PHYSICAL REVIEW VOLUME 89, NUMBER 1 JANUARY 1, 1953

The Decay of V^0 Particles*

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(Received September 15, 1952)

In a set of 23,000 cloud-chamber photographs taken in a study of penetrating showers, 134 examples of the decay of neutral V-particles, and 18 of the decay of charged V-particles, were observed. An analysis of the 152 examples leads to the following principal conclusions: (1) V-particles result from the impact of mesons and probably also of nucleons, upon nuclei. (2) V-particles are generally produced singly and not in pairs. (3) Two independent kinds of data, one based on measurements of angles and other purely spatial relationships, and the other based on measurements of momentum and specific ionization, lead to the conclusion that more than 80 percent of these neutral V-particles decayed by the production of a heavy positive and a light negative particle. The mass of the heavy positive particle in most instances was consistent with that of a proton, but in a few cases may have been somewhat less. The negative particle appeared most often to be a π-meson, although in a few cases a μ-meson was indicated. In about 7 percent of the cases, the positive particle was light and had a mass consistent with that of a π- or μ-meson. In these cases the mass of the negative particle was not well determined. So far, therefore, in these investigations, there is no direct evidence that a neutral V-particle decays into two π-mesons, or into a positive π-meson and a negatively charged proton, although a few cases may be so interpreted. (4) The data are consistent with the assumption of a two-body decay for a majority of the neutral V-particles, and therefore a rather extensive analysis is given based upon this assumption. (5) The energy release, or Q-value, of the decay of neutral V-particles was computed, on the assumption of a two-body decay, for those cases in which the production of a heavy positive particle was clearly indicated, and where momentum measurements were possible. On the assumption of a decay into a proton and a π^- meson, the Q-values obtained ranged from 10 Mev to about 100 Mev. The great majority of cases, however, may be described in terms of discrete Q-values at 35 ± 3 Mev, and 75 ± 5 Mev, although, of course, the data are consistent with distributions about these values. For the same set of cases, if the positive particle is assumed to be as light even as $1250m_e$, and/or the negative particle is assumed to be a μ-meson, the distribution of Q-values is not greatly changed, and the apparent necessity for at least two different Q-values remains. In those few cases mentioned in (3) above, in which the positive particle was light, and in which the mass of the negative particle was undetermined, the energy release, computed on the basis of a two-body decay, depends upon the assumed identity of the decay products, and is about 100–130 Mev for the assumption that two π-mesons are produced, about 50–80 Mev for a positive π-meson and a negative τ-meson, and about 30–80 Mev for a positive π-meson and a negative proton. (6) The rest mean lifetime of V^0 particles, which appear to yield protons and π^--mesons as decay products, was found to be 1.6×10^{-10} sec for 26 cases having Q-values greater than 50 Mev, and 2.9×10^{-10} sec for 48 cases having Q-values less than 50 Mev, on the assumption of a two-body decay. In view of the rather poor statistics, the above two lifetimes are consistent with a single value, and lead to an average of $2.5\pm0.7\times10^{-10}$ sec. The above lifetimes are not appreciably changed if a multibody decay of the neutral V-particle is assumed. (7) The data are not adequate to distinguish conclusively between a two-body and a multi-body decay, and, therefore, a discussion is also given in terms of a variety of possible decay schemes of the neutral V-particle.

I. INTRODUCTION

In the few years since V-particles were first observed[1] in cosmic-ray penetrating showers, their existence has become firmly established,[2] and some of their properties have been determined.[2–7] The present paper reports some of the results of an analysis of an additional 134 cases of the decay of neutral V-particles and 18 cases of the decay of charged V-particles which occurred in a set of 23,000 cloud-chamber photographs. These results seem to indicate a rather great complexity in the phenomena associated with the decay of V-particles, and do not provide complete answers even to such obvious questions as those concerning the number and identity of the decay products. In some respects they substantiate conclusions drawn from previous observations, and in other respects they do not. Oftentimes an unambiguous choice between various alternatives of interpretation is precluded by the rather large inherent errors in some of the measurements and by the statistical character of the available information. An attempt has been made throughout to allow properly for these limitations in the data.

II. APPARATUS

The apparatus used in these experiments was a counter-controlled double cloud chamber operated in a magnetic field. Each chamber was rectangular in shape, approximately 33 cm wide, 19 cm high, and of 12 cm illuminated depth. Between the two chambers was a space approximately 2.5 cm high, which was occupied by a lead plate of that thickness; the total amount of absorber between the chambers, including the brass chamber walls, was 34 g/cm^2. The chambers were illuminated from the side by light, from a linear quartz flashtube, which passed through a glass cylindrical lens system; the energy used per exposure was about 500 joules. Stereoscopic exposures were made on 70 mm Kodak Linagraph Pan film using a lens opening of $f/11$ and a magnification of 6.3× from film to cloud chamber. The centers of the lenses were 14 cm apart, and 93 cm from the rear plane of the cloud chambers. The cham-

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* Supported in part by the joint program of the ONR and AEC.

[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**, 113 (1951).

bers were filled with pure argon gas, and a saturated mixture of 65 percent ethyl alcohol and 35 percent water, to a total gauge pressure of 20 cm of Hg. The expansion ratio was about 1.07.

The magnet, of pole diameter 45 cm, was operated at an induction of 5000 gauss at a power of 13 kw. The rectangular pole faces, between which the chambers were situated, were thermostatted within approximately ±0.1°C, as were the copper-lined walls of an insulated box which surrounded these pole faces and the cloud chambers. In spite of these precautions, distortions were sometimes present, so that the maximum detectable momentum for long tracks varied from about 2 Bev/c to about 5 Bev/c.

The arrangement of counters and lead around the chambers is shown in Fig. 1. The lead blocks were placed as close as possible above the upper chamber, in order to minimize the loss of V-particles through decay. The rectangular shape of the chambers was well suited to this purpose. The top tray of six 1 in.×12 in. counters was well shielded against soft radiation by 10 cm of lead above, 5 cm of lead below, and by the magnet windings at front and rear. The lower tray of six 1 in.×12 in. counters was located immediately below the lower chamber and was shielded only by the chambers and magnet windings.

A pulse-height-discrimination-coincidence circuit was used to select events in which any n or more counters of the upper tray, and any m or more of the lower tray, were discharged simultaneously. Such an event is here called an $n-m$ coincidence. In part of the experiment the apparatus was situated at 220 m elevation, where 1–3 coincidences were used; in another part it was located at 1750 m elevation, where 1–3 coincidences, and later 2–3 coincidences, were used. The 1–3 counting rate at 220 m elevation was about 4 hr^{-1}, and at 1750 m, about 12 hr^{-1}. At 1750 m the 2–3 counting rate was about 3.5 hr^{-1}.

The chamber was allowed about two minutes for recovery after each expansion, during which time a coincidence could not actuate it. Thus the rate at which the chamber operated was somewhat less than the above counting rates.

The results to be described are based upon a total of 23,000 photographs of which 14,000 were taken at 220 m elevation with 1–3 coincidences, 7000 at 1750 m with 1–3 coincidences, and 2000 at 1750 m with 2–3 coincidences. At 220 m, about 8 percent of the photographs, and at 1750 m, about 20 percent of the 1–3 photographs and about 40 percent of the 2–3 photographs, showed penetrating showers (i.e., two or more collimated, time associated, nonelectronic particles). The figures here given represent lower limits to the percentage of cases in which the chamber was actuated by a penetrating shower, for many additional photographs showed slow protons and mesons, or other evidences of a penetrating shower.

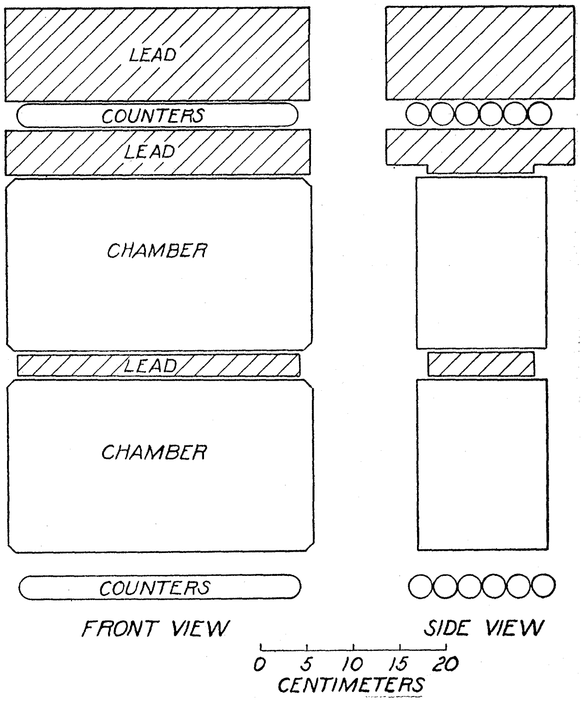

FIG. 1. The arrangement of counters and lead blocks around the cloud chambers. Only the inner walls of the chambers are indicated; the pole structure, yoke and magnet windings, which constituted additional absorber, are not shown.

III. THE PRODUCTION OF V-PARTICLES

In this set of photographs, a total of 134 V^0 particles, 7 V^+ particles, and 11 V^- particles were observed to decay. Ten photographs showed more than one V-particle: in 3 cases, two V^0 decays; in 1 case, three V^0 decays; in 4 cases, one V^0 decay and one $V^\pm$ decay; and in 2 cases, two $V^\pm$ decays. Only in three of these cases, however, did the V-particles appear to be produced in the same nuclear event. Examples of V-particle decay are shown in Figs. 2–5.

In order to investigate the manner in which V-particles are produced, it is useful to classify them according to the circumstances of their occurrence. Considering first the neutral V-particles, one finds that 72 occurred in penetrating showers whose origins were in the lead blocks above the chambers, 37 were produced in nuclear interactions (or stars) in the lead plate between the chambers, and 25 occurred alone in the chamber, or were not clearly associated with any nearby event. Of the 37 stars in the lead plate from which V^0 particles emerged, 27 were produced by charged particles which were themselves penetrating shower secondaries from a nuclear collision somewhere above the chamber,[8] 6 were produced by single charged particles, unaccompanied by

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[8] In order to be sure that an event was actually initiated by a charged particle, it was required that this particle should have been visible in the lower chamber, had it traversed the plate without deflection, and that it actually be deflected by at least five degrees at a point coinciding, within the accuracy of measurement, with the nuclear event in question.

FIG. 2. Example of the production of a V^0 particle by a single charged particle. The initiating particle enters the lead plate between the chambers almost vertically from above and slightly to the right of the center of the chamber. In the lead plate it undergoes a nuclear collision, from which six charged particles, the V^0 particle, and an unknown number of neutral particles emerge. The V^0 particle decays near the bottom of the lower chamber into a heavily-ionizing positive particle and a negative particle of about minimum ionization. These products are probably a proton and a π^- meson, respectively. The shortness of the tracks does not permit accurate measurements of the momenta.

a shower or other indication of nearby nuclear events, and 4 were apparently produced by neutral particles. A similar classification of the charged V-particles showed that: 9 of these occurred in penetrating showers whose origins were above the chamber, and 9 were produced in stars in the lead plate. Of the 9 stars in the lead plate yielding charged V-particles, 8 were initiated by charged penetrating-shower secondaries, and 1 was produced by a single charged particle. None of these stars was produced by a neutral particle.

It has been generally supposed that V-particles are produced in energetic nucleon-nucleon collisions, presumably with about equal cross-section in $n-n$, $n-p$, or $p-p$ collisions. The above observations indicate, however, either (1) that protons are many times more effective in producing both charged and neutral V-particles than are neutrons, (2) that energetic protons are many times more numerous than energetic neutrons, or (3) that *meson*-nucleon collisions can result in V-particle production. Of these alternatives, the last appears to be the most acceptable in view of the large body of experimental evidence in favor of charge-independence of nuclear forces.

It would thus appear that in this experiment the great majority of both the neutral and charged V-particles were produced by mesons. However, this result does not necessarily indicate a larger cross section for V-particle production by mesons than for production by nucleons, since the number of high energy mesons present in a penetrating shower is known[9] to be much greater than the number of high energy nucleons. Also, V-particle production by mesons does not necessarily imply production by π-mesons, or by π-mesons alone, since it is now thought[10] that, at the very high energies prevailing in the original nuclear collisions with which we are here concerned, other heavier mesons may be produced about as copiously as are π-mesons.

A second conclusion regarding V-particle production,

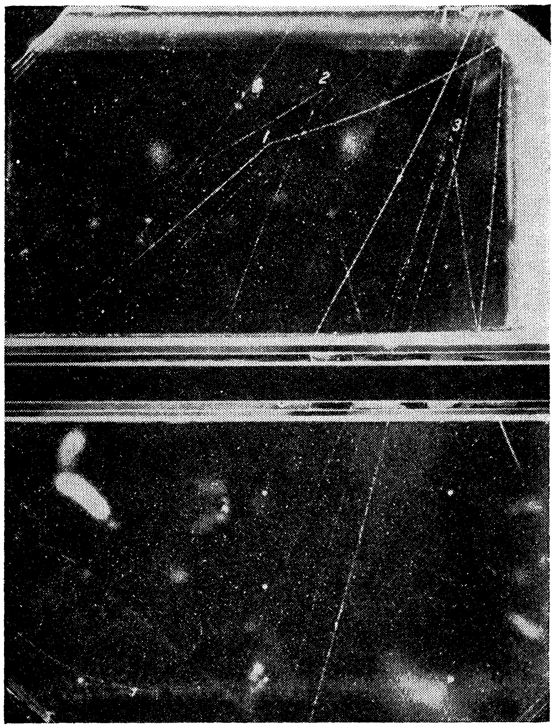

FIG. 3. A rare example of the production of several V^0 particles in a single nuclear event. Most of the tracks in the upper chamber are those either of secondary particles from a nuclear event in the lead blocks above the chamber, or of V^0 particle secondaries. Two of the three V^0 decays (Nos. 2 and 3) are in excellent alignment with the origin of the nuclear event, while No. 1, both of whose decay particles are heavily ionizing, is not aligned with this origin. This indicates either that this last decay yields three or more secondary particles, or that the assumed line of flight of the V^0 particle is not the correct one for this case. All of the decay tracks are consistent with the assumption that the negative particles are π-mesons, and that the positive particles are protons. The energies released in these three cases, assuming two-body decay, are $Q_1=41\pm7$ Mev, $Q_2=51\pm8$ Mev, and $Q_3=34\pm7$ Mev. Unfortunately, the distortions in the upper chamber were unusually severe.

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[9] Camerini, Davies, Fowler, Franzinetti, Muirhead, Lock, Perkins, and Yekutieli, Phil. Mag. **42**, 1241 (1951).

