A *V*-Decay Event with a Heavy Negative Secondary, and Identification of the Secondary *V*-Decay Event in a Cascade*

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Two cosmic-ray decay events have been photographed in a cloud chamber under conditions that yield mass values from combined magnetic-field momentum measurements and ionization measurements from droplet counting. A method has been developed for assigning meaningful probable errors to the ionization measurements. The first event is interpreted as the decay of a neutral V particle into a positive π meson and a negative particle of mass $1850\pm250m_e$. On the assumption of a two-body decay, the Q value for the decay is 11.7 ± 4 Mev. The second event is a cascade decay that can be summarized by the following reaction:

$$V^-\rightarrow 67\pm12\text{ Mev}+\pi^-+\Lambda^0$$
$$\searrow 40\pm13\text{ Mev}+\pi^-+p.$$

The proton of the Λ^0 decay is identified by a measured mass of $2050\pm350m_e$. On the assumption of a two-body decay, the mass of the primary V particle is $2600\pm34m_e$.

INTRODUCTION

THE two events to be described were photographed in an expansion-type cloud chamber that has been operated in a 4200-gauss magnetic field for the purpose of obtaining good momentum measurements combined with ionization measurements made by droplet counting. A penetrating-shower selection system requiring a multiple coincidence from counters embedded in lead above and below the chamber was used to take the two photographs, which occurred in a series of about 10 000 cosmic-ray pictures taken at sea level.

The chamber, which is 48 cm square, is filled with a gas mixture of 2 parts of helium to 1 part of argon, saturated at 27°C with vapor from a liquid mixture of 2 parts of ethyl alcohol to 1 part of water. The total absolute pressure is 100 cm Hg with the chamber compressed. Good thermal isolation of the chamber from the magnet plus a small vertical temperature gradient result in sufficiently small convection currents that the limiting factor in momentum measurements is the diffuseness of the tracks. A "delayed expansion" is not used so that the tracks are sufficiently sharp for a curvature of 100 m^{-1} to be easily detected in a full-length track. Multiple-scattering errors are small for the tracks to be considered. Corrections are made for variations in magnitude and direction of the field, although these are of minor importance for the two events to be described.

Droplet counts for ionization measurements are made while viewing stereoscopically two pictures selected from pictures made by four lenses focused at different depths in the chamber. This method of counting the droplets eliminates the necessity for a background correction. Each expansion is calibrated individually for minimum ionization by means of electron tracks of known momenta appearing in the picture so that the value of the condensation efficiency does not enter in the determination of the ionization. The statistical errors in the ionization measurements are assigned by a method discussed at the end of the article, that makes use of a probability distribution curve determined experimentally. An allowance is made for counting errors on the basis of the reproducibility of the counts and the consistency of the ionization values for electron tracks in different regions of the chamber. The errors in ionization, and all other errors listed, are probable errors.

EVENT I

The stereoscopic pictures in Fig. 1 of the first decay event show tracks in the shape of a V with an included angle of $23\pm2°$ opening downward from a point in the upper left corner of the picture near the origin of a penetrating shower that occurred in a lead block above the chamber. The right leg undergoes a sharp deflection of $16\pm5°$ about $\frac{1}{4}$ of the way downward from the apex. Since the particle deflected almost directly away from the camera, the angle is difficult to measure and also difficult to observe unless the pictures are viewed stereoscopically. The momenta and angle are consistent within experimental error with the interpretation that a $\pi-\mu$ decay event occurred at the deflection. The momentum of the π meson measured directly from the curvature is 135 Mev/c, but this measurement is rough since the track is short and has a scarcity of droplets near the center. However, a better value of momentum can be obtained if the momentum of the μ meson, 130 ± 10 Mev/c, and the known Q value of a $\pi-\mu$ decay are used. The resulting momentum of the π meson, 165 ± 25 Mev/c, also checks with the observed ionization.

A line drawn from the apex of the V to an origin indicated by the intersection in three-dimensional space of two tracks in the shower is coplanar with lines tangent to the tracks at the apex of the V, within ex-

