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# A Cloud-Chamber Investigation of Nuclear Interactions of Cosmic Rays*

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A magnet cloud chamber recently constructed at Yale University was operated at mountain altitudes (Climax, Colorado, elev. 11 200 feet) during the late fall of 1952. The cloud chamber was electronically controlled to photograph penetrating shower events initiated by high-energy cosmic rays. Five examples of neutral $V$-particle decays have been observed. One photograph reveals the decay of two $V_2^0$ particles that probably originated in a single nuclear interaction.

Secondary particles in the penetrating showers have been examined for sign of charge. From the positive-to-negative ratio of charge of the secondary particles, it has been determined that 30 percent of the observed proton-plus-meson secondary particles are protons. This percentage is a lower limit, but is probably close to the actual value.

## I. INTRODUCTION

IN recent years cloud chambers have been used[1–11] to determine properties of very high-energy nuclear interactions of cosmic rays. This article reports an investigation of nuclear interactions of high-energy cosmic rays carried out at mountain altitudes during the late fall of 1952. During the course of this study, five neutral $V$-particle decays have been observed. Secondary particles arising from observed high-energy nuclear interactions have been analyzed with respect to sign of charge. From the ratio of the number of positive-to-negative charges of the secondary penetrating particles, a proton-to-meson ratio has been determined for the observed secondary particles of high-energy nuclear interactions. Results are largely in agreement with conclusions of the sea-level cloud-chamber experiments of Rochester, Barker, Rosser, and Butler.[1–3]

## II. THE MAGNET CLOUD CHAMBER

The magnet cloud chamber utilized in this experiment is a double chamber of the expansion type, composed of two separate chambers, each rectangular in cross section. The two chambers are separated by a $\frac{7}{8}$-inch gap. The gap may be used to accommodate a proportional counter to assist with the triggering arrangement, or may be used for easy insertion of absorbing material between the two chambers. The chamber walls are constructed of aluminum. Total illuminated dimensions of the double chamber are 25 cm$\times$25 cm$\times$8 cm in depth.

A strong magnetic field is provided across the chamber by a large six-ton electromagnet. The yoke of soft iron supports a large coil on each pole piece, and power is supplied by a 25-kva motor generator. The magnetic field strength across the chamber has been measured by three separate methods—with a flip coil and galvanometer arrangement, with measurements of the curvature of a current-bearing wire suspended in the magnetic field, and with a commercially available "fluxmeter," or rotating flip coil. The magnetic field strength was found to be 8200 oersted across the gap between the pole pieces, and to be homogeneous across the illuminated region of the cloud chamber to within plus or minus 5 percent.

Stereoscopic photographs of the cloud chamber are obtained with a single lens and camera system. In order to photograph along the direction of the magnetic field, and consequently to record the curvature of trajectories of particles traversing the magnetic field, a large hole was cut in the front pole piece. This hole, rectangular in cross section, is lined along two sides with aluminized mirrors. The lens and camera mounted in the hole photograph both mirror views of the chamber in addition to the direct view. The spatial representation of tracks may be determined by reprojecting the film image through an identical optical system, using the original lens. Photographs are recorded on 35-mm Linagraph Pan film, with a Baltar 40-mm, $f/2.3$ lens.

Illumination is provided with xenon-filled Edgerton-type flash tubes constructed in this laboratory. The flash tubes are constructed from Vycor tubing to withstand the intense heat of the discharge. Two flash tubes are discharged simultaneously, dissipating 800 joules each. Uniform illumination across the chamber

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† This paper is based on a dissertation by N.R.W. in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Yale University. N.R.W. is now at General Electric Research Laboratory, Schenectady, New York.

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[1] G. D. Rochester and C. C. Butler, Proc. Phys. Soc. (London) **61**, 535 (1948).

[2] Butler, Rosser, and Barker, Proc. Phys. Soc. (London) **A63**, 145 (1950).