[10] Bristol Conference on V-particles and Heavy Mesons, December, 1951 (unpublished).

namely, that they are probably not always produced in pairs, can be deduced from the number of multiple V-particle decays that were observed in this series of photographs. For, if V-particles were always produced in pairs, one would expect to have seen many more cases than were observed in which two V-particles decay inside the cloud chamber. Consider, for example, V-particles that are produced in collisions in the lead plate between the chambers. Assuming a mean rest lifetime of 3×10^{-10} sec[2], and a time dilation factor of 5 (as a reasonable upper limit), one can calculate a probability of approximately 0.2 as a lower limit that the decay of such a V-particle would occur in the lower chamber. For slower speeds of travel, the probability of decay inside the lower chamber is greater than this, except for speeds less than about $\beta=0.1$, which seem quite unlikely to occur in view of the high energies in these events. Thus one would expect that, in at least 7 of the 37 cases in which V^0 particles were produced in the lead plate and were observed to decay in the lower chamber, a second V^0 particle or a $V^\pm$ particle would have been observed also. This is to be compared with the single such case in which a V^0 particle and a V^+ particle, produced in the same star in the lead plate, both decayed inside the chamber. This result alone strongly suggests that V-particles are not produced in pairs; a less direct suggestion follows from the fact that the number of double V^0 decays, in which the origins of the two particles are different, actually exceeds the number in which both proceed from the same origin. The possibility is not excluded, of course, that a V-particle may be produced along with another particle whose mean rest lifetime is either much longer or much shorter than 3×10^{-10} sec.†

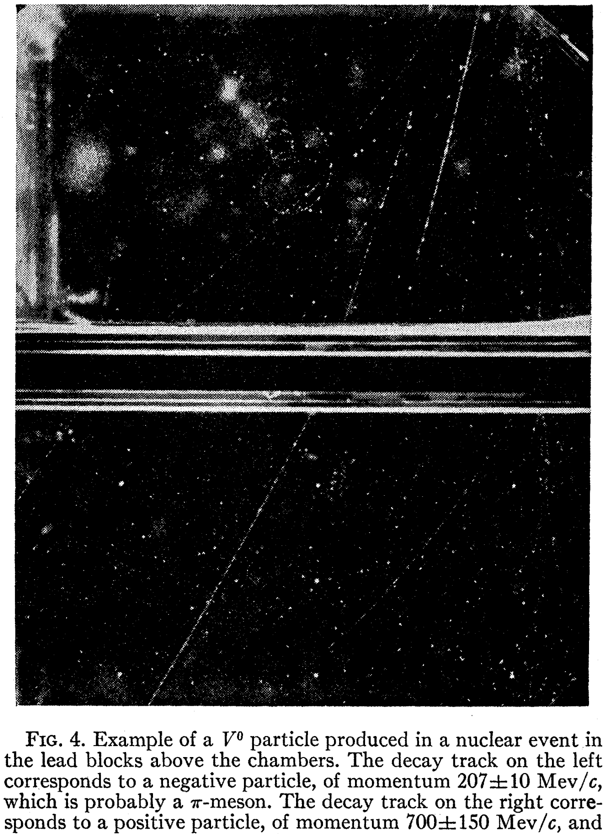

FIG. 4. Example of a V^0 particle produced in a nuclear event in the lead blocks above the chambers. The decay track on the left corresponds to a negative particle, of momentum 207±10 Mev/c, which is probably a π-meson. The decay track on the right corresponds to a positive particle, of momentum 700±150 Mev/c, and is probably a proton, but in the lower chamber its ionization and momentum indicate a somewhat lower mass. The energy release, assuming the products to be a π-meson and a proton, is $Q=42\pm6$ Mev.

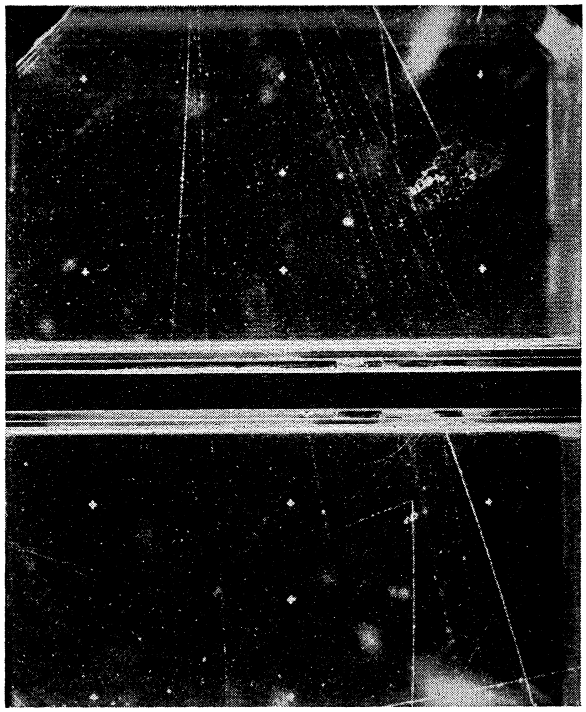

FIG. 5. Example of unrelated V^0 decays. One V^0 decay occurs very near the top and somewhat to the left of the center of the upper chamber, yielding a heavily ionizing positive particle which travels downward and toward the camera, and a lightly ionizing negative particle whose tracks is very short. This V^0 particle is probably produced in the same nuclear event, in the lead blocks above the chamber, that gives rise to the penetrating shower to the right. One of these shower particles in turn undergoes a nuclear collision in the lead plate between the chambers, from which a second V^0 particle emerges. This V^0 particle decays above the center of the lower chamber, and similarly yields a heavily ionizing positive particle which travels almost vertically downward, and a lightly ionizing negative particle whose track length is short. Both of the negative particles in these decays are ejected at such angles that they pass out of the front or rear wall of the chamber after traveling only a short distance. The positive particles in both of these decays are probably protons, although that of the lower decay may be somewhat lighter than a proton. The energy release of the lower decay is $Q=37\pm5$ Mev. That of the upper decay is not known, since the meson track was not measurable.

IV. THE PRODUCTS OF NEUTRAL V-PARTICLE DECAY—COPLANARITY

Before discussing the more complicated measurements that can be used to study the products of V^0 decay, we shall first derive some information concerning the

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† Of course, if a substantial fraction of the neutral V-particles were to decay into neutral particles, the above conclusion would be weakened.

number and identity of these products by making use of certain purely geometrical properties of the decay. One of these properties is the so-called "coplanarity" of the decay, i.e., the angular relationship between the line of travel of the V^0 particle and the "decay-plane" defined by the tracks of its two charged decay products; another is the angular relationship of each charged particle track to the line of travel of the V^0 particle.

To measure the angular deviation from coplanarity for a given decay, one must know the path of the V^0 particle as well as the paths of its two charged decay products. This information is available in those cases where the event in which the V^0 particle originated also yielded a number of charged particles whose tracks appear in the chamber. The path of the V^0 particle is then taken to be along the straight line connecting this origin (located by backward extrapolation of the charged particle tracks) with the point at which the decay occurred.

In these experiments the numerical data required for calculating the orientations of the decay-plane and the path of the incident V^0 particle were obtained in each case from a graphical construction. A sheet of tracing paper was placed on a viewing screen upon which the two sets of track images from the stereoscopic photographs were projected. Careful pencil traces were then made of the two track-images of the V-particle and of other particles on the photographs. The additional required graphical constructions were also made on the same sheet of paper.

Figure 6 illustrates schematically the reprojection system used. In this system, which was optically identical to the camera system, the surface of the viewing screen was made to correspond to the rearmost interior surface of the cloud chamber. Fiducial marks, scribed on this cloud chamber surface and present on each photograph, were brought into register on the screen—thus assuring the spatial correspondence of these surfaces. A point, P, in the interior of the cloud chamber thus appeared upon reprojection as two points separated by a distance Δx given by the formula,

$$\Delta x = zS/(D-z), \tag{1}$$

where the symbols are defined in Fig. 6. In the present experiment the quantities S and D were, respectively, 14 cm and 93 cm.

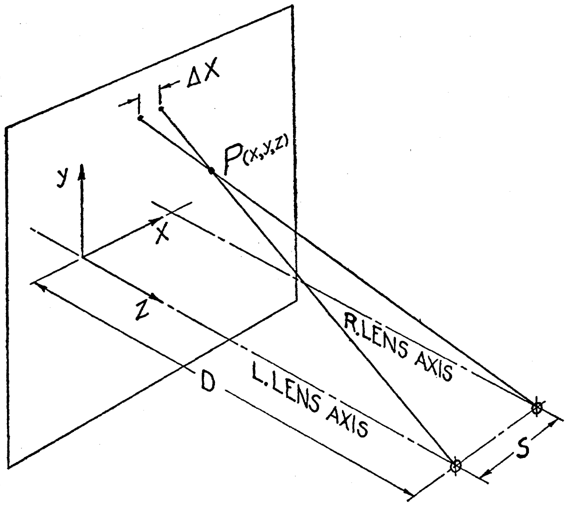

FIG. 6. Perspective diagram of the geometry of the reprojection system. The two stereoscopic views were reprojected through the same optical system as was used in the original camera, onto a screen perpendicular to the two camera axes. A point P, which lay at the point (x, y, z) when photographed, thus reprojects into two points on the screen. These two points are separated by an amount Δx, given by Eq. (1) of the text.

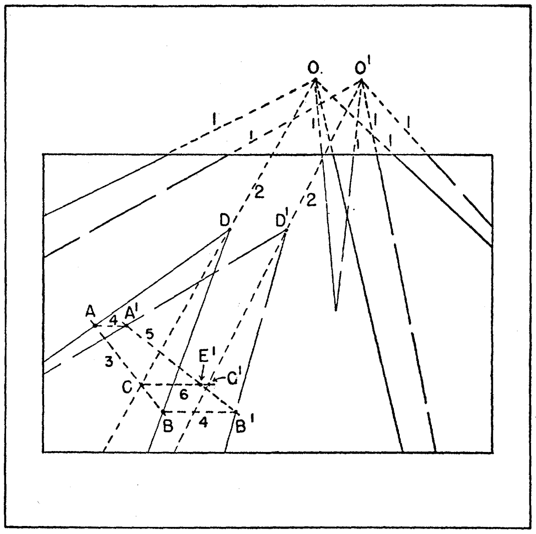

FIG. 7. Schematic diagram of the coplanarity test. The larger rectangle represents the screen, the smaller one the boundaries of the visible region of the cloud chamber. The two sets of tracks resulting from projection through the left and right lenses are shown dashed and solid, respectively. If the V^0 path (DC, $D'C'$) lay in the decay-plane (ADB, $A'D'B'$), the two points E' and C' would coincide.

The construction by which the deviation from coplanarity was measured is represented schematically in Fig. 7. The two sets of track images resulting from projection through the left and right lenses are shown dashed and solid, respectively. In the case of V-particle secondaries, tangents to the tracks at the apex of the decay were used, instead of the tracks themselves. Auxiliary lines are shown dotted and are numbered in the order of their construction. First, the tracks radiating from the origin of the V-particle are projected backward to their intersection point (O, O'). Next, the path of the V^0 particle (OD, $O'D'$) is constructed and extended beyond the decay point (D, D'). The problem now consists in determining the angle that this extended line makes with the decay-plane, namely, the plane formed by the two lines (DA, $D'A'$) and (DB, $D'B'$). To accomplish this, an arbitrarily chosen sloping line (AB, $A'B'$), lying in the decay-plane is drawn as indicated. (Note how points A' and B' are found by construction lines 4 drawn parallel to DD'.) Upon the

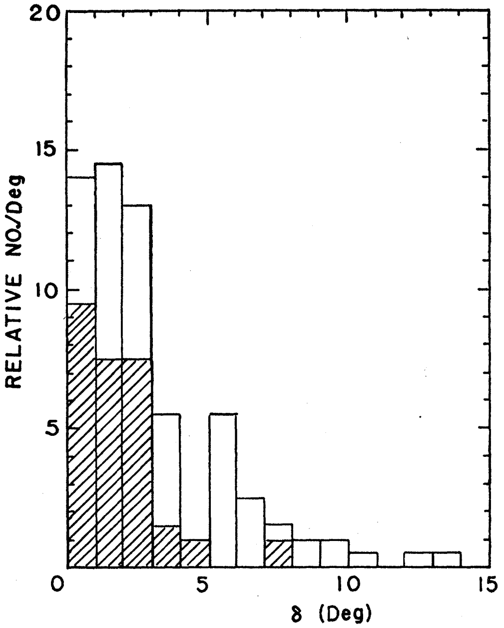

FIG. 8. Distribution of angular deviation δ from coplanarity for 60 cases. The cross-hatched portion of the distribution represents the contribution of the 28 cases whose estimated errors of measurement were 2° or less.

completion of lines 5 and 6, two points appear which are of particular importance, i.e., a point (C, C') on the extended V^0 path, and a point (C, E') in the decay-plane. The horizontal distance $E'C'$ on the diagram can readily be converted by Eq. (1) into a difference in depth of these two points. This in turn is then readily converted into an angle δ between the line $(DC, D'E')$ and the V^0 path $(DC, D'C')$ and thence to the angle δ_1 between the V^0 path and the decay-plane. The last step was rarely taken, since δ is always larger than δ_1, and thus provides a sharper test of coplanarity.

The accuracy with which it is possible to carry out the above construction varies from case to case for several reasons: The accuracy with which an origin can be located depends upon the number of tracks available for the backward extrapolation, and the distance of the extrapolation (sometimes as great as 20 cm); the angular accuracy with which the V^0 path can be drawn depends upon the distance from the V^0 particle decay-point to the origin; the accuracy with which tangents to the decay-tracks can be drawn depends upon the length of the tracks; and the sensitivity of the coplanarity test depends upon the orientation of the V^0 decay, it being most sensitive when the decay-plane is seen edgwise in one camera view. The over-all accuracy with which the coplanarity could be measured thus varied from about 1° to about 10°, but was usually in the range 2°–4°. This accuracy represents a significant improvement over that of a previously reported result.[2]

Sixty of the 134 V^0 decays exhibited origins and thus could be analyzed for coplanarity. Of these, 37 had origins in the lead plate between the chambers, and the remaining 23 had origins in the lead blocks above the chambers. The distribution of δ for these 60 cases is shown in Fig. 8. The cross-hatched portion of the diagram represents the 28 most accurate cases obtained by eliminating all those whose estimated error of measurement is greater than 2°. It appears from this distribution that almost all of the decays could have been exactly coplanar, and hence could have been two-body decays.

Perhaps a more meaningful test of coplanarity is a comparison of the measured deviation δ with the smaller of the two angles, θ_+ or θ_-, (see Fig. 10) between the charged particle tracks and the V^0 path, since in any case δ cannot exceed the smaller of these angles. The ratio $\sin\delta/\sin\theta_s$ (where θ_s denotes the smaller of the two angles) is a quantity which compares approximately the components, perpendicular to the decay-plane, of the momentum of the V^0 particle, with the component, perpendicular to the V^0 path, of the momentum of one of the charged products. The distribution of $\sin\delta/\sin\theta_s$ is shown in Fig. 9. Again almost all of the decays could have been coplanar, and hence could have been two-body decays. However, we cannot rule out any type of decay in which the transverse momentum carried by a third decay particle is on the average less than about 50 percent of that carried by one of the charged particles. Several decay processes can be imagined which would satisfy this condition. Some of these will be discussed later.

Since the observed distributions of δ and $\sin\delta/\sin\theta_s$ are wholly consistent with a two-body mode of decay for at least a large fraction of the V^0 particles, we shall continue our analysis, for the time being, under the assumption of a two-body decay, and then later consider the data in terms of possible multibody decay schemes.