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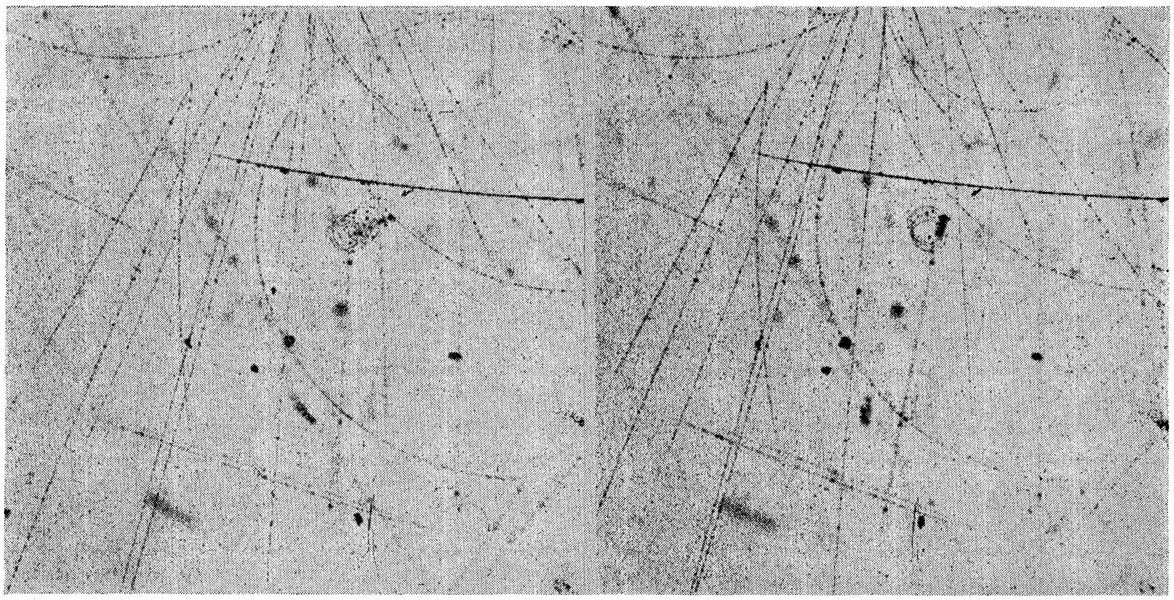


FIG. 1. A V-decay event with a heavy negative secondary.

perimental error. The transverse momenta of the two legs of the V also balance about this line, within experimental error. These facts indicate that the event is the decay of a neutral V particle that originated in the lead above the chamber into a positive π meson and a negative charged particle.

The alternative interpretation that the left leg of the V is a positive charged V particle traveling upward toward the origin of the shower and decaying into a π meson moving downward requires not only a very unlikely direction for the motion of the V particle and a direction for the decay almost exactly in the line of motion but also is inconsistent dynamically with any decay scheme known at present.

The momentum of the left leg of the V, which is negative for motion downward, is 875 ± 70 Mev/c and the ionization is 1.70 ± 0.19 times minimum ionization. These values correspond to a mass of 1850 ± 250 electron masses.

In light of the errors of measurement, the mass of this particle is near or equal to that of a proton and is not consistent with the mass of any negative particle that has been identified, e.g., the hyperon of cascade events ($\sim2600m_e$) or the κ or τ mesons ($\sim1000m_e$). There is no clear evidence that the particle is actually an antiparticle to the proton. No annihilation phenomenon is observed, and the Q value for the decay is definitely below the accepted range of values for the Q of the $\Lambda^0(V_1^0)$ decay, which yields a π meson and a proton.

The Q value calculated on the basis of a two-body decay and using the momentum of the π meson from direct curvature measurement is 8.6 Mev. A somewhat better value is obtained if the momentum of the π meson calculated from the $\pi-\mu$ decay is used, and this value of the Q is 11.7 ± 4 Mev.

If the negative decay product of the V particle is neither a negative proton nor a particle that decays into a negative proton, then it presumably decays into lighter particles, but no information is furnished concerning such a decay other than the fact that the particle observed lived longer than 10^{-9} sec.

Still other possibilities, although unlikely, must be considered. On the basis of calculated values of ionization for velocities above the minimum ionization value, the ionization of the negative particle is consistent within the probable error with that of an electron of the observed momentum. (All known mesons with this momentum and mass less than $1000m_e$ have an ionization less than 1.1.) The probability that the event is an electron pair with the observed 23° angle is exceedingly small, and in addition the production of a pair with this angle and the observed momenta requires the transfer of sufficient momentum to a nucleus so that a blob of droplets should be observed. Also the 16° deflection in the positive track must then be explained as an unlikely radiative collision. However, the decay products could be an electron and a π meson. The Q value on the assumption of a two-body decay with these decay products is 225 ± 20 Mev.

EVENT II

Photographs of the second event, a V-particle cascade, are shown in Fig. 2. A negatively charged V particle entered the chamber at the upper left and decayed into a meson, which produced a track nearly at right angles to the charged V particle, and a neutral V particle,