[3] K. H. Barker and C. C. Butler, Proc. Phys. Soc. (London) **A64**, 4 (1950).

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

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[11] Bridge, Peyrou, Rossi, and Safford, Phys. Rev. **91**, 362 (1953).

is obtained with a lens system utilizing the aplanatic points of a cylindrical Lucite rod as suggested by Lofgren, Ney, and Oppenheimer.[12] An electric sweeping field of 300 volts clears the chamber gas of old ions. This electric sweeping field is removed from the chamber within a microsecond after the coincidence circuits have been actuated.

The chamber is filled with helium and argon to nine lb/in.$^2$ above atmospheric pressure, in the ratio of three parts helium to one part argon by pressure, and absolute alcohol provides the vapor. To prevent gas in the chamber from leaking through the semiporous aluminum castings, it was found necessary to line the chambers with a thin sheet of rubber. No absorber was placed between the two chambers during this experiment.

### III. THE PENETRATING SHOWER DETECTOR

The cloud chamber and accessory equipment were mounted in a 22-foot trailer and transported to mountain altitudes at Climax, Colorado (elev. 11 200 feet). The cloud chamber was electronically controlled to photograph secondary particles occurring in penetrating showers resulting from nuclear interactions of high-energy cosmic rays in the lead absorber placed directly above the chamber. The penetrating shower detector is presented in Fig. 1. In order that the nuclear interactions could occur as close as possible to the chamber, 12 cm of lead was placed immediately above the cloud chamber. Above this was located a tray containing four Geiger counters followed by 20 more cm of lead. Below the chamber was placed a tray of four Geiger counters, followed by 10 cm of lead and another tray of counters.

To select penetrating shower events, it was required that at least one counter in tray *a*, two counters in tray *b*, and one counter in tray *c* be discharged simultaneously. The counting rate with this triggering arrangement was 10 per hour of sensitive time. Two thousand pictures were obtained with this experimental arrangement, 1200 of them of suitable quality for accurate momentum measurements. Twenty percent of the two thousand photographs contained two or more collimated particles that could have been secondary particles originating in penetrating showers, indicating that the efficiency of this equipment for penetrating shower detection is twenty percent. As will be shown later (Sec. V) the efficiency of this arrangement for detecting penetrating showers is actually much better.

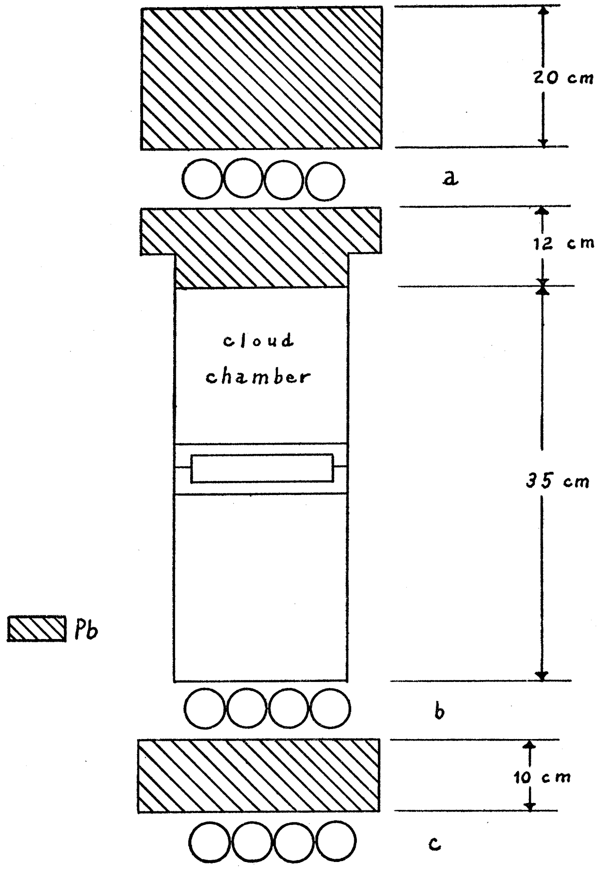

FIG. 1. Side view of penetrating shower detector and Yale cloud chamber.