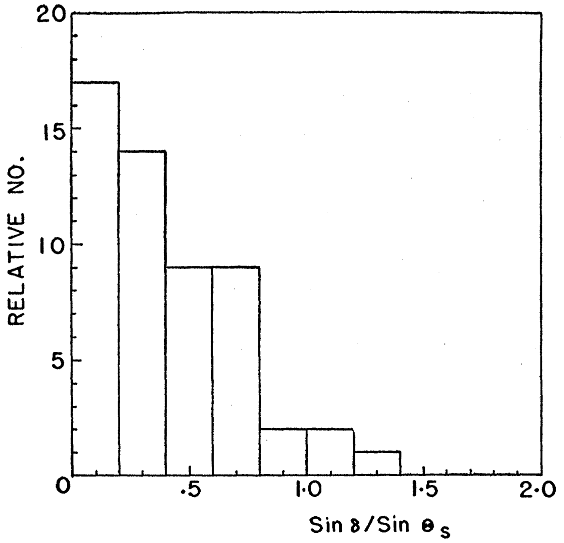

FIG. 9. The distribution of $\sin\delta/\sin\theta_s$ for 54 cases. The entire width of this distribution could have been due to errors of measurement or to scattering of the V^0 particle before decay, so that almost all of the decays could have been exactly coplanar.

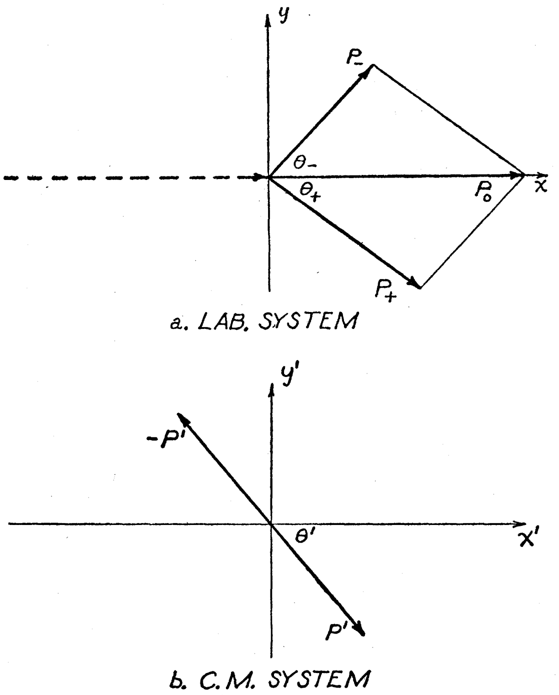

FIG. 10. Momentum diagrams of the decay $V^0 \rightarrow M_+ + M_- + Q$ as seen in the laboratory system (cloud chamber) and in the center-of-mass system moving with the V^0 particle.

V. THE PRODUCTS OF NEUTRAL V-PARTICLE DECAY —FURTHER GEOMETRICAL CONSIDERATIONS

A second property of V^0 decay which provides information concerning the decay products is the size of θ_+ relative to θ_-. Consider the two-body decay of a V^0-particle of mass M_0 into charged particles of mass M_+ and M_- (Fig. 10). In the center-of-mass system (henceforth denoted by c.m.) each particle has a momentum of magnitude P', and the positive particle is emitted at an angle θ' with respect to the direction of travel of the V^0 particle. In the laboratory system, moving with speed $-\beta c$ along the x axis relative to the c.m. system, the momenta are $\mathbf{P}_+$ and $\mathbf{P}_-$, at angles θ_+ and θ_- with the path of the V^0 particle. The transformation equations between the laboratory system and the c.m. system can be written in the form

$$\begin{aligned}
&\text{(a)}\quad P_{+x}=\frac{P_0P'\cos\theta'}{M_0\beta}+\frac{P_0}{2M_0^2}[M_0^2+(M_+^2-M_-^2)],\\
&\text{(b)}\quad P_{+y}=P'\sin\theta',\\
&\text{(c)}\quad P_{+z}=0,\\
&\text{(d)}\quad P_{-x}=\frac{-P_0P'\cos\theta'}{M_0\beta}+\frac{P_0}{2M_0^2}[M_0^2-(M_+^2-M_-^2)],\\
&\text{(e)}\quad P_{-y}=-P'\sin\theta',\\
&\text{(f)}\quad P_{-z}=0,
\end{aligned}\tag{2}$$

where P_{+x} is the x component of $\mathbf{P}_+$, etc., P_0 is the magnitude of the momentum of the V^0 particle, and

$$P'=[M_0^2-(M_+-M_-)^2]^{\frac{1}{2}}\times[M_0^2-(M_++M_-)^2]^{\frac{1}{2}}/2M_0, \tag{3}$$

all momenta, masses, and energies being written in energy units. From the momentum parallelogram of Fig. 10, using the law of cosines,

$$\begin{aligned}
&\text{(a)}\quad P_{+x}=P_+\cos\theta_+=(P_0^2+P_+^2-P_-^2)/2P_0,\\
&\text{and}\\
&\text{(b)}\quad P_{-x}=P_-\cos\theta_-=(P_0^2+P_-^2-P_+^2)/2P_0.
\end{aligned}\tag{4}$$

Inserting these expressions in Eq. 2(a) and 2(d), subtracting 2(d) from 2(a), and dividing by P_0, we obtain

$$\frac{P_+^2-P_-^2}{P_0^2}=\frac{M_+^2-M_-^2}{M_0^2}+\frac{2P'\cos\theta'}{M_0\beta}. \tag{5}$$

The value of the quantity on the left has been used by the Manchester workers[7] as a criterion for the classification of V^0 decays into two groups, into which they assume that all V^0 particles must fall. We shall adopt their notation and designate the quantity α to be

$$\alpha=\frac{P_+^2-P_-^2}{P_0^2}=\frac{\sin^2\theta_--\sin^2\theta_+}{\sin^2\theta_T}=\frac{\sin(\theta_--\theta_+)}{\sin(\theta_-+\theta_+)}, \tag{6}$$

where the second equality follows from the law of sines applied to the momentum parallelogram, and θ_T is the total angle between the secondary tracks. Equation (5) indicates that, for a given mode of two-body decay, a given speed βc, and an isotropic distribution in the c.m. system, the quantity α has an average value equal to $(M_+^2-M_-^2)/M_0^2$, and is uniformly distributed, with amplitude $2P'/M_0\beta$, on either side of the average. The actual distribution of α for a given two-body decay scheme is the result of a number of such uniform distributions, each having the same average value but a different amplitude, because of the different speeds βc of the various cases. The total distribution thus should have a maximum at the value $(M_+^2-M_-^2)/M_0^2$ and should be symmetrical about this maximum. Thus by evaluating α for those cases in which θ_+ and θ_- can be

TABLE I. Central values of α and minimum amplitudes of the α-distribution for various decay products.

No.	Decay products $M_+(m_e)$	$M_-(m_e)$	Q Mev	Central value $(M_+^2-M_-^2)/M_0^2$	Amplitude $2P'/M_0$
1	276	276	120	0	0.71
2	276	210	120	0.06	0.73
3	500	276	50	0.22	0.44
4	1000	276	50	0.49	0.32
5	1837	276	35	0.69	0.17
6	1837	210	35	0.74	0.19

measured, one can hope to gain some information as to the relative masses of the decay products.

The values of α were computed for the 60 cases for which origins were available. The distribution of those values is shown in group I of Fig. 11. On the figure are drawn several vertical lines, which correspond to the expected average values of α for the various decay schemes indicated in Table I. The energy release or Q-value was assumed to correspond roughly to those obtained by direct calculation from the data. (A detailed discussion of Q-values will be given in Sec. IX.) The average value of α is not very sensitive to the assumed Q-value, but the width of the α-distribution $(2P'/M_0\beta)$, which varies approximately as $Q^{\frac{1}{2}}$, is. From the great preponderance of positive values of α it is immediately apparent that at least a large majority of these decays, if not all of them, yielded a relatively heavy positive particle and relatively light negative one. (Negative values of α are quite possible, even for a large positive average value of α, if the V^0 is moving sufficiently slowly when it decays.) The position of the rather sharp peak of the distribution at a value of α corresponding to a decay into a proton and a negative π- or μ-meson, leads one to conclude that a great majority of the decays are probably of this type.[11] However, since the distribution is not symmetrical about this peak, and since the selection of cases could hardly have been biased against large positive values of α, we conclude, on the other hand, that some of the decays are probably of another type.

It has been postulated that V^0-particles exist which decay into two π-mesons. However, the number of negative values of α (some of which will later be shown to correspond to a decay into a heavy and light particle) suggests that at least very few, if any, of the decays yielded particles of equal, or nearly equal, mass.[7] For, even if one takes all of the negative α-values, and an equal number of the positive values, as corresponding to a decay into particles of equal mass, one obtains only about 20 percent which could possibly be of this type.

There are, of course, other possible two-body decay schemes that would lead to the observed α-distribution, such as, for example, a decay in which the product particles are of unequal mass, the heavier of mass about 500–1200m_e, perhaps a τ- or κ-meson, and the lighter of π- or μ-meson mass. Most of the negative values of α might, then logically be interpreted in terms of a decay into the corresponding anti-particles.

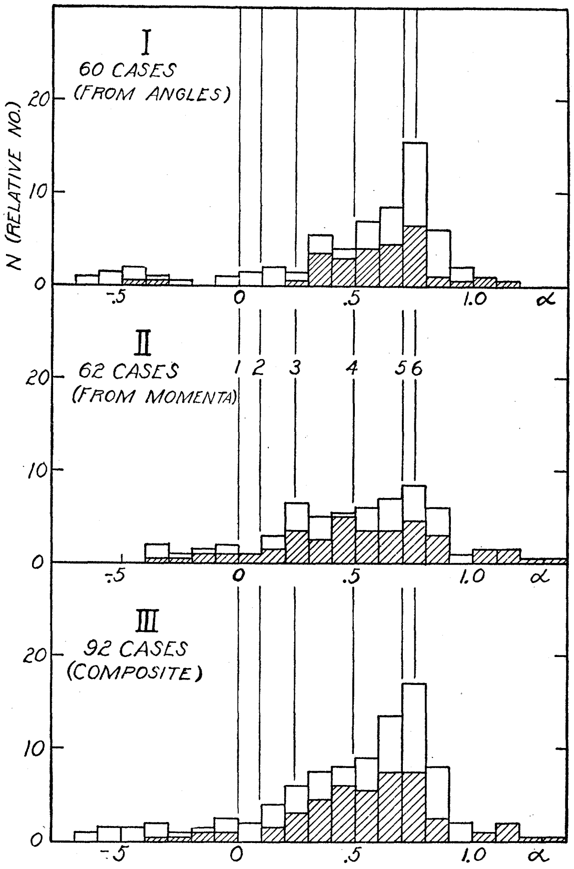

FIG. 11. Distribution of α for V^0 decay. The quantity α is defined by Eq. (6) of the text. For a given two-body decay scheme, given speed βc for the V^0 particle, and isotropic decay in the c.m. system, this quantity has an average value equal to $(M_+^2-M_-^2)/M_0^2$ and is uniformly distributed about this average with an amplitude $2P'/M_0\beta$ (see Eq. (5) of the text).

Group I is the distribution of those values of α that were derived from the angles θ_+ and θ_-.

Group II is a similar distribution, but in this case the values of α were evaluated from the measured momenta only.

Group III is a composite distribution.

The cross-hatched portion of each distribution indicates the contribution made by cases whose positive particles, being heavily ionizing, were known to be much heavier than π-mesons. Vertical lines extending through all three distributions identify the average values of α to be expected for decay of a V^0 particle into particles whose masses are indicated in Table I.

These distributions give clear indication of the existence of V^0 decays leading to a proton and a π- or μ-meson, and strongly suggest the existence of at least one other type of V^0 decay scheme, but do not serve to identify clearly the nature of this latter scheme.

VI. NATURE OF DECAY PRODUCTS—MOMENTUM MEASUREMENTS

Additional information about the decay products can be gained from measurements of their momenta. We shall consider first a new distribution of the quantity α, calculated now from the measured momenta of the decay products. (It will be recalled that α can be expressed in terms of the momenta of the particles as well as in terms of angles as was done previously [Eq. (6), Sec. V].)

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[11] It is interesting to note that one can estimate a Q-value from the half-width of this distribution peak. Assuming a decay into a proton and a π-meson, and taking $\beta\approx 1$, $M_0=M_p+M_\pi+Q\approx M_p+M_\pi=1079$ Mev, the half-width of the peak equal to 0.15, and assuming that the π^- meson is nonrelativistic, one obtains

$$0.15=2P'/M_0=2P'/1079,$$

and

$$Q\approx\frac{P'^2(M_p+M_\pi)}{2M_\pi M_p}=\frac{0.15^2\times 1079^2}{8\times 141\times 0.87}=26\text{ Mev}.$$

This value agrees surprisingly well with actual measurements (see references 4, 6, and 7) of the energy release.

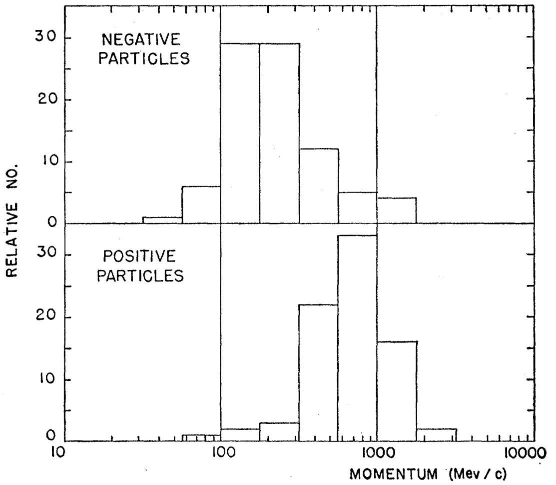

FIG. 12. Distribution of momentum of 79 positive and 86 negative V^0-decay secondaries. Only those particles whose momenta were measurable, or derivable from momentum balance, are included. Particles whose tracks were too short or too straight for accurate measurement are thus omitted.

The momenta of the decay products were determined from measurements of the curvatures of the tracks in the magnetic field. In order to make these measurements sufficiently precise, it was necessary to incorporate certain refinements which have been neglected in previous cloud chamber work. It has usually been assumed that the magnetic field, although not constant in strength throughout the chamber, is at least unidirectional, and that the radius of curvature of a track on the film corresponds to the radius of curvature of a helix whose axis is parallel to the magnet axis. Neither of these assumptions is strictly correct, for actually the field may have sizable components transverse to the magnet axis, and also the track image on the film is not an orthogonal projection of a helix onto a plane, but is rather a projection through a point (i.e., through the lens aperture) onto a plane. An exact expression, which takes both of these effects into account, has been derived relating the true momentum of a particle to the measured curvature of its track on the film. To make use of this exact relationship it was necessary to measure the three rectangular components of the magnetic field throughout the chamber, and thus to make allowance for the direction of the magnetic field as well as for the variation in its axial component. In the application of this formula to the track measurements, the only assumption involved is that the measured average radius of curvature over the length of the track is equal to the true radius of curvature at the center of the track. The correction arising from the use of this more exact formula was found usually to be about 5–10 percent, but in some cases was as great as 20 percent.

