing the two types of decay. A small deflection in the track of 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.

[23] R. B. Leighton and S. D. Wanlass, Phys. Rev. **86**, 426 (1952).

[24] C. O'Ceallaigh, Phil. Mag. **42**, 1032 (1951).

[25] 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.

In addition to those events which have been described as charged V-decays and which may in part be κ- or χ-mesons decaying respectively into a μ- or π-meson plus one or more neutral particles, two examples have been obtained[23] of a charged particle decaying into three charged particles. Each of the three decay products in these two events has a mass consistent with that of a π-meson and the primary particle appears to be identical with the τ-mesons which have previously been observed in nuclear emulsions.[26] Although a reliable estimate of the lifetime of this particle cannot be made from only two cases, the relatively long paths of these τ-mesons in the chamber before decay and the estimates of P/M indicate a mean lifetime greater than that of the neutral V-particle, and perhaps greater than 10^{-9} sec.

VII. CONCLUSION

In the present attempt to determine the mean lifetime of V-particles, a worth-while numerical analysis is permitted only for those cases in which the decay is consistent with Eq. (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.

Apparatus which is now in operation should overcome many of the difficulties encountered here, because of the larger chambers which are 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-particle treated here and for the short-lived charged V-particle, 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-particles which have been proved to exist[7,8] but which have essentially been ignored in this paper because of the small number of cases observed. For the apparently longer-lived κ-, χ-, and τ-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.

[26] Brown, Camerini, Fowler, Muirhead, Powell, and Ritson, Nature **163**, 82 (1949).

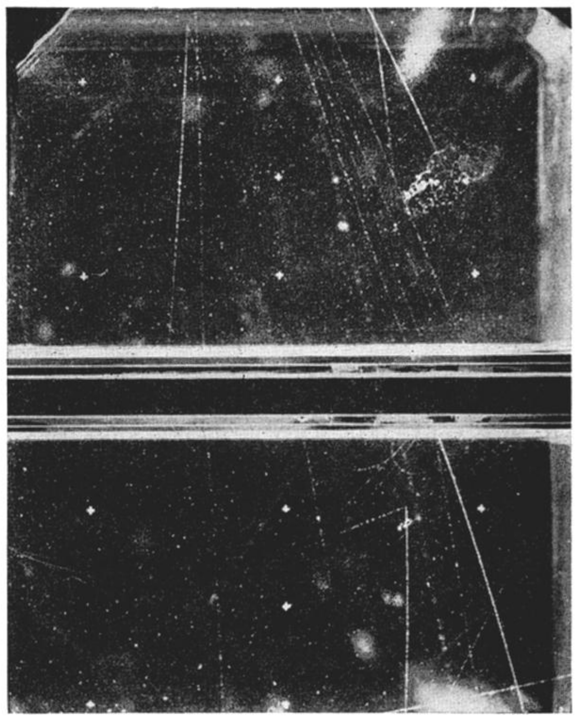

FIG. 3. Two examples of the decay of a neutral V-particle. The decay products are consistent with a proton and a negative pi meson. The trajectory of the V-particle in the lower chamber is described in part III.