### IV. THE DECAY OF NEUTRAL *V* PARTICLES

Five decays of neutral *V* particles have been observed in photographs of sufficiently good quality that momentum measurements are obtainable. Information derived from these neutral *V*-particle decays largely agrees with results and conclusions of other workers.[4–11] One of the decays has been identified as the decay of a $V_1{}^0$ particle into a proton and a negative pi meson,

TABLE I. $V^0$ particle data.

| Particle No. | Event | Classification | Momentum of positive secondary (Mev/$c$) | Momentum of negative secondary (Mev/$c$) | $\theta$ (degrees) | $Q$ (Mev) |
|---|---|---|---|---|---|---|
| I | 4-278 | $V_1{}^0$ | 625±200 | 170±50 | 53.5° | 49±20 |
| | | $V_2{}^0$ | | | | 162±55 |
| II | 6-89 | $V_2{}^0$ | 450±200 | 600±250 | 40.7° | 176±75 |
| III | 6-89 | $V_2{}^0$ | 875±300 | 700±400 | 31° | 221±100 |
| IV | 11-40 | $V_1{}^0$ | 180±50 | 230±40 | 24° | 76±30 |
| V | 6-28 | $V_2{}^0$ | 800±400 | 800±400 | 38° | 312±170 |

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[12] Lofgren, Ney, and Oppenheimer, Rev. Sci. Instr. **19**, 271 (1948).

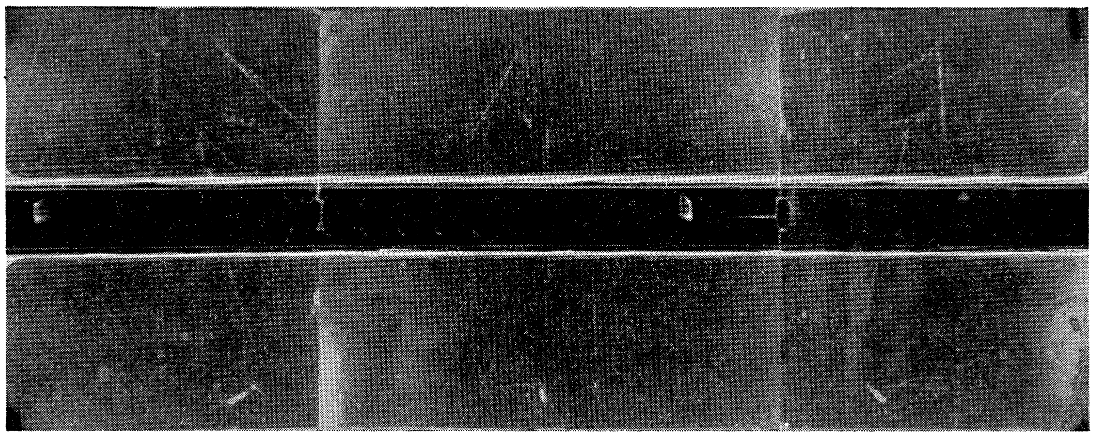

FIG. 2. Two neutral $V$ particles which are apparently produced in the same event. From their momenta and angles these particles are tentatively classified as $V_2^0$ particles.

and three have been identified as decays of $V_2^0$ particles into two mesons. One neutral $V$-particle decay does not allow positive identification of the event.

$Q$ values for each of the decays have been calculated from measurements of the momentum of each of the secondary particles and the included angle between the secondaries. The angle included between the secondaries has been measured by three separate methods. The first method is to project the film image back through an optical system identical to that used in photographing the cloud chamber. The original lens is used in this reprojection. With the three available views, the spatial representation of the tracks is obtained. The included angle may be measured directly on a small screen, equipped with many degrees of freedom of rotation, which has been adjusted until all of the secondary track images have been brought into proper alignment.