The curvature of a track was measured on each stereoscopic view, and a value of the momentum was calculated from each measurement. In each case an uncertainty was assigned whose size was appropriate to the length and quality of the track. These two values of the momentum were then combined to obtain the final measured momentum. The final uncertainty was taken to be somewhat less than that of either of the individual uncertainties, but was always large enough to include both measured values, and was never taken to be less than the error to be expected from multiple scattering or less than $P/40$ percent (P in Mev/c).

In a few cases the momentum of one of the decay particles was computed from a knowledge of the momentum of the other particle and the angle that each made with the V^0-path, using conservation of momentum, with the assumption of a two-body decay of the V^0-particle.

The momenta carried by the positive and negative decay-particles are shown in Fig. 12, and the momenta of the V^0 particles, themselves, obtained by vector addition of the momenta of the positive and negative particles for each case, are shown in Fig. 13. All of these histograms represent only those cases in which the momenta could be measured with reasonable accuracy, so that those decays whose tracks inside the chamber were very short, and those whose tracks, although long, were too straight for measurement, are not represented. The dotted lines of Fig. 13 represent approximately the contribution that might be expected from the unmeasurable cases. This contribution was obtained by assigning to each unmeasurable case a momentum calculated on the assumption that the observed angle, θ_T, corresponded to the maximum possible angle. It must be remembered, of course, that these distributions, even when corrected for the observed but unmeasurable cases, do not correctly describe the momentum distribution of all the V^0 particles actually produced. This results from the fact that the probability that a V^0 particle will decay in the cloud chamber depends upon its velocity as well as upon its mean life.

An α-distribution, computed only from measured momenta, is shown in Fig. 11, group II. This distribution is seen to be somewhat similar to that of group I, which was obtained only from geometrical data. The peak corresponding to a decay into a proton and a π- or μ-meson is not as pronounced as that of group I, but occurs at about the same value of α.

The difference in the shapes of the α-distributions of groups I and II can be explained by the difference in the selection of the measurable cases included in the two groups. The sole criterion for the inclusion of a case in group I was that it possess an origin so that the angles θ_+ and θ_- could be measured. This distribution is, therefore, unbiased, since the value of α depends only upon the speed of the V^0 particle and upon the orientation of the decay in the c.m. system. On the other hand, the criterion for the inclusion of a case in group II was that *both* decay particles have measurable momenta. This criterion tends to exclude decays in which the V^0 particle, and hence at least one of its decay particles, possesses a very high momentum. These excluded decays, for the most part, will be those for which the momentum of the heavier particle would have been unmeasurable no matter in what direction it might have been ejected in the c.m. system, but some borderline cases will also be excluded in which the momentum of the heavy particle was unmeasurable only because it was ejected in a forward direction in the c.m. system. Thus the sharp peak would be less pronounced, and the center of gravity of the distribution would be shifted toward smaller values of α.

A composite α-distribution is shown in Fig. 11, group III. This distribution was constructed by combining groups I and II. In the 30 cases in which α was known both from angle division and from momenta, that value was used that was considered to be the more accurate.

The cross-hatched portions of the three α-distributions represent the contribution of those cases whose positive particle was identifiable as being much more massive than a π- or μ-meson. An analysis similar to that outlined above can be used to explain the differences between the sub-distributions and the total ones: The cases in which the positive particle is heavily ionizing will tend more often to be those in which the positive particle is ejected in a backward direction in the c.m. system and is therefore moving more slowly in the laboratory system. These cases correspond to *negative* values of $\cos\theta'$ and hence to *smaller* values of α than the average for the particular type of decay in question.

A slightly sharper upper limit upon the number of cases that can be interpreted as decaying into two equally massive, relatively light particles, can now be made. If one removes from the negative α-values of group III those that are cross-hatched, and then doubles the remaining number from symmetry considerations, it appears that no more than about 15 percent of those decays included on these α-distributions could be of the above type.

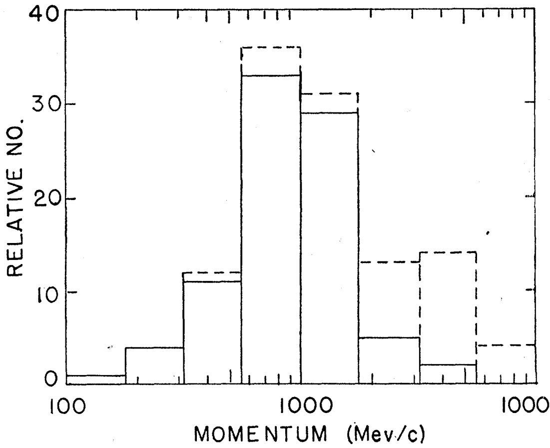

FIG. 13. Distribution of momenta of 85 V^0 particles. The momenta were determined by vector addition of the momenta of the decay particles. As in the preceding figure, cases whose decay tracks were unmeasurable are not included. The dotted distribution represents an estimate of the contributions that might have been made by the unmeasurable particles, based upon an assumed relationship between θ_T and the V^0 particle momentum.

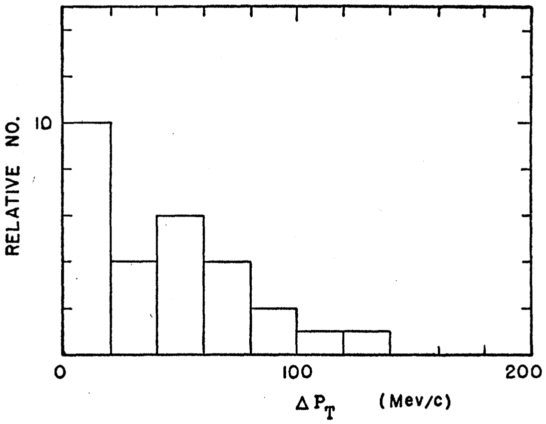

FIG. 14. The distribution of $\Delta P_T = |P_+ \sin\theta_+ - P_- \sin\theta_-|$ for 28 cases. This quantity represents the "missing" transverse momentum in the plane of the decay. The width of this distribution could be due entirely to errors in measurement, but is also not inconsistent with the distribution to be expected for certain types of multibody decay.

Further evidence as to the number of particles resulting from the decay of a V^0 particle can be obtained by testing the balance of the components of momentum transverse to the V^0 path in those cases where θ_+ and θ_- and also P_+ and P_- are known independently. The difference $\Delta P_T = |P_+ \sin\theta_+ - P_- \sin\theta_-|$ is a measure of this balance, and should have the value zero if momentum transverse to the direction of the V^0 particle is conserved. The distribution of this quantity is shown in Fig. 14. It is seen that almost all of the decays could have satisfied the condition of transverse momentum balance, but, as in the discussion of coplanarity, we cannot exclude certain types of multibody decay in which the transverse momentum of an unseen neutral particle is small on the average compared to the transverse momenta of the visible particles. The restriction that can be placed upon this "missing" transverse momentum is about the same as in the case of the coplanarity test—namely that it be less than about 50 percent of the transverse momentum of the visible particles.

For comparison with Fig. 14, the distribution of the transverse momentum of the negative particles, $P_- \sin\theta_-$, is given in Fig. 15.

It should be emphasized that the assumption of a two-body decay underlies the whole discussion of the distributions of the quantity, α, in this section of the paper, and that the presence of a substantial fraction of multibody decays would alter considerably the significance of these distributions.

VII. NATURE OF DECAY PRODUCTS—SPECIFIC IONIZATION

Further information as to the character of the decay products is provided by a determination of their specific

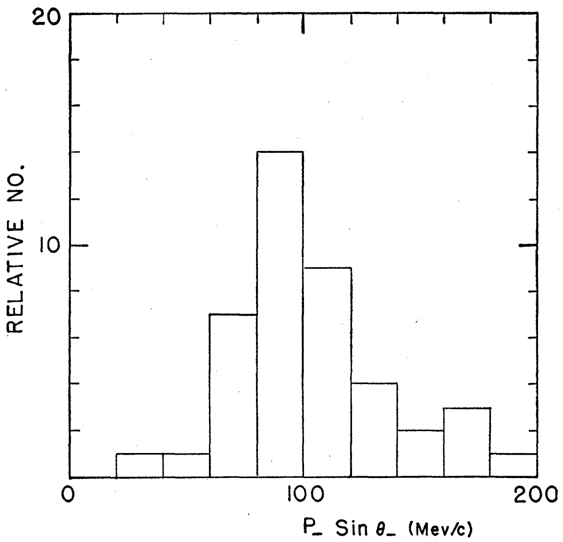

FIG. 15. The distribution of $P_- \sin\theta_-$ for 42 cases. This quantity is equal to transverse momentum $P' \sin\theta'$ if the decay is a two-body decay. The sharp peak in this distribution falls at about 95 Mev/c, the limiting value to be expected for a two-body decay into a proton and a π-meson with an energy release of 35 Mev. The presence of transverse momenta substantially greater than this limiting value strongly suggests the presence either of two-body decays, or of multibody decays, with energy releases greater than 35 Mev.

ionization. The accurate measurement of ionization is exceedingly difficult, even in cases where the droplets along the track are actually resolved. Fortunately, a considerably larger error can be tolerated in the ionization than in the momentum (for ionizations greater than twice minimum) to obtain a mass measurement of given accuracy. In the present experiment, the specific ionizations for individual tracks were estimated independently by two or more observers, and were evaluated a second time by the same observers several weeks later. The estimates were made by visual comparison with other tracks on the same photograph whose ionizations were considered known. For example, a straight penetrating shower-particle track (>1000 Mev/c) was taken to be at minimum ionization, while an electron track (50–100 Mev/c) was assumed to be 1.3 times minimum. If a track appeared indistinguishable from such comparison tracks, it was assigned an ionization less than 1.5 times the minimum value.

In some cases a track appeared definitely heavier than a track of minimum ionization, and yet not as heavy as one of twice minimum; in such a case a value of 1.1–1.8 times minimum might be assigned. A track whose ionization was above twice minimum could often be compared with heavily ionizing mesons and protons of known momenta and therefore of known specific ionizations. In all cases a range of ionization was determined within which all observers could agree that the actual value almost surely lay, and outside of which it was very unlikely to lie. This range of values thus does not represent a "probable error" or "standard deviation" in the usual sense.

Inasmuch as the mass of a particle of unit charge is determined from the momentum and ionization by an equation of the form

$$M = P\cdot f(I), \tag{7}$$

where P is the momentum and $f(I)$ is a function of the specific ionization only, it follows that the error in the mass value that arises from errors in momentum and ionization is approximately

$$\frac{\Delta M}{M} = \frac{\Delta P}{P} + \frac{f'(I)\Delta I}{f(I)}. \tag{8}$$

It can be assumed that the errors in the estimate of ionization, while perhaps rather large and not subject to direct statistical treatment, are at least independent of the identity of the particle. Thus it was possible to evaluate the accuracy with which ionization can be estimated by calibrating on heavily ionizing π-mesons, for which the momenta could be measured very accurately.

VIII. NATURE OF DECAY PRODUCTS—MEASURED MASSES

In 87 of the 134 V^0 decays it was possible to measure the momentum of at least one of the decay particles. Some of these particles were also heavily ionizing so that estimates of their masses could be made. Many of the particles, on the other hand, were essentially at minimum ionization so that only upper limits could be placed upon their masses. These limits often served to distinguish between "heavy" and "light" particles, and thus permitted a rough classification of the decays according to the relative masses of the secondaries, as shown in Table II. In each of the 42 cases of group 1*b* the positive particle, because of its ionization and momentum, is definitely known to be heavier than the negative particle. One can conclude in addition that the majority of the 29 positive particles of group 1*c*, which are at minimum ionization, must also be more massive than their companion negative particles. This conclusion follows from the relative populations of groups 3*a* and 1*c*, which would be expected to be equal for any

TABLE II. Classification of secondary particles in V^0 decay.

M_- / M_+	1 $M_-<700m_e$	2 $M_->700m_e$	3 M_- indeterminate	Total
a $M_+<700m_e$	2	1	4	7
b $M_+>700m_e$	42	0	3	45
c M_+ indeterminate	29	0	6	35
Total	73	1	13	

decays which yield positive and negative particles of equal mass. Thus the direct mass determinations tend to support the conclusion previously drawn that probably not over 15 percent of these decays could yield particles of equal mass.

Three of the cases appearing in Table II are of special interest. Group 1*a* seems to indicate the existence of decays, of the type postulated by the Manchester Group, in which the two products have equal mass, while the single case in group 2*a* seems to indicate the existence of decays leading to a light positive particle and a heavy negative one. These three interesting cases will now be discussed.

Let us first consider the two cases in group 1*a* in order to determine whether a decay into two π-mesons is indeed indicated. The first of these cases may not be a V^0 decay at all. The apex of the V^0-particle, while in the gas of the cloud chamber, was just outside the visible region, so that it may actually represent a chance coincidence of two unrelated tracks. In addition, the momentum and ionization of the positive particle restrict M_+ to be less than 700–800m_e, and thus a π^+ meson is not necessarily indicated. Finally, additional doubt is cast upon this case because of the lack of transverse momentum balance with respect to an assumed line of flight from a nearby origin.

The second case is certainly a V^0 decay. In this case, the momentum of the positive particle was about 295 Mev/*c*, and its ionization was less than 1.5 times minimum, and thus its mass was less than about 500m_e. The track of the negative particle, however, was so short that its curvature could not be measured. The momentum of this particle was evaluated from transverse momentum balance with respect to an assumed line of flight from a clearly defined nearby origin. Although this procedure is probably permissible statistically, it must be used with caution in individual cases, since the identification of an origin is not always trustworthy, and in any case the V^0 particle might have been appreciably scattered before decay. We therefore conclude that there is little direct evidence in these data that indicates the existence of decay into equal particles, but that a few of the decays (groups 1*a* and 3*a* and four or five of 1*c*) might be interpreted as being of this type.

The single case in group 2*a* is especially interesting. It is shown in Fig. 16. The momentum of the positive particle is 190±20 Mev/*c*, and its ionization is less than 1.5 times minimum. This restricts its mass to be less than about 350m_e. The momentum of the second particle (which is negative if it is going away from the apex of the *V* and positive if going toward it) is 210±40 Mev/*c*. Its ionization is estimated to be 2–4 times minimum, which indicates that its mass lies in the range 450–1000m_e. Thus, even if one allows for extreme errors in the determination of both the curvature and the ionization, it is extremely difficult to interpret this particle as a π-meson.