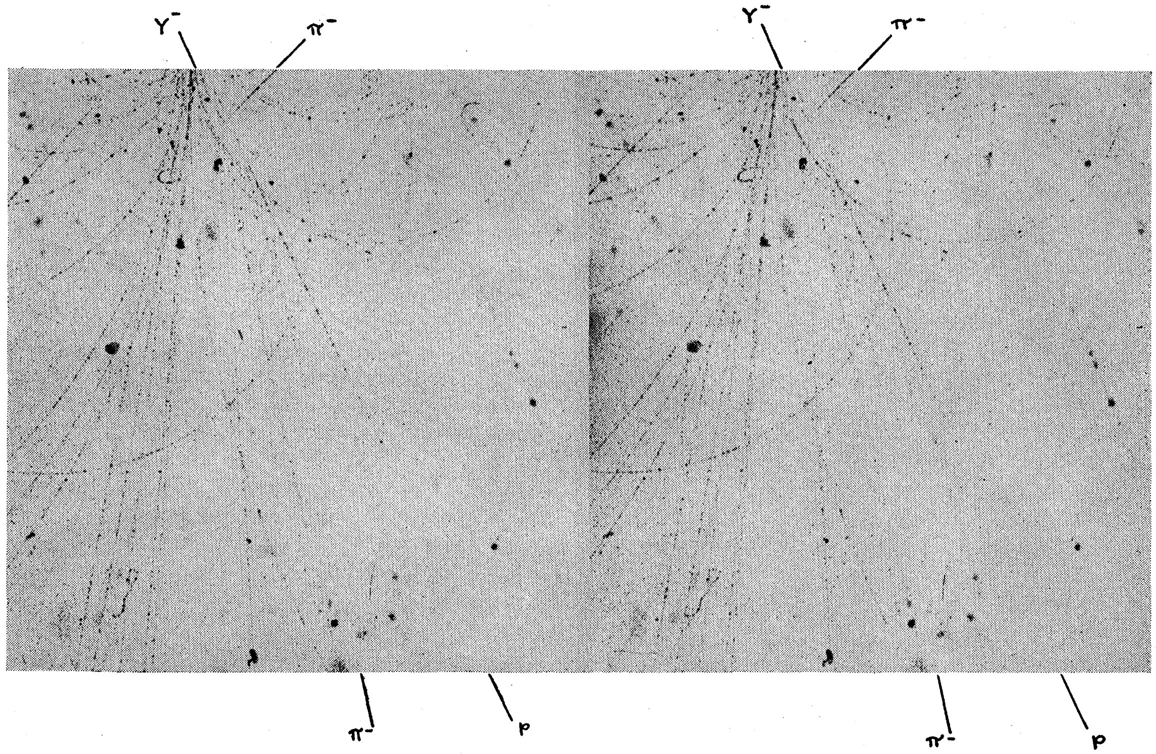


FIG. 2. A cascade event in which a negative charged V particle decays into a π meson and a neutral V particle that in turn decays into a π meson and a proton.

which traveled only 1.6 cm before decaying into two charged particles.

A number of such cascade events have been reported.[1,2] A single picture containing a charged and neutral V particle cannot be proven with certainty to be a cascade since the path of the neutral V particle can never be retraced with certainty. However, the event described here presents an unusual amount of evidence in favor of its being a cascade, and the identification of the neutral V particle is possible.

Only two origins are indicated by the intersection in three dimensions of the extensions of the tracks of penetrating particles in the chamber. One of these origins was a source of four charged particles and a neutral V particle, which decayed near the top of the chamber and is not connected with the cascade. The second origin, a short distance below and to the left of the first, was the source of a proton and the charged V particle of the cascade. A line drawn from either of these origins through the point of decay of the secondary V particle passes outside of the angle included between the tangents to the tracks at the apex of the V. If the secondary V decay event is a two-body decay, which is indicated by the identification of the V particle, the neutral V particle must have originated at the decay point of the charged V particle or else have come from some origin not indicated by the presence of other charged particles in the chamber. The fact that the charged and neutral V particles cannot have come from the same origin is of considerable importance, since other cascade events have not ruled out the possibility that "cascades" are the production of neutral and charged V particles in pairs, with a strong angular correlation.

In addition, if the neutral V particle is assumed to originate from the decay of the charged V particle, the following properties to be expected of a cascade event check well within experimental error: (1) coplanarity of the decay products of the secondary V particle with its origin, (2) transverse momentum balance of the decay products about the line of flight of the neutral V particle, (3) coplanarity of the lines of flight of the primary charged V particle, the meson resulting from the first decay, and the secondary neutral V particle, (4) transverse momentum balance of the decay products of the primary V particle about its line of flight.

Items (3) and (4) cannot be measured with sufficient accuracy to establish that the primary decay event gives rise to only two particles, since the directions of flight of the primary and secondary V particles differ by only about 4°, and the latter direction is determined by two points close together.

[1] Armenteros, Barker, Butler, Cachon, and York, Phil. Mag. **43**, 597 (1952).

[2] Anderson, Cowan, Leighton, and van Lint, Phys. Rev. **92**, 1089 (1953).