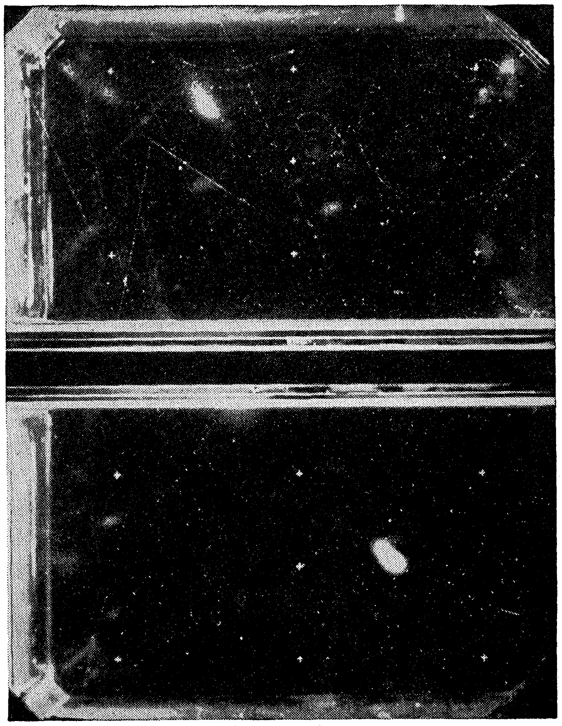

FIG. 16. Example of V^0 decay leading to a positive meson (presumably a π-meson) and a negative particle whose mass is considerably greater than that of a π-meson. The decay is in the upper left part of the upper chamber; the positive particle proceeds downward from the decay point, and the negative, toward the right and slightly downward.

The positive particle enters the lead plate but passes outside the visible region of the lower chamber; the negative particle passes through the front wall of the upper chamber after traveling about 8 cm through the chamber. This decay is described further in the text.

This decay is in general alignment with the two high momentum tracks that traverse both chambers, but there is no identifiable origin with which it is associated. On the other hand, this can also be said of many of the V^0 decays. If it were to be interpreted as a V^+ decay or a κ^+ meson decay, the particle would have been traveling upward, and would similarly not have been proceeding from an identifiable origin. Of the 18 V^+ particles observed in the present experiment, none were traveling upward, and all were clearly associated either with a penetrating shower or with a nuclear interaction origin in the lead plate between the cloud chambers. Furthermore, the kinetic energy of the π- or μ-meson in the center-of-mass system of an assumed V^+ or κ^+-decay is greater than 200 Mev, a value considerably higher than is now thought to be associated with either of these types of decay. Thus this case most probably represents a V^0 decay.

Therefore, this case appears to support an alternative hypothesis suggested above to explain the appearance of the α-distribution, i.e., that V^0 particles may exist that decay into a $\pi^\pm$ or $\mu^\pm$ meson and a particle of mass 500–

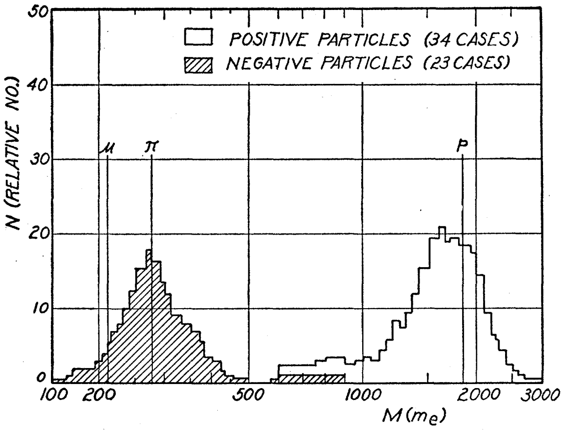

FIG. 17. The measured masses of V^0 particle secondaries. In this diagram each measurement is represented by a rectangular area whose width corresponds to the mass limits determined by the limits of the estimated ionization and by the central value of the measured momentum, and whose height is adjusted to give equal area to each rectangle. The ordinate at a given mass value is thus the sum of the heights of the rectangles containing that value, with a weight for each measurement inversely proportional to the range of values (on the logarithmic scale) covered by that measurement. The broken curve so obtained therefore represents a weighted frequency curve for the mass measurements. This procedure was used in order to allow for the widely varying accuracy of the individual measurements.

The results indicate that almost all of the negative particles were probably π-mesons, but that a few might have been μ-mesons and a few others were probably heavier than π-mesons; likewise, almost all of the positive particles were probably protons, but they could all have been somewhat lighter than protons, and a few seem to be considerably lighter than protons. The greater spread of the frequency curve of the positive particles may result entirely from greater errors in momentum measurement, but would also be consistent with a mixture of protons and lighter particles amongst the decay products.

$1200m_e$, the heavier particle being possibly a τ- or κ-meson, or a somewhat lighter particle.[12]

The measured masses of the secondary particles, as determined by their measured momenta and estimated ionizations are shown in Fig. 17. Only those cases in which a particle was heavily ionizing are represented. All cases represented in the diagram are plotted as rectangles of the same area, whose widths correspond to the mass ranges derived from the central values of the measured momenta and the extreme limits of the ionization estimates.

The most striking feature of the diagram is the peak corresponding to the mass of a π-meson. As was pointed out in Sec. VII, the error in the mass measurement of a light particle is determined almost entirely by the error in the ionization estimate. The sharpness of this peak thus indicates, not only that the negative particles are most probably π-mesons, but also that the estimates of ionization were sufficiently reliable, statistically, to distinguish π-mesons from μ-mesons.

Although the mass distribution indicates that almost all of the light particles are π-mesons, there were five cases, two heavily ionizing and three at minimum ionization, whose measured masses or upper mass limits were too low to reconcile with the mass of a π-meson. This number of cases suggests that μ-mesons may sometimes be produced in V^0 decay, but is surely too small to permit any strong conclusions as to decay schemes with which they may be associated. For these five decays, however, it can be stated that (1) four exhibited heavy positive decay-particles, presumably protons, but possibly τ- or κ-mesons. In the remaining decay the mass of the positive particle was indeterminate. (2) Three, with which points of origin could be associated, were consistent with "coplanarity," and hence with a two-body decay. (3) Four of the decays seemed to lead to an energy release or "Q-value" of about 40 Mev, but one, which might possibly be a κ^- meson traveling upward, required a Q-value of 11 ± 3 Mev. If it were a κ^- meson decay, the energy of the μ-meson in the center-of-mass system of the decay would be about 44 Mev, a value not inconsistent with other observed cases[12,13] (see Fig. 19).

The spread in the measured masses of the positive particles is broader than that of the negative particles, because of the greater difficulty of measuring the higher values of momenta here involved. The distribution reaches a maximum at a value somewhat lower than a proton mass; after considerable study of the measurement technique that was used, it was concluded that this does not necessarily indicate a mass lower than that of a proton for all of these particles, but that a few τ- or κ-mesons could have been present. The positive particles of Figs. 4 and 5 are examples of the few whose masses seemed too low to be protons.

In addition to the case shown in Fig. 16 and discussed above, one or two further examples of slow heavy decay particles were found whose measured masses seemed to lie in the range 600–$1200m_e$. A few cases were also found whose upper mass limit was sufficiently low to exclude a proton, and whose accompanying particle was apparently a π-meson. (Some of these cases are included in groups 1*c* and 3*a* of Table II, since the arbitrary division at $700m_e$ classifies as "indeterminate" a few cases whose upper mass limits lie between $700m_e$ and about $1000m_e$.) None of these slow particle tracks was of sufficiently high quality to yield a reliable mass determination, so that these data must be regarded only as supporting evidence for, but not conclusive proof of, the hypothesis advanced above regarding the possible existence of a second type of V^0 decay in which a τ- or κ-meson may be produced.

Finally, before leaving this discussion of the nature of V^0 decay products, it should be pointed out that there is no evidence, either from the α-distributions of Fig. 11 or from actual mass measurements, that requires the presence of V^0 particles whose decay leads to a positive meson and a negative proton, although a small number of the decays might have been of this type.

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

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

IX. ENERGY RELEASE IN V^0 DECAY

The energy release, or Q-value, of the two-body decay of a neutral V-particle can be determined from the momenta of the two decay-particles and the included angle between their paths, if the masses of the decay-particles are known. In the decay described by Fig. 10, we have, in the laboratory system,

$$E_0 = E_+ + E_- = (P_+^2 + M_+^2)^{\frac{1}{2}} + (P_-^2 + M_-^2)^{\frac{1}{2}},$$

and

$$P_0^2 = P_+^2 + P_-^2 + 2P_+P_- \cos\theta_T,$$

so that

$$\begin{aligned} M_0^2 = E_0^2 - P_0^2 &= M_+^2 + M_-^2 + 2E_+E_- - 2P_+P_- \cos\theta_T \\ &= (M_+ + M_-)^2 + 2E_+E_- - 2M_+M_- \\ &\qquad - 2P_+P_- \cos\theta_T; \end{aligned} \tag{9}$$

we have therefore

$$\begin{aligned} Q &= M_0 - (M_+ + M_-) \\ &= (M_+ + M_-)\left(\left[1 + \frac{2Q_1}{M_+ + M_-}\right]^{\frac{1}{2}} - 1\right) \qquad (10) \\ &= Q_1 - \frac{Q_1^2}{2(M_+ + M_-)} + \cdots, \qquad (11) \end{aligned}$$

where

$$\begin{aligned} Q_1 &= \frac{E_+E_- - M_+M_- - P_+P_- \cos\theta_T}{M_+ + M_-} \\ &= \frac{M_+T_- + E_-T_+ - P_+P_- \cos\theta_T}{M_+ + M_-}, \end{aligned}$$

and E_+, T_+ and E_-, T_- are the total and kinetic energies, respectively, of the product particles in the laboratory system, the remaining quantities having the same significance as in Eqs. (2)–(6). The quantity Q_1 was introduced in order to simplify the computation of Q; it will be noted that $Q \approx Q_1$ for small values of Q.

The decays for which sufficient data were available to permit the calculation of a Q-value were classified into three groups according to their decay products.

Group A consists of those decays which clearly yielded a light negative and a heavy positive particle. The 38 decays in this group constitute practically the entirety of class 1b of Table II. A Q-value was calculated for each of these, assuming a two-body decay yielding a negative π-meson and a proton. The Q-values so obtained ranged from 10±3 Mev to 87±15 Mev, and were distributed within this range as indicated by the cross-hatched portion of the histogram of Fig. 18.[14]

Group B consists of those remaining cases in which there was no evidence against the assumption of decay into π-mesons and protons, and in which the α-values, in being greater than $+0.5$, actually gave some support for this assumption. The 25 decays in this group constitute practically the entirety of class 1c of Table II. Q-values were calculated for these decays assuming two-body decay into a π-meson and a proton. The Q-values so obtained ranged from 10±5 Mev to 97±30 Mev, and were distributed within this range as is indicated by the unshaded portion of the histogram of Fig. 18. The contributions of groups A and B to the total distribution are seen to be quite similar, within reasonable statistical fluctuation.

Group C consists of seven decays that seemed to exhibit properties which would preclude an interpretation in terms of a decay into a negative π-meson and a proton. These decays were those of classes 1a, 2a, and 3a of Table II. Q-values were calculated for various possible two-body decay schemes chosen to fit the observed properties of each individual case, with the following results: (1) Three of the decays, which could have yielded a positive and a negative π-meson, gave Q-values of about 110 Mev for this decay scheme. (2) Two of the above three decays might alternatively have

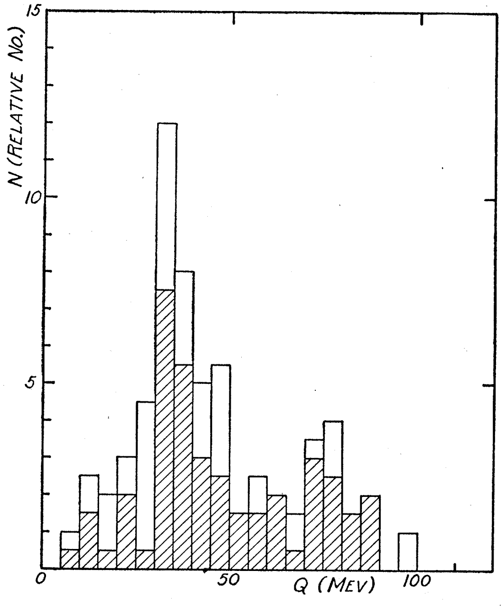

FIG. 18. The distribution of measured Q-values for 63 cases in which the decay $V^0 \rightarrow p + \pi^-$ was indicated. The cross-hatched portion of this histogram represents those cases in which the positive particle was surely much heavier than a π-meson, and the unshaded portion, those of the remaining cases, whose α-values were greater than $+0.5$, and in which there was no evidence against the assumed decay scheme.

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[14] In three of these decays the lighter particle seemed too light to be a π-meson, and in five other decays the heavier particle seemed too light to be a proton. Q-values were therefore recalculated for these eight decays assuming in the first three cases a two-body decay yielding a μ-meson and a proton, and in the latter five cases a two-body decay yielding a π-meson and a τ-meson of mass $975m_e$ or a κ-meson of mass $1250m_e$. These alternative Q-values were approximately equal to the Q-values calculated for $\pi + p$ decay, and were spread over a comparable range. In view of the small number of these "anomalous" cases and the large inherent errors in an individual mass measurement, particularly in the case of a massive positive particle, these cases, calculated for $\pi + p$ decay, were included in the histogram along with the "genuine" $\pi + p$ decays.

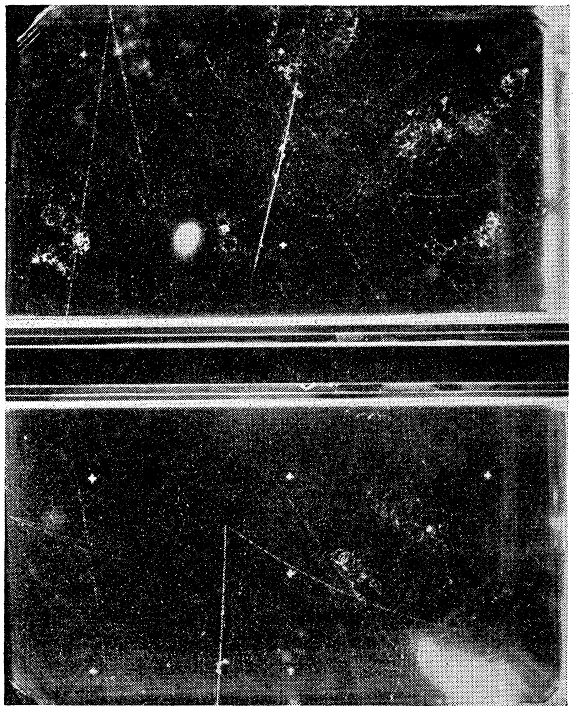

FIG. 19. A probable V^0 decay which has a very low Q-value. The decay occurs near the middle of the lower chamber. The negative meson, in this case probably a μ-meson, curves downward and to the right, and the proton goes almost straight downward, from the decay point. The data for this case are given in column 1 of Table III. The Q-value for this case is 10±3 Mev. This decay may be alternatively interpreted as the decay of a negative κ-meson entering the chamber from the bottom. This interpretation seems rather unlikely, however.

yielded a negative π-meson and a positive τ- or κ-meson. One of the other decays (see the previous discussion in connection with Table II) seemed to yield a positive π-meson and a negative τ- or κ-meson. These three decays, interpreted in terms of a decay into a $\pi^{\pm}$ and a $\tau^{\mp}$ meson, all gave Q-values of about 60 Mev. (3) The remaining three decays were of much poorer quality and could be interpreted in terms of either of the above decay schemes, but the Q-values did not seem to agree with those indicated above or with one another.