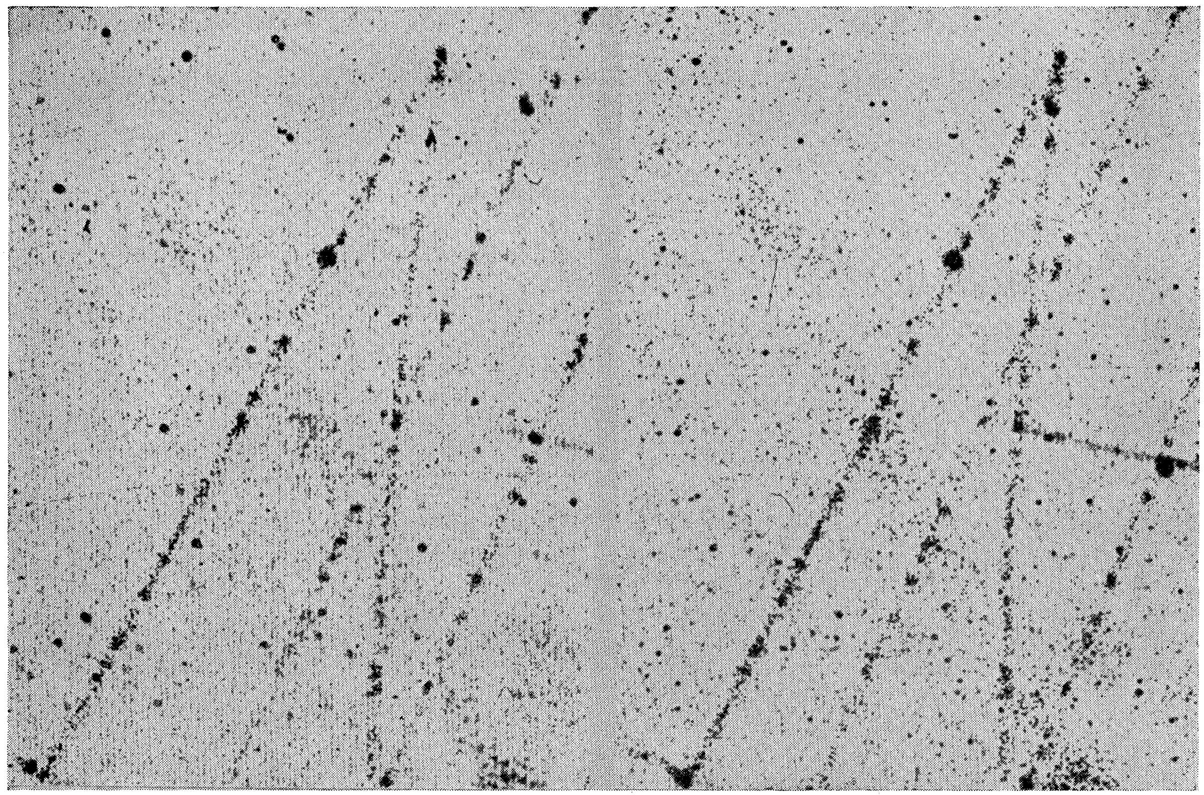


FIG. 3. Enlarged view of region near apex of V in Event I.

The momentum of the positive decay product of the secondary V particle is 730 ± 100 Mev/c and the ionization is 2.35 ± 0.26 times minimum ionization. These values correspond to a mass of 2050 ± 350 electron masses, and this particle is assumed to be a proton. The momentum of the negative decay product is 295 ± 40 Mev/c, the ionization 1.21 ± 0.14, and the included angle of the V is $6.5\pm1°$, giving a Q value of 40 ± 13 Mev. These characteristics check with the properties of a Λ^0 particle.

The meson decay product of the charged V particle has a momentum of 69 ± 10 Mev/c and an ionization 3.4 times minimum ionization. The method developed for determining ionization probable errors has not been extended to values of ionization this large, but experience with other similar tracks has shown that the values of ionization obtained from droplet counting in such cases are usually too small. Since a μ meson of the above momentum is ionizing only 2.6 times minimum ionization, whereas the corresponding ionization of a π meson is 3.7, the first meson of the cascade is probably a π meson. The included angle between the lines of flight of the primary decay products is $95\pm3°$.

On the assumption of a two-body decay, the Q value of the primary decay is 67 ± 12 Mev, and the complete reaction of the cascade is as follows:

$$V^- \rightarrow 67\text{ Mev} + \pi^- + \Lambda^0$$
$$\searrow$$
$$p + \pi^- + 40\text{ Mev.}$$

With the above assumption, the mass of the primary V particle is 2600 ± 34 electron masses.

ERRORS IN IONIZATION MEASUREMENTS

The problem of assigning statistical errors to ionization comparisons made by droplet counting for tracks of nearly equal ionization has been approached in the following manner. A track is divided into cells of length about equal to the width of the track by means of a transparent scale placed over the picture, with the starting point of the scale taken at random. The number of droplets in each cell is recorded, with the exception that all numbers exceeding 25 are discarded. From the numbers for a large group of cells, a probability curve is plotted giving the probability of finding a given number in a cell as a function of that number, and the average and mean square deviation are determined from this curve.

The central limit theorem of probability theory then permits the evaluation of the probable error in the droplet count of a track consisting of cells that have

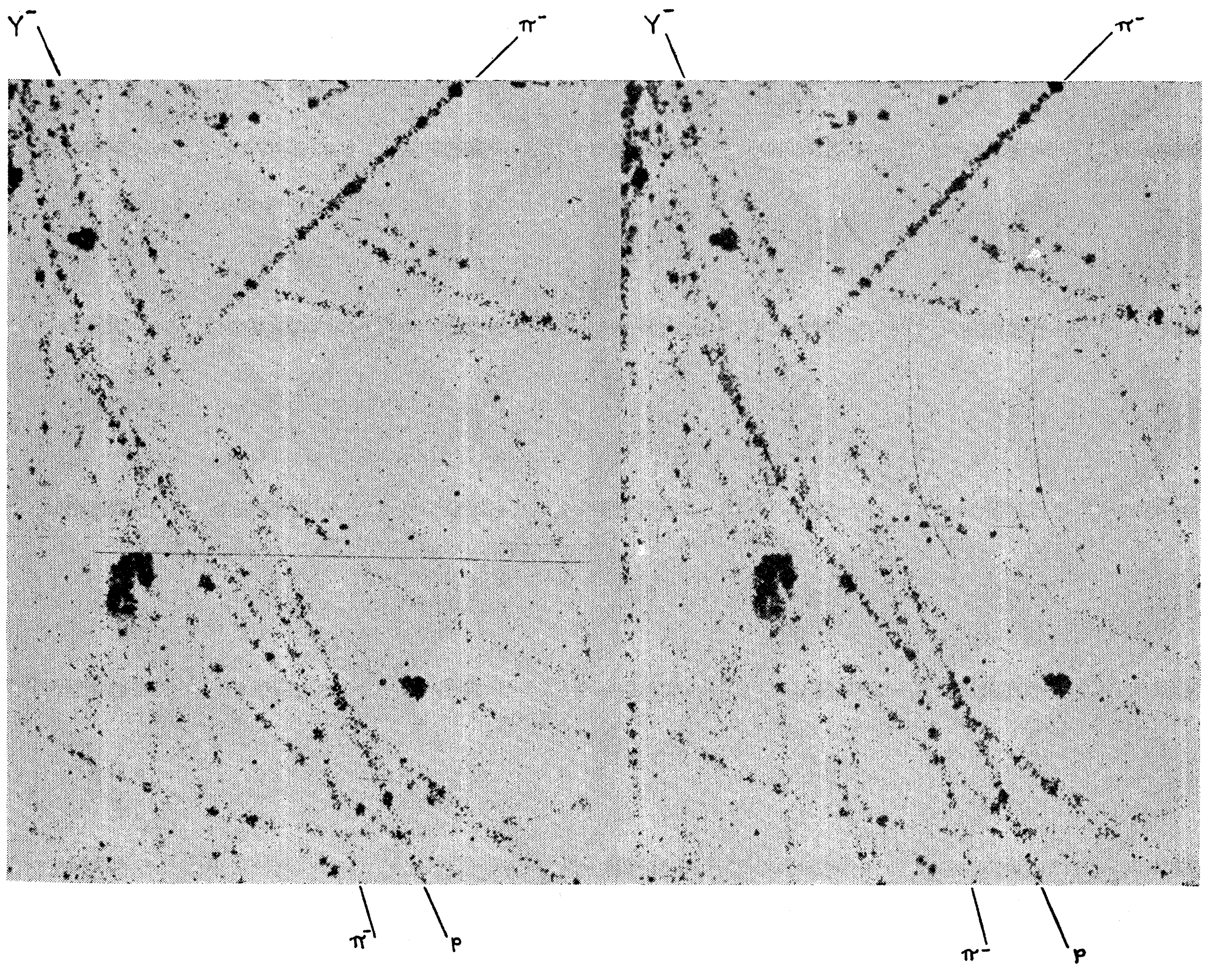


FIG. 4. Enlarged view of region near apex of *V* in Event II.

this same probability curve. This result is independent of whether or not the probability distribution is a Gaussian distribution as long as the number of cells in each track is large, but the result applies only to the comparison of tracks of the same ionization.

For tracks of about 1.5 times minimum ionization, the average of the probability curve mentioned above is about 9 droplets, and the square root of the second moment or root-mean-square deviation is 5.

Approximately 1.5 percent of the cells exceed the limit of 25 and are discarded. Since the tracks compared in this article all lie in the range of ionization between 1.1 and 2.4, the general shape of the probability curve for all is the same with small shifts in the average value.

For this range of ionization, the average for the probability distribution is assumed to be proportional to the ionization calculated on the basis of a maximum energy transfer corresponding roughly to the production of 25 droplets by a single ionizing event. Although the number of droplets in a cell can exceed the limit of 25 either because of the production of a large number of droplets in one event, or because of statistical fluctuations in the position of ionizing events along the track, only a small proportion of the cells is discarded, and the shape of the ionization curve as a function of velocity in the region of interest is relatively insensitive to the assumed value of the maximum energy transfer.

On the basis of the analysis outlined above, the probable error arising from statistical fluctuations in the ionization of tracks in the range mentioned has been found to be 1.7 times the probable error calculated on the basis of a Gaussian distribution involving the total number of droplets. This is the same as the probable error that would be calculated on the basis of a Gaussian distribution of primary ionizing events with each event producing 3 ions, which is about the average number actually produced.

A second source of error, about equal in magnitude to the statistical error, arises in counting the droplets. This error is introduced by the necessity of estimating the number of droplets in small clumps that contain a few droplets too close together to be resolved. The difficulty in making this type of estimate for regions

TABLE I. Ionization data.

Track	Momentum (Mev/c)	Nos. droplets counted	Experimental ionization	Calculated ionization
Event I				
Electron	13	414	1.12±0.14	1.23
Electron	25	1006	1.27±0.14	1.34
Electron	21	595	1.50±0.17	1.31
[a]π of V^0	165	227	1.31±0.17	1.39
μ of V^0	130	406	1.38±0.16	1.37
Neg. leg of V^0	875	631	1.70±0.19	...
Neg. leg of V^0	(with min. ionization determined by μ of V^0 only		1.68	...
Event II				
Electron	22	1045	1.46±0.16	1.32
Electron	69	886	1.38±0.15	1.47
Electron	120	889	1.25±0.14	1.53
π of V^0	295	491	1.21±0.14	1.06
[b]π of V^-	69	497	3.45±(0.4?)	3.7
Pos. leg of V^0	730	582	2.35±0.26	...
Pos. leg of V^0	(with min. ionization determined by π of V^0 only)		2.06	...