It is clear that many more of these "anomalous" decays will be required before an assignment of decay scheme can be made. For that reason, the remainder of the present discussion will concern only the results of the Q-value calculations for groups A and B.

The histogram of Fig. 18 was constructed by counting the number of Q-values within each 5 Mev range, without regard to the errors involved in the individual measurements. This histogram strongly suggests the existence of at least two Q-values, one at about 35±3 Mev, another at about 75±5 Mev, and possibly a third near 45 Mev, although a continuous distribution with or without one or more discrete values would also be consistent with the observed distribution. Armenterous *et al.*[7] obtained Q-values for twelve cases which were distributed in excellent agreement with the above histogram. These authors concluded, however, that their data indicated a single Q-value at 46±6 Mev. In order to determine whether the present results will support such a conclusion, it is necessary to investigate the errors involved in the Q-value determination.

The accuracy with which the Q-value may be determined from the measured momenta and the angle depends upon the accuracy with which these three quantities are known. The error in Q-value is often much more sensitive to the error in a certain one of the quantities, usually the momentum of the lighter particle, than to errors in the other quantities. This can be seen by evaluating the derivatives

$$\text{(a)}\quad \frac{\partial Q}{\partial P_+}=\left(\frac{E_-P_+}{E_+}-P_-\cos\theta_T\right)\bigg/(M_++M_-+Q);$$

$$\text{(b)}\quad \frac{\partial Q}{\partial P_-}=\left(\frac{E_+P_-}{E_-}-P_+\cos\theta_T\right)\bigg/(M_++M_-+Q);\qquad (12)$$

$$\text{(c)}\quad \frac{\partial Q}{\partial \theta_T}=(P_+P_-\sin\theta_T)/\,57.3(M_++M_-+Q)(\text{Mev}\cdot\text{deg}^{-1}).$$

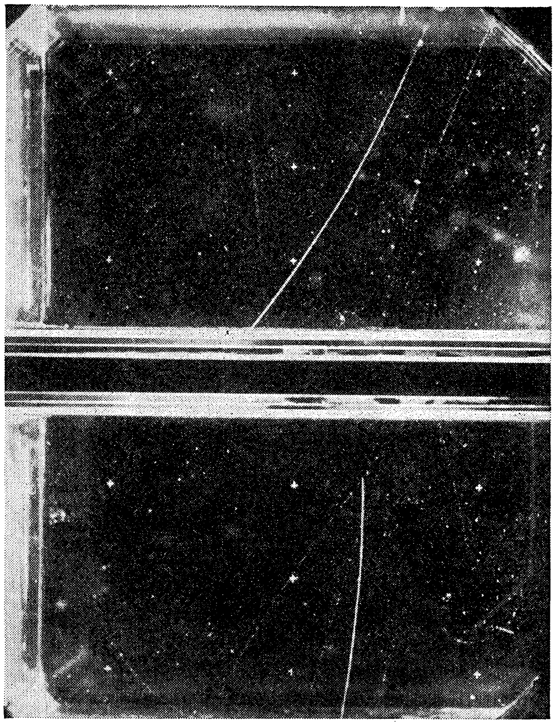

FIG. 20. A V^0 decay which has an intermediate Q-value. The decay occurs near the top of the lower chamber, and slightly to the right of the center. The positive particle, which is very heavily ionizing, travels almost straight downward, and the lightly ionizing negative particle travels downward and to the left from the decay point. The data for this case are given in column 4 of Table III. The Q-value for this case is 37±3 Mev.

The numerical values that were commonly found for these derivatives were, for $\pi+p$ decay,

(a) $\partial Q/\partial P_+ = -0.1$ to $+0.2$ (usually about $+0.07$);

(b) $\partial Q/\partial P_- = 0.3$ to 1.0 (usually about 0.6);

(c) $\partial Q/\partial \theta_T = 0.5$ to 3.0 Mev/deg (usually about 1.5).

To each Q-value an uncertainty was assigned whose magnitude was derived from the estimated errors in the momenta and the included angle, using the partial derivatives of Eq. (12) for this purpose. The absolute uncertainty tended to be smaller, the lower the Q-value, whereas the percentage error was roughly independent of the Q-value. The estimated errors were about ± 30 percent on the average, and about ± 15 percent in several of the best cases. Thus the average estimated uncertainty in the Q-value might be large enough to permit an interpretation in terms of a single Q-value at 46 ± 6 Mev. However, if this were the case one would expect that the distribution would, within a reasonable statistical fluctuation, show a maximum near 46 Mev; also, those Q-values having small estimated uncertainties should be distributed more closely about this value than are those of large estimated uncertainty so that the few best cases should give Q-values very close to 46 Mev.

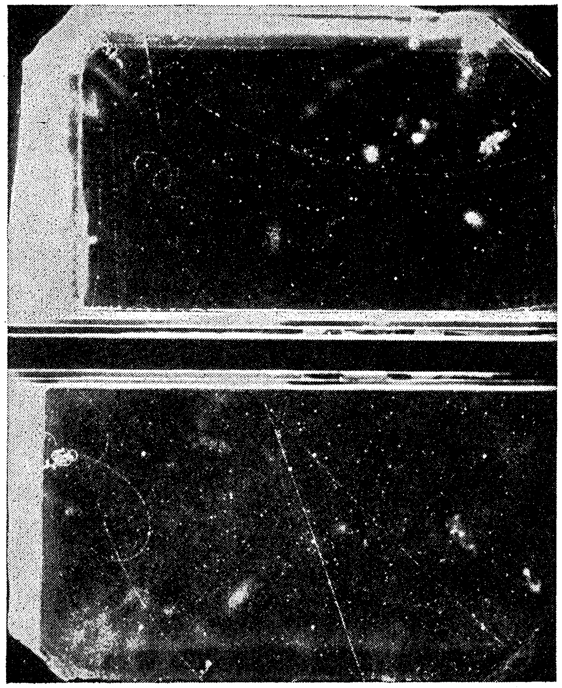

FIG. 21. A V^0 decay which has a high Q-value. The decay occurs near the top center of the lower chamber. The positive particle is heavily ionizing, and moves downward and slightly toward the right from the decay point, while the negative particle is near minimum ionization and travels diagonally downward and to the right from the decay point. The data for this case are given in column 7 of Table III. The Q-value calculated for this case is 72 ± 10 Mev.

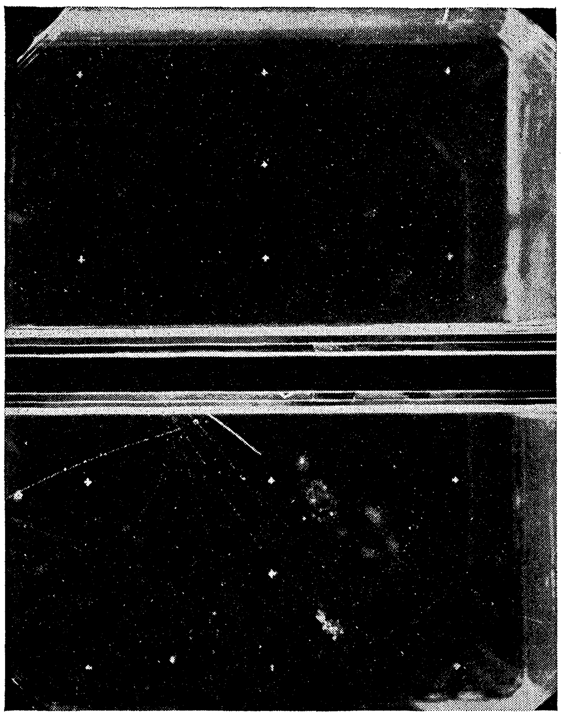

FIG. 22. A V^0-decay which has a high Q-value. The V^0 particle, which is produced in the nuclear interaction in the lead plate between the chambers, decays immediately below the top of the lower chamber. The positive particle appears to be slightly above minimum ionization, and travels downward and toward the right from the decay point. The negative particle is heavily ionizing and travels toward the left and somewhat downward from the decay point. The data for this case are indicated in the last column of Table III. The Q-value calculated for this case is 79 ± 15 Mev. This is in many respects the most convincing example of a high Q-value decay so far observed, both because of the internal checks upon the momenta that are afforded by the heavy ionization of both decay-particles, and because the Q-value cannot be reduced below about 65 Mev even by assuming quite large errors in the momenta and ionizations.

To illustrate the above point, photographs of some of the best cases are shown in Figs. 19 to 22, and the measured quantities bearing upon the Q-value calculations for these cases are indicated in Table III. It would appear to be very difficult to reconcile these cases with a single Q-value.

X. DISCUSSION

In the preceding sections of this paper it was shown that the great majority of V^0 decays ($\sim$80 percent) yield a heavy positive and a light negative particle as decay products, which in most instances are best interpreted as a proton and a π^- meson. These decays were rather extensively analyzed on the assumption that they all were two-body decays, an assumption that was quite consistent with the data up to that point. However, the apparent existence of an non-unique Q-value suggests the presence, either of more than one mode of

TABLE III. Q-values for eight examples of V^0-decays that yield a proton and a meson.

Quantity	25686 (Fig. 19)	14539	31044	31817 (Fig. 20)	19063 (1) [Fig. 3 (1)]	30514	19955 (Fig. 21)	28167 (Fig. 22)
P_+(Mev/c)	375±100	390±50	660±100	72±20	400±50	510±50	500±50	800±150
I_+(×min)	4–8	3–4	1.5–3	>15	3–6	2.5–4	2–4	1.5–2
$M_+(m_e)$	1600–2400	1350–1650	1200–2300	>700	1400–2200	1500–2100	1300–2200	1500–1900
P_-(Mev/c)	67±7	150±10	205±10	125±5	60±5	130±5	300±25	77±7
I_-(×min)	1.5–3	1–2	<1.5	1.5–3	3–6	1.5–2.5	<1.5	3–4
$M_-(m_e)$	130–230	<370	<380	230–430	205–330	240–380	<550	265–310
θ_+(deg)	—	—	8	—	—	14	—	9.5
θ_-(deg)	—	—	24	—	—	56	—	104.5
θ_T(deg)	53±1	45±1	32±1	52±1	151±2	70±1	19±1	114±1
$\partial Q/\partial P_+$	0.015	−0.025	−0.027	0.061	0.10	0.043	−0.11	0.11
$\partial Q/\partial P_-$	0.19	0.42	0.35	0.51	0.68	0.50	0.42	0.77
$\partial Q/\partial \theta_T$	0.29	0.65	1.1	0.11	0.19	0.97	0.80	0.82
Q(Mev)	10±3	33±5	36±5	37±3	41±7	46±4	72±10	79±15

two-body decay, or of multibody decay. It seems appropriate, therefore, to discuss these data in terms of various alternative modes of decay, a few of which will now be considered in relation to the present measurements of coplanarity, Q-value, decay product mass, and lifetime[15]:

$$\text{(A)} \qquad V^0 \rightarrow p + \pi^- + E.^{16} \qquad (1)$$

As previously shown this hypothesis, which assumes a unique mass of the V^0 particle, is consistent with the measurements of coplanarity. However, if all V^0 particles which seem to yield protons and π^- mesons were of this type, then the entire spread in Q-values would have to be ascribed to errors of measurement, a possibility which is considered to be quite unlikely, but which cannot, of course, be completely excluded.

$$\text{(B)} \qquad \begin{aligned} V^0 &\rightarrow p + \pi^- + \nu + E, &\quad (2)\\ V^0 &\rightarrow p + \pi^- + \pi^0 + E. &\quad (3) \end{aligned}$$

The above three-body decay schemes, one yielding a neutrino and the other a neutral π-meson, have been considered by Brueckner and Thompson.[17] Under the assumption that the emission of the particles in the c.m. system is governed only by statistical factors, these authors have calculated two distribution curves for each of these decay schemes. The first, which can be compared with the observed values of δ, is a distribution of $\gamma\beta\delta$, where $\gamma = (1-\beta^2)^{-\frac{1}{2}}$ and βc is the speed of the V^0-particle. The second is a distribution of Q-values, where Q is the apparent energy release calculated on the assumption of a two-body decay as in Sec. IX of this paper. In these distributions a value for the true energy release, E, was assumed such that the most probable Q-value appears at 35 Mev. The true energy release then corresponds to 130 Mev for decay (2), and 70 Mev for decay (3). Even though these distributions are based on several simplifying assumptions, a considerable significance may be attached to them.

In Fig. 23 the distribution of $\gamma\beta\delta$, for the 50 observed cases in which both δ and β are known, is plotted as a histogram, and is compared with the corresponding distributions calculated by Brueckner and Thompson. The observed distribution of $\gamma\beta\delta$, allowing for statistical fluctuations, is not inconsistent with either of the calculated distributions, although the observed cases occur more often at the smaller values of $\gamma\beta\delta$. A somewhat sharper comparison is obtained if one selects only those cases in which the estimated error in $\gamma\beta\delta$ is relatively small. Thirty-two cases, in which the error is less than 2.5°, are plotted in Fig. 24. Again, in view of the small number of cases, the observed distribution cannot be

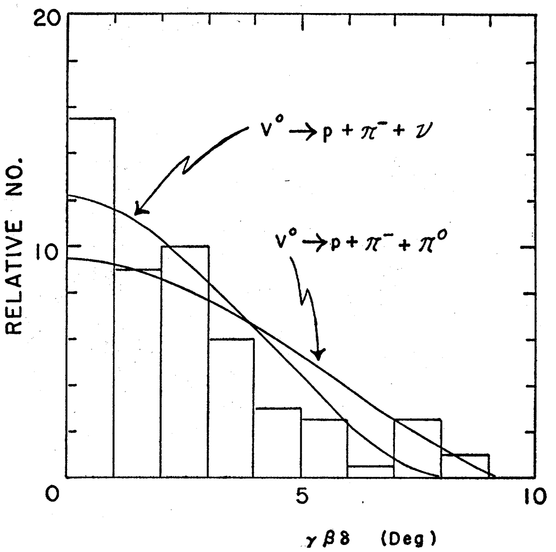

FIG. 23. A comparison of the measured deviations from coplanarity with those to be expected on the basis of a three-body decay of the V^0 particle. The quantity $\gamma\beta\delta$, whose distribution is here given, is defined in the text.

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[15] Tentative results of measurements of lifetimes of V^0 particles will be used. The details of the lifetime measurements will be reported elsewhere.

[16] The symbol E is used to denote the *true* energy release associated with a decay scheme. The term Q-value refers to the energy release calculated upon the assumption that the charged secondaries are the only secondaries produced in a decay. If no neutral particles are produced in a decay then the Q-value is of course identical with the true energy release, E. If one or more neutral particles are also produced the Q-values are distributed up to a maximum value equal to the true energy release, E.

[17] K. A. Brueckner and R. W. Thompson, Phys. Rev. **87**, 390 (1952).

said to be inconsistent with either of the calculated distributions, although it now shows a still greater proportion of cases corresponding to small values of $\gamma\beta\delta$. Inasmuch as the errors of measurement will tend to broaden the observed distributions, the large number of cases at small values of $\gamma\beta\delta$ suggests that an appreciable fraction, if not all, of the V^0 decays may be of a two-body type.