[a] Not included in calibration of minimum ionization because momentum is uncertain.
[b] Not included in calibration of minimum ionization because ionization is outside of the range to which analysis of errors applies.

in the chamber with different illumination is increased by the tendency of some of the negative ions to form smaller droplets than the positive ions, apparently due to a delay in the initial attachment of some electrons to form negative ions. Since the tracks to be compared are of nearly the same ionization, no attempt is made to correct for the effect of the overlap of droplet images in small groups of droplets.

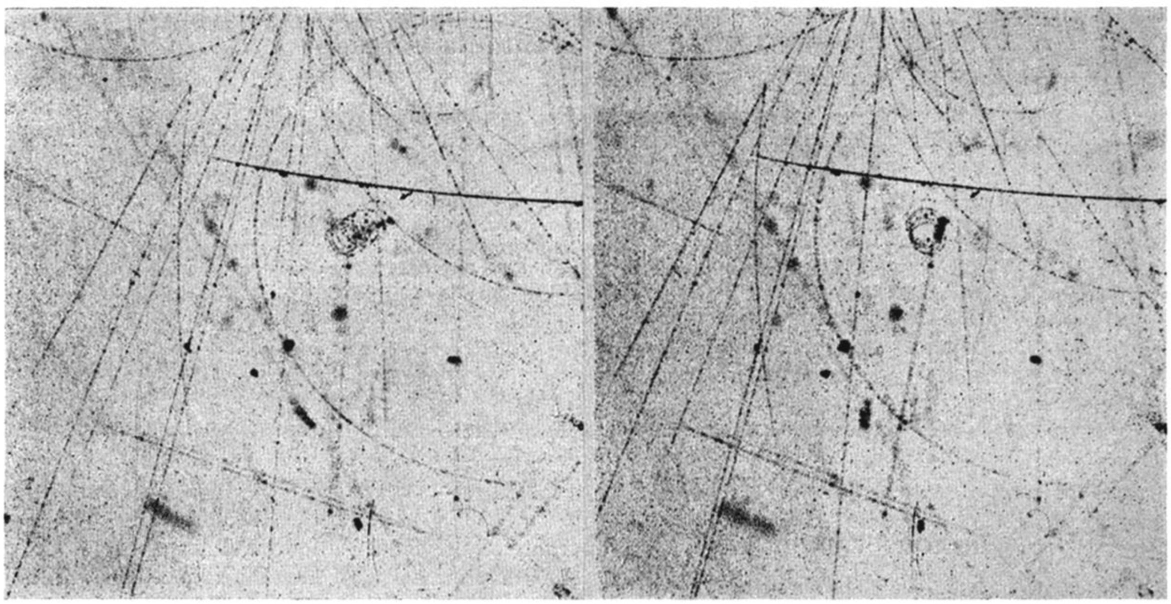
Table I gives the ionization values and total number of droplets counted for the tracks of interest and the calibration electron tracks and lists probable errors that include an estimated 10 percent error in counting. This estimated counting error is considerably larger than the differences obtained in successive droplet counts of the same track. The values of ionization for the known tracks, which are taken from several different parts of the picture, show internal consistency within the limits of the listed errors.

The value of minimum ionization, with which each track is compared, is determined separately for each of the two events from a weighted mean of the droplet counts for the tracks of known ionizations, each track being weighted in proportion to the number of droplets counted. For the electron tracks the ionization corresponding to the known momentum has been calculated by means of a formula for ionization that includes the effects of polarization in the gas for velocities greater than that required for minimum ionization. Preliminary results from a separate experiment with the same chamber involving droplet counts in small electron showers indicate that the calculated values of ionization for these electrons may be somewhat too large, but the difference is not sufficient to affect appreciably any of the conclusions drawn above.

In each of the two neutral V-decay events discussed, the heavy decay product of the V particle passes out of the illuminated region of the chamber side by side with the meson decay product of known ionization. A direct comparison of the ionization of the two particles, which are in the same region of the chamber and therefore nearly identical illumination, reduces considerably the counting errors but increases the statistical errors, since the number of droplets in the meson track used to determine the value of minimum ionization is smaller than the number in the several electron tracks previously used for calibration. This type of direct comparison of the two tracks of the V-decay event gives a mass of 1800 electron masses for the heavy negative particle of Event I and 1850 electron masses for the heavy positive particle of Event II, with about the same total probable errors as previously listed.

The enlargements in Figs. 3 and 4 show regions near the apex of the two V-decay events and gives some idea of the spacing of the droplets in the tracks. With only a visual estimate of the ionization, it is possible to establish with reasonable certainty that the heavy particle in both of the events has a mass greater than 1000 electron masses.

I would like to acknowledge many helpful suggestions concerning this work from Dr. C. D. Anderson, Dr. R. F. Christy, and Dr. R. B. Leighton.



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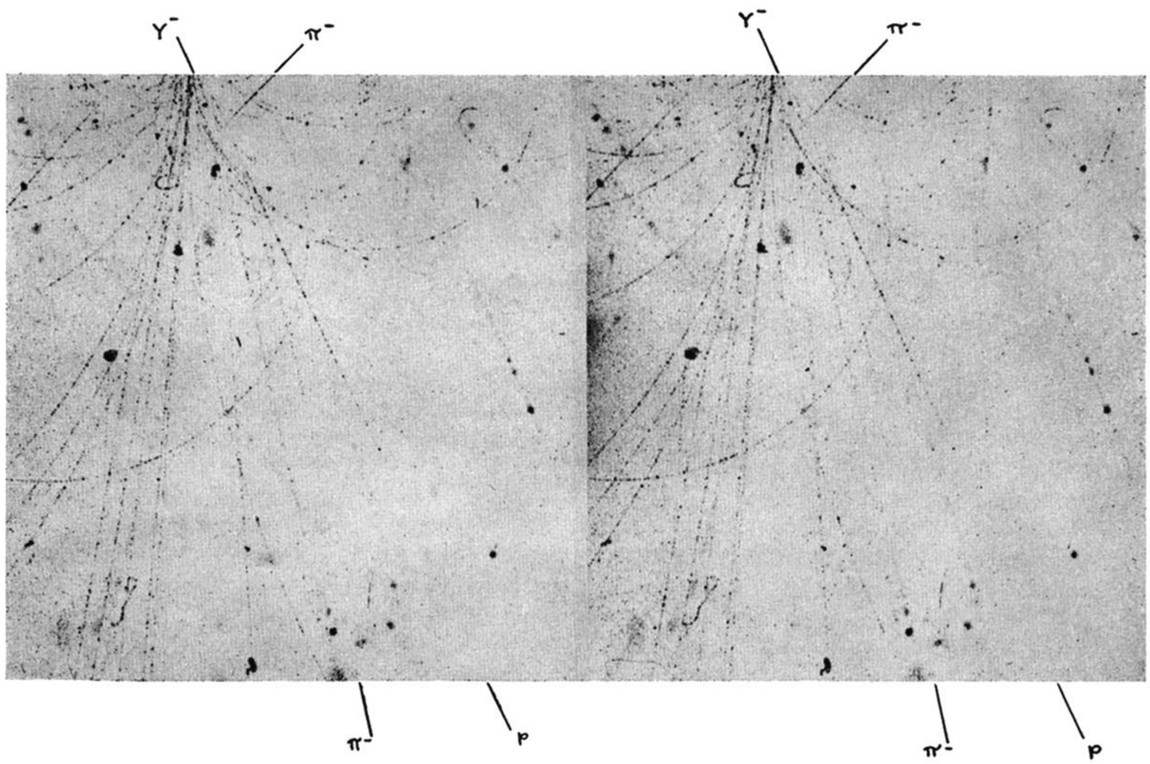

FIG. 2. A cascade event in which a negative charged V particle decays into a π meson and a neutral V particle that in turn decays into a π meson and a proton.