In Fig. 25 the distribution of 63 observed Q-values, plotted as a histogram, is compared with the corresponding calculated distributions. The observed distribution does not appear to correspond closely to the calculated distribution for the decay scheme in which a π^0 meson is produced. It cannot, however, be said to be inconsistent with the calculated distribution for the decay scheme in which a neutrino is produced, although the rather sharp peak suggests the presence of a discrete Q-value at about 35 Mev, and is an indication again that a substantial fraction of the V^0 particles may undergo two-body decay.

For both of the three-body decay schemes here considered, the V^0-decays of high Q-value, corresponding to low kinetic energies of the neutral particle, should, on the average, show smaller deviations from coplanarity than the decays of low Q-value. That such a correlation is not indicated in the present observations can be seen in Fig. 26, in which the deviation from coplanarity is plotted *versus* the observed Q-values. Of course, in view of the small number of cases and the magnitude of the errors of measurement, the data cannot be said to be inconsistent with either of the three-body decays here under discussion. However, the apparent concentration of points in the region of Q-value near 35 Mev and $\gamma\beta\delta$ near zero again suggests that a substantial fraction of the V^0 particles may undergo two-body decay with an energy release of about 35 Mev.

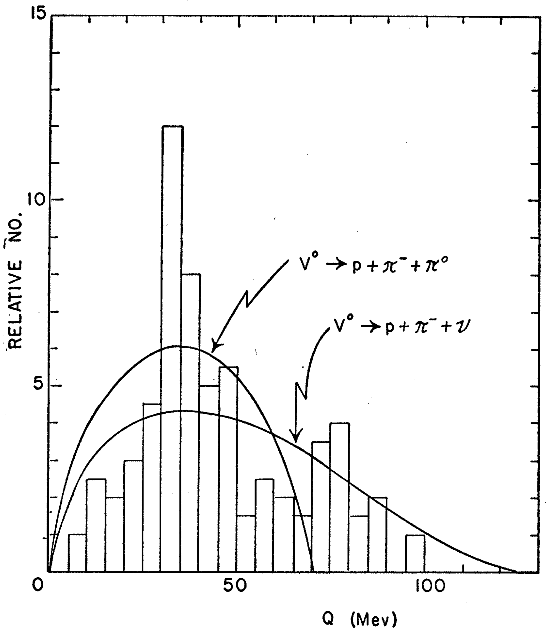

FIG. 25. A comparison of calculated Q-values with the distributions to be expected on the basis of three-body decay of the V^0 particle.

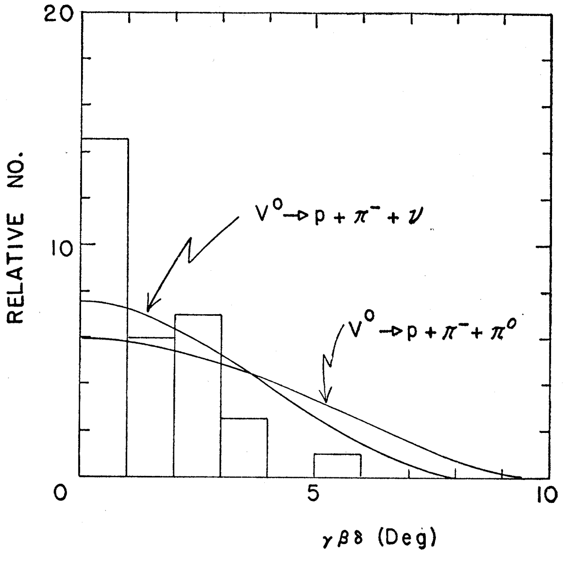

FIG. 24. A comparison similar to Fig. 23, except that all $\gamma\beta\delta$ values whose estimated errors are greater than 2.5° are omitted.

$$\text{(C)}\qquad V^0 \begin{array}{l} \nearrow\ p+\pi^-+E_1 \quad \text{(a)},\\ \searrow\ p+\mu^-+\nu+E_2 \quad \text{(b)}. \end{array} \qquad (4)$$

A branching decay scheme, such as the above, in which a unique V^0 particle decays by either of two alternative modes, would lead both to a unique Q-value and to a distribution. The decay (a) would not show deviation from coplanarity, and would correspond to a unique Q-value, E_1, which might be associated with the observed peak at 35 Mev. The decay (b) would show deviations from coplanarity and a distribution in Q-value up to a limiting value, E_2. One sees that E_2-E_1 should equal 33 Mev, the difference in mass of the π- and μ-mesons. Such a relationship is not completely excluded by the data in Fig. 18, inasmuch as the larger errors are associated with the higher Q-values.

Furthermore, according to this hypothesis, π^- mesons should be associated with the unique Q-value (i.e., 35 Mev) and μ^- mesons with the distributed Q-values, Such a correlation, however, is not indicated in Fig. 27. in which the measured masses of the decay products are plotted *versus* the measured Q-values; in fact, the few μ^- mesons, whose presence seems to be indicated, are found for the most part in the region near 40 Mev, whereas the π^- mesons are distributed over all values of Q.

$$\text{(D)}\qquad V_n{}^0 \rightarrow p+\pi^-+E_n. \qquad (5)$$

According to this hypothesis the V^0 particle occurs in more than one energy state, E_n, and undergoes two-body decay. All decays would then be exactly coplanar, and thus in this respect would be consistent with the observations. The discrete Q-values, E_n, might be correlated with the observed Q-values. However, the measured mean lifetimes of V^0-particles with low Q-value (less than 50 Mev) and high Q-value (greater than 50 Mev) differ from one another by less than a factor of two, and, in fact, are consistent with a single mean value of $2.5\pm0.7\times10^{-10}$ sec, within expected fluctuations. Upon this hypothesis it would thus be necessary to assign comparable lifetimes to V^0-particles in different energy states, whereas one might expect very wide differences in the lifetimes associated with the different states.

$$\text{(E)} \qquad \begin{array}{l} V^0 \rightarrow p_n + \pi^- + E_n; \\ p_n \rightarrow p + h\nu_n. \end{array} \qquad (6)$$

According to this hypothetical decay of a unique V^0 particle, the resulting proton is left in one or more states of excitation, p_n, and subsequently returns to its ground state, e.g., by the emission of a photon. If the mean lifetime associated with the transition of the excited proton to its ground state is very short compared with the mean lifetime (2.5×10^{-10} sec) of the V^0 particle itself, then one would expect to find a distribution of Q-values corresponding to each state of excitation of the proton, where the breadth of the distribution would be determined by the energy of the photon, $h\nu_n$. This follows from the fact that the proton would have decayed to its ground state before producing the track in the cloud chamber. Furthermore, deviations from coplanarity would be expected if an excited proton were produced, although these deviations would be small if the energies of the photons were small.

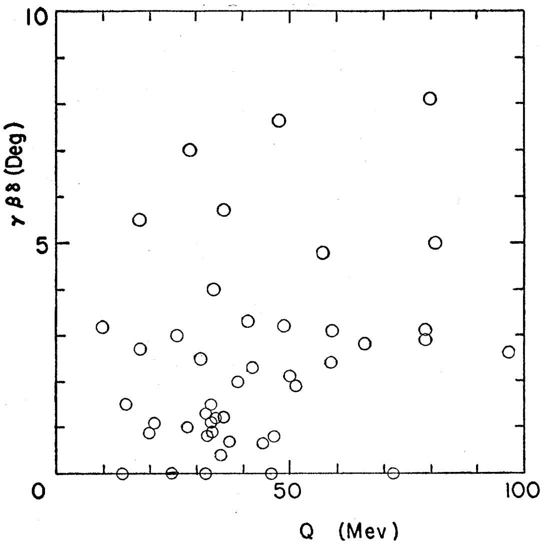

FIG. 26. A plot of observed deviations from coplanarity *vs* calculated Q-value for 44 cases.

Only in those cases where the V^0 decay results in a proton already in its ground state would one expect a discrete Q-value. Such decays would show no deviation from coplanarity and should correspond to the high Q-values. Such a correlation is not borne out by the observations (see Fig. 26), but in view of the statistical nature of the observations, such a mixture of cases, some of which are coplanar and correspond to a unique Q-value, and others which show slight deviations from coplanarity and correspond to a distribution of Q-values, can be said to be consistent with the present data. Of course, there is no evidence at present for the existence of excited protons, nor is there evidence that photons accompany V^0 decay. On the other hand, there is no evidence against the existence of such photons, for photons of energies of a few tens of Mev might very easily escape detection.

While it is true that this hypothesis circumvents the difficulty associated with assigning two nearly equal lifetimes to different particles (or different degrees of excitation), it does imply the production of comparable numbers of excited and unexcited protons.

$$\text{(F)} \qquad \begin{array}{l} V^0 \rightarrow X_n{}^0 + h\nu_n; \\ X_n{}^0 \rightarrow p + \pi^- + E_n. \end{array} \qquad (7)$$

A non-unique Q-value associated with an apparently unique lifetime might also be explained in terms of a branching and cascade two-body decay scheme involving an intermediate particle. For example, a unique V^0 particle decays by photon emission into a secondary particle, $X_n{}^0$, which subsequently undergoes a two-body decay into a proton and π^- meson. If the lifetime associated with the decay of the secondary particle is very short ($<10^{-12}$ sec) compared with that ($\sim2.5\times10^{-10}$ sec) associated with the incident V^0 particle, then the $X_n{}^0$ particle would not move an appreciable distance in the cloud-chamber before it decays, and the point of origin of the proton and π^- meson tracks would be essentially the point of decay of the incident V^0 particle. Decays of this type would therefore show deviations from coplanarity of an amount corresponding to the energies of the photons $h\nu_n$. A set of discrete Q-values, E_n, would be expected corresponding to the various degrees of excitation of the secondary particle. A decay scheme such as the above could be considered as consistent with the present measurements of coplanarity, Q-values and lifetime. However, this decay scheme again implies comparable probabilities for competing decays.

$$\begin{tikzcd} & X^0+\mu^0+E_1, \quad X^0\rightarrow p+\pi^-+E_3; \qquad (8a) \\ \text{(G)} \quad V^0 \arrow[ur] \arrow[dr] & \\ & X^+ + \pi^- + E_2, \quad X^+\rightarrow p+\mu^0+E_4. \qquad (8b) \end{tikzcd}$$

Another hypothetical decay scheme leading to a non-unique Q-value and an apparently unique lifetime, is the one represented above, in which there are two alternate modes of decay of the V^0-particle, each of which results in the production of an intermediate unstable particle, X^0 or X^+. If the mean lifetimes of the intermediate particles are both very short compared with the mean lifetime of the V^0-particle, then deviations from coplanarity would be expected for both modes (a) and (b), if the coplanarity measurements are made in the usual manner on the proton and π^- meson tracks. The Q-value measurements, however, if also carried out in the usual manner, would lead to a unique value for mode (a) and to a distribution for mode (b). As is apparent from the previous discussion a decay scheme of this type could also be consistent with the present data, but would imply again comparable probabilities for decay by modes (a) and (b).

The foregoing decay schemes have all been chosen to yield a proton and a π^- meson as the visible (i.e., charged) products of V^0 decay. It should be recalled, of course, that the experimental evidence does not require that the heavy particles actually be protons, or that all of them be protons. In addition, the few cases in which the negative particle seems to be a μ^- meson have largely been ignored; and the few decays whose positive decay-particle seems to be a π^+ or μ^+ meson have not been considered because of the lack of information as to the nature of the negative particles for these latter cases. Many decay schemes could probably be imagined that would fit all of the data so far obtained, if some specific assumption were to be made as to the nature of these negative decay particles, but to discuss them at the present time seems rather premature. It is at least clear that much remains to be learned about almost all aspects of V-particle decay, and that much more data, of much better quality than is at present available, will be needed to establish clearly the nature of V-particles.

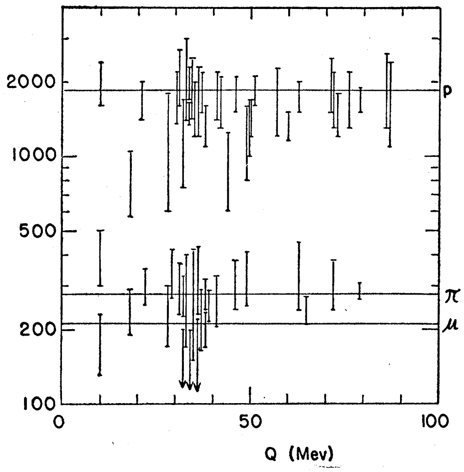

FIG. 27. A plot of the measured masses of the secondary particles of V^0 decay *vs* the calculated Q-value. Each particle is represented on this diagram by a vertical line which extends over the range of mass values defined by the limits of the estimated ionization and the central value of the measured momentum. Only heavily ionizing particles, for which upper and lower mass limits could be estimated, are shown, except for three negative particles of minimum ionization whose upper mass limits seemed too low to reconcile with the mass of a π-meson. All of the particles whose upper mass limit is less than $500m_e$ are negative particles, the remainder positive.

We take pleasure in acknowledging the able assistance of Dr. E. W. Cowan and of Mr. William L. Alford and Mr. Frank H. Shelton. Our thanks are also due the Carnegie Institution of Washington for laboratory space on Mount Wilson, California.

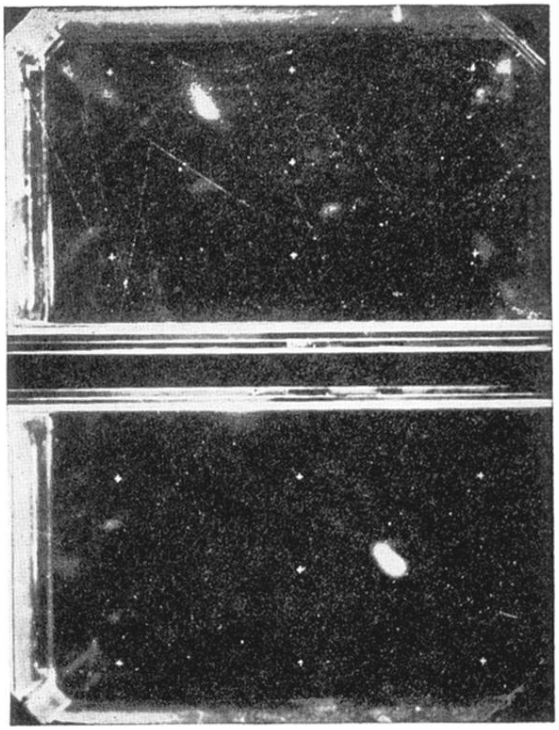

FIG. 16. Example of V^0 decay leading to a positive meson (presumably a π-meson) and a negative particle whose mass is considerably greater than that of a π-meson. The decay is in the upper left part of the upper chamber; the positive particle proceeds downward from the decay point, and the negative, toward the right and slightly downward.

The positive particle enters the lead plate but passes outside the visible region of the lower chamber; the negative particle passes through the front wall of the upper chamber after traveling about 8 cm through the chamber. This decay is described further in the text.

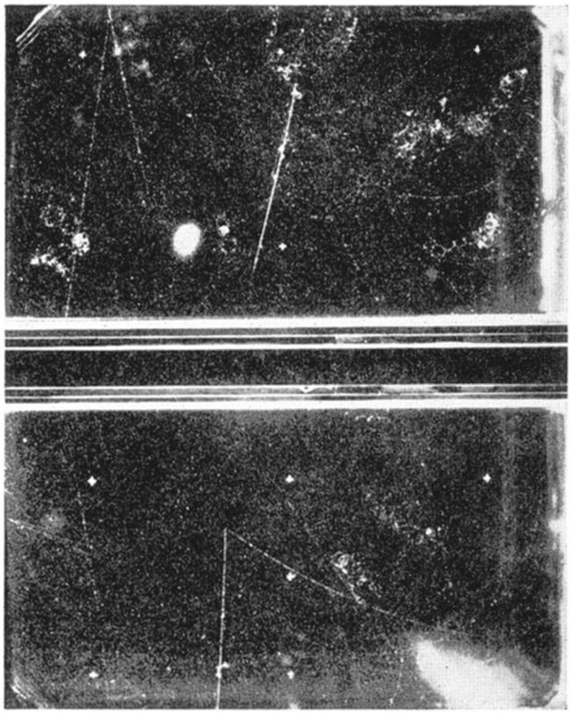

FIG. 19. A probable V^0 decay which has a very low Q-value. The decay occurs near the middle of the lower chamber. The negative meson, in this case probably a μ-meson, curves downward and to the right, and the proton goes almost straight downward, from the decay point. The data for this case are given in column 1 of Table III. The Q-value for this case is 10±3 Mev. This decay may be alternatively interpreted as the decay of a negative κ-meson entering the chamber from the bottom. This interpretation seems rather unlikely, however.

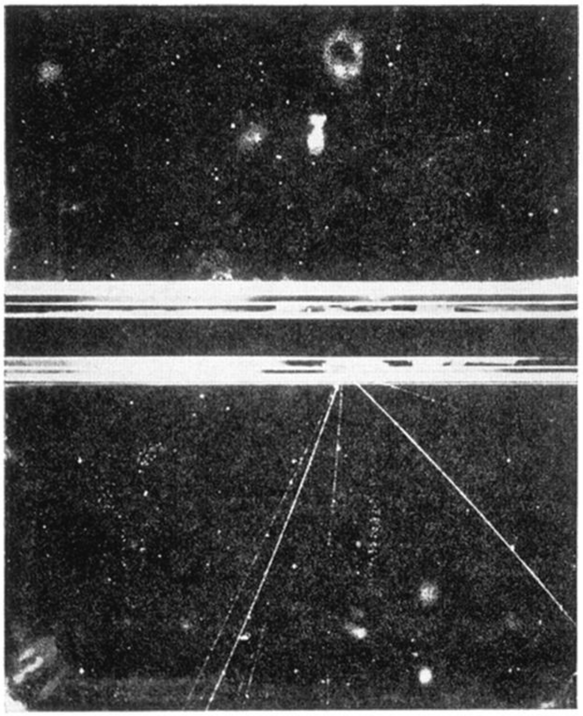

FIG. 2. Example of the production of a V^0 particle by a single charged particle. The initiating particle enters the lead plate between the chambers almost vertically from above and slightly to the right of the center of the chamber. In the lead plate it undergoes a nuclear collision, from which six charged particles, the V^0 particle, and an unknown number of neutral particles emerge. The V^0 particle decays near the bottom of the lower chamber into a heavily-ionizing positive particle and a negative particle of about minimum ionization. These products are probably a proton and a π^- meson, respectively. The shortness of the tracks does not permit accurate measurements of the momenta.

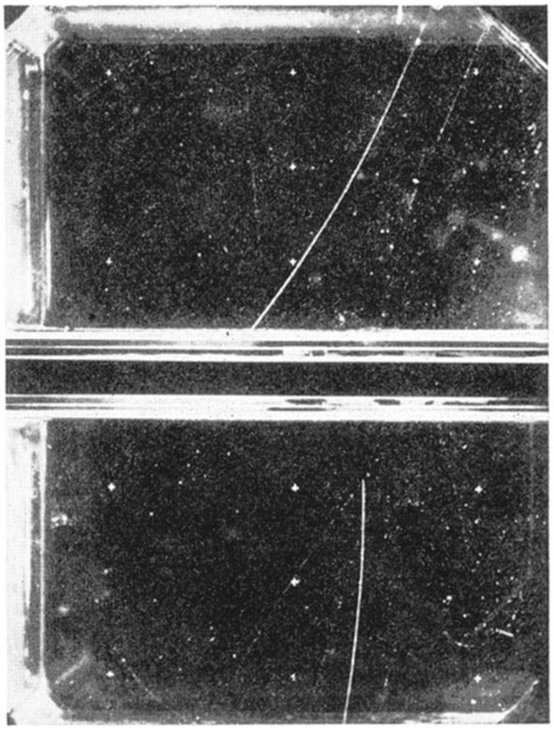

FIG. 20. A V^0 decay which has an intermediate Q-value. The decay occurs near the top of the lower chamber, and slightly to the right of the center. The positive particle, which is very heavily ionizing, travels almost straight downward, and the lightly ionizing negative particle travels downward and to the left from the decay point. The data for this case are given in column 4 of Table III. The Q-value for this case is 37±3 Mev.

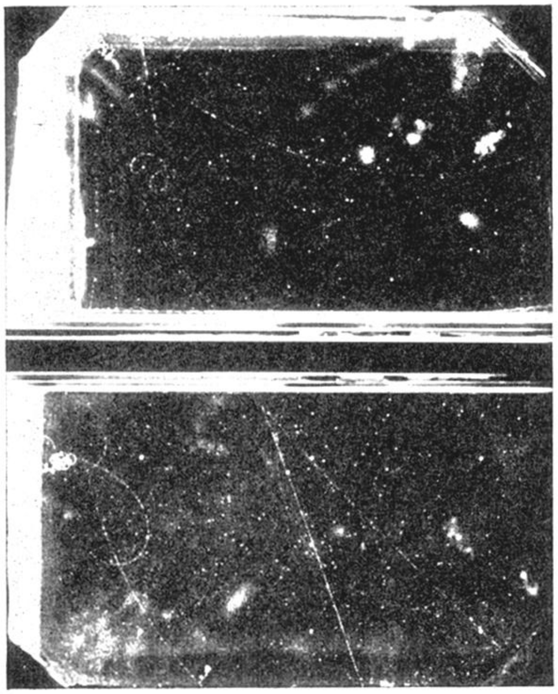

FIG. 21. A V^0 decay which has a high Q-value. The decay occurs near the top center of the lower chamber. The positive particle is heavily ionizing, and moves downward and slightly toward the right from the decay point, while the negative particle is near minimum ionization and travels diagonally downward and to the right from the decay point. The data for this case are given in column 7 of Table III. The Q-value calculated for this case is 72±10 Mev.

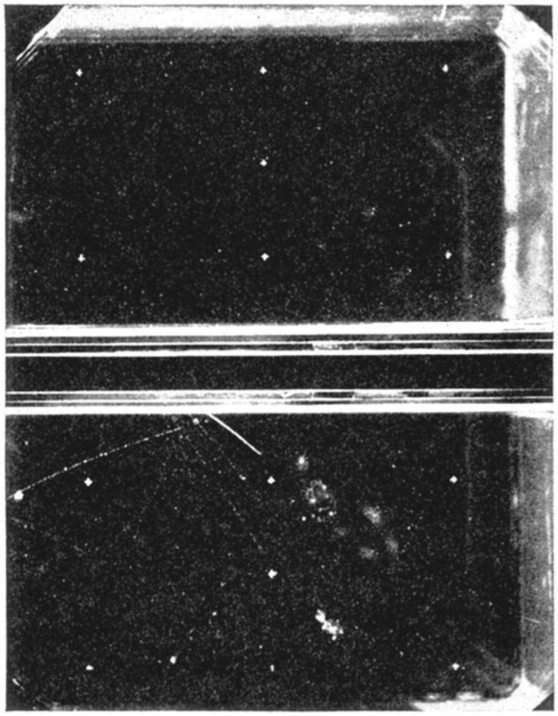

FIG. 22. A V^0-decay which has a high Q-value. The V^0 particle, which is produced in the nuclear interaction in the lead plate between the chambers, decays immediately below the top of the lower chamber. The positive particle appears to be slightly above minimum ionization, and travels downward and toward the right from the decay point. The negative particle is heavily ionizing and travels toward the left and somewhat downward from the decay point. The data for this case are indicated in the last column of Table III. The Q-value calculated for this case is 79 ± 15 Mev. This is in many respects the most convincing example of a high Q-value decay so far observed, both because of the internal checks upon the momenta that are afforded by the heavy ionization of both decay-particles, and because the Q-value cannot be reduced below about 65 Mev even by assuming quite large errors in the momenta and ionizations.

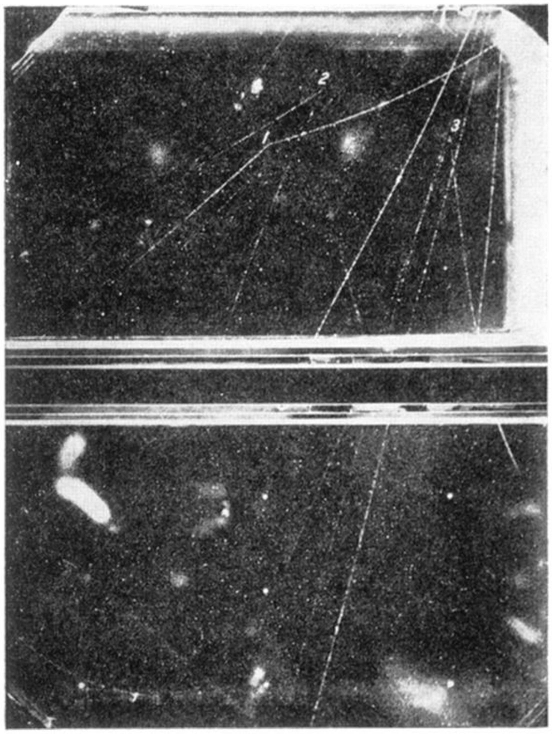

FIG. 3. A rare example of the production of several V^0 particles in a single nuclear event. Most of the tracks in the upper chamber are those either of secondary particles from a nuclear event in the lead blocks above the chamber, or of V^0 particle secondaries. Two of the three V^0 decays (Nos. 2 and 3) are in excellent alignment with the origin of the nuclear event, while No. 1, both of whose decay particles are heavily ionizing, is not aligned with this origin. This indicates either that this last decay yields three or more secondary particles, or that the assumed line of flight of the V^0 particle is not the correct one for this case. All of the decay tracks are consistent with the assumption that the negative particles are π-mesons, and that the positive particles are protons. The energies released in these three cases, assuming two-body decay, are $Q_1=41\pm7$ Mev, $Q_2=51\pm8$ Mev, and $Q_3=34\pm7$ Mev. Unfortunately, the distortions in the upper chamber were unusually severe.

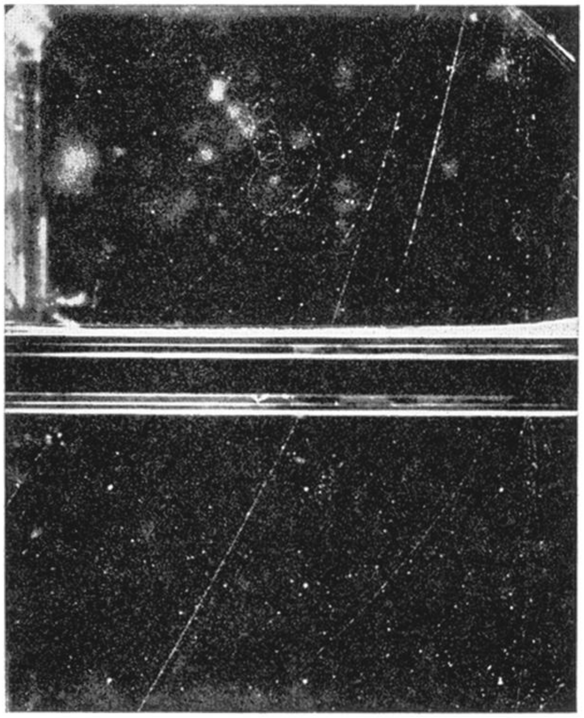

FIG. 4. Example of a V^0 particle produced in a nuclear event in the lead blocks above the chambers. The decay track on the left corresponds to a negative particle, of momentum 207 ± 10 Mev/c, which is probably a π-meson. The decay track on the right corresponds to a positive particle, of momentum 700 ± 150 Mev/c, and is probably a proton, but in the lower chamber its ionization and momentum indicate a somewhat lower mass. The energy release, assuming the products to be a π-meson and a proton, is $Q=42\pm6$ Mev.

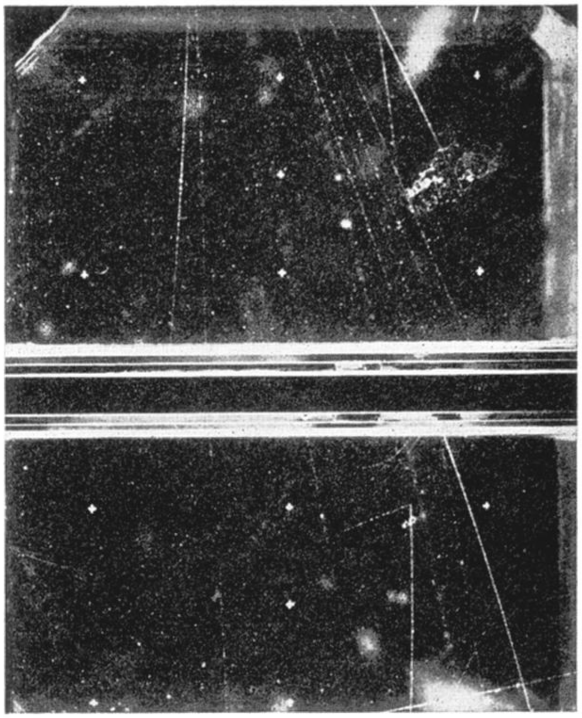

FIG. 5. Example of unrelated V^0 decays. One V^0 decay occurs very near the top and somewhat to the left of the center of the upper chamber, yielding a heavily ionizing positive particle which travels downward and toward the camera, and a lightly ionizing negative particle whose tracks is very short. This V^0 particle is probably produced in the same nuclear event, in the lead blocks above the chamber, that gives rise to the penetrating shower to the right. One of these shower particles in turn undergoes a nuclear collision in the lead plate between the chambers, from which a second V^0 particle emerges. This V^0 particle decays above the center of the lower chamber, and similarly yields a heavily ionizing positive particle which travels almost vertically downward, and a lightly ionizing negative particle whose track length is short. Both of the negative particles in these decays are ejected at such angles that they pass out of the front or rear wall of the chamber after traveling only a short distance. The positive particles in both of these decays are probably protons, although that of the lower decay may be somewhat lighter than a proton. The energy release of the lower decay is $Q=37\pm5$ Mev. That of the upper decay is not known, since the meson track was not measurable.