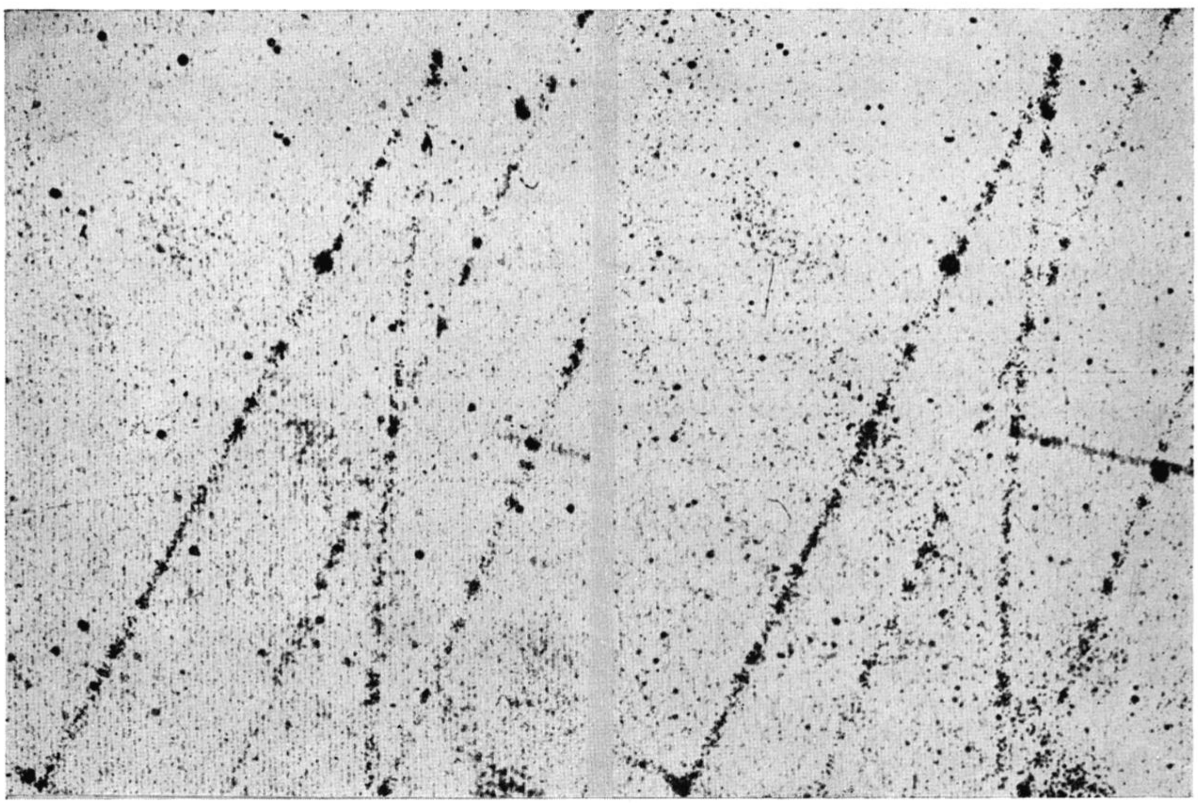

FIG. 3. Enlarged view of region near apex of V in Event I.

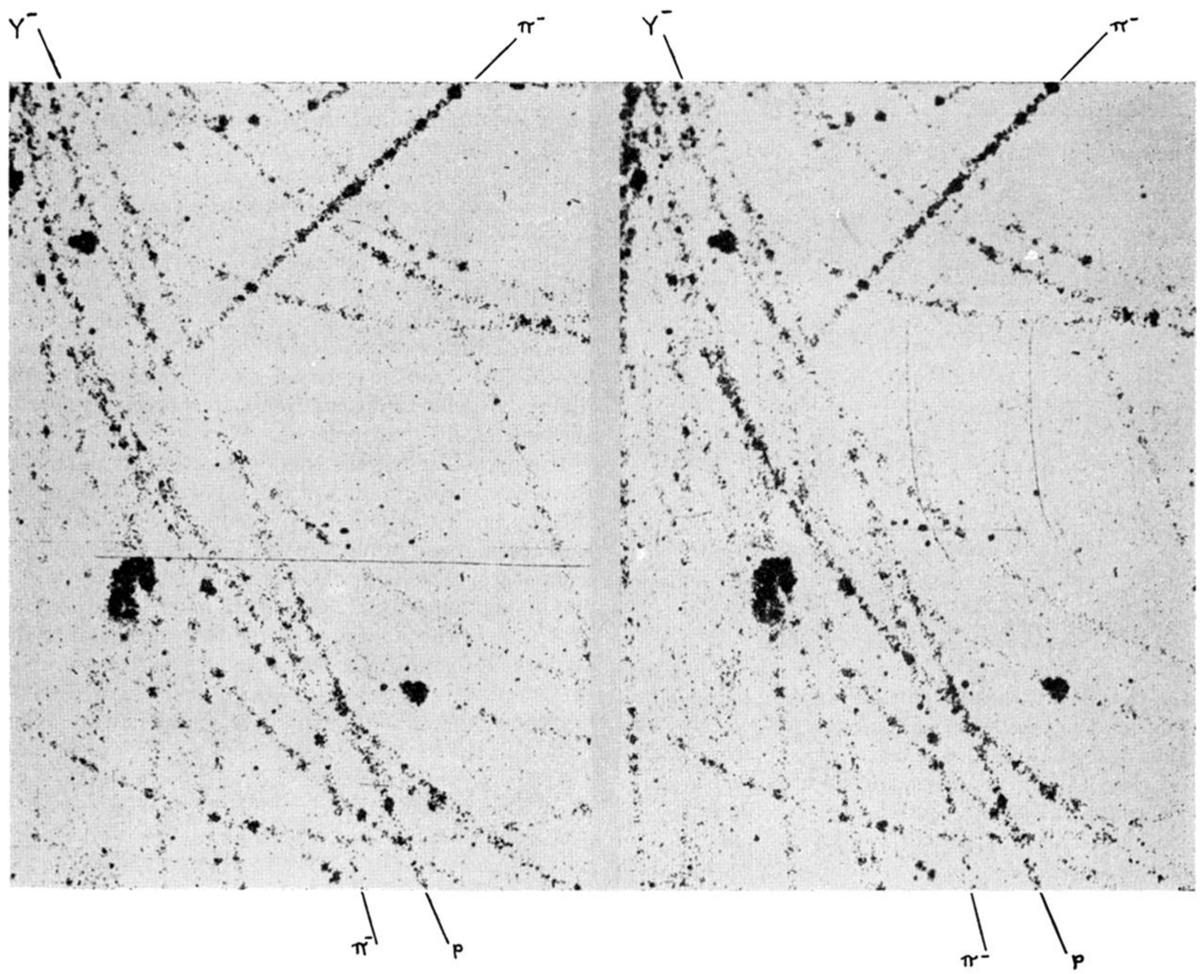

FIG. 4. Enlarged view of region near apex of V in Event II.