The second method used to measure the included angle between the secondary particles is similar to that described by Campbell and Welch,[13] and utilizes descriptive geometry techniques to obtain orthographic views of the decay and the true angle between the secondaries. The third method obtains algebraic equations for the trajectories of the secondaries from the projected views of the film image. The included angle may then be easily calculated. All three of these methods usually agree to within less than one degree. The data for the five measurable $V$-particle decays are presented in Table I.

Photograph 6–89 shows the decay of two neutral $V$ particles that probably originated in a single nuclear interaction. (Fig. 2). Both $V$ particles decay near the front glass of the chamber, and the secondaries slope downward and toward the back of the chamber. The upper decay occurs $\frac{1}{8}$ inch behind the front glass. Both decays may be seen well in stereoscopic reprojection. When the value[14] $\alpha=(P_+^2-P_-^2)/P^2$ is plotted *versus* $P_t$ (transverse momentum), both $V^0$ particles are consistent with the decay scheme $\pi^++\pi^-+220$ Mev. (See Fig. 3.) Although the errors in the momentum measurements are large, it does not seem possible to interpret either of these as $V_1^0$ particles. This event can therefore be interpreted as the production of two $V_2^0$ particles in the same nuclear interaction.

Photograph 4–278 contains a decay which can be interpreted as a $V_2^0$ as well as a $V_1^0$ decay. The calculated value of alpha for this decay is $0.73\pm0.08$. On the assumption of a $V_1^0$ decay the calculated $Q$ value is $49\pm20$ Mev, and on the assumption of a $V_2^0$ decay the calculated $Q$ value is $162\pm55$ Mev. The plane of the $V$-particle secondaries is coplanar to within two degrees with the point of nuclear interaction determined by reprojecting the other tracks in the shower back to their common origin.

Photograph 11–40 contains a decay which has been classified as a $V_1^0$ decay since one of the secondaries is identified as a proton on the basis of ionization and momentum. The $Q$ value calculated for this decay is $76\pm30$ Mev.

## V. THE SECONDARY PARTICLES IN THE PENETRATING SHOWERS

The 1200 good quality photographs were analyzed with respect to the secondary particles of the penetrating showers. Photographs showing penetrating showers with two or more well-collimated particles produced in the lead above the chamber were first selected. Particles in this category having momentum greater than 125 Mev/$c$ and not occurring in identifiable electronic showers were analyzed for sign of charge. It was required that all particles traverse the entire chamber and not interact in the $\frac{1}{2}$-inch aluminum wall

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[13] J. S. Campbell and D. F. Welch, Nucleonics **10**, 62 (1952).

[14] C. C. Butler, *Progress in Cosmic Ray Physics*, edited by J. G. Wilson (North-Holland Publishing Company, Amsterdam, 1952), Chap. 2.

between the two chambers. The data for this group are given in Table II. It should be pointed out that no lead was used between the chambers to select penetrating particles. However, all photographs containing a recognizable electronic component were excluded. Three hundred and seventy-eight particles were included in this group in 120 penetrating-shower photographs. Two hundred and thirty-five of the secondary particles could be classified as to sign of charge.

The ratio of positively charged secondaries to negatively charged secondaries is 1.83. If one assumes that positive and negative mesons are present in equal numbers, that a negligible number of electrons is present, and that the excess positive particles are protons, then the ratio of protons to mesons is 0.42. The percentage of protons among the observed secondary particles is therefore 30 percent. If electron-positron pairs are present, or if many electrons are present, this percentage would represent a lower limit for the protons present among the penetrating particles (protons plus mesons). This result agrees well with the results of Barker, Rosser, and Butler,[2,3] in which they conclude in a similar experiment at sea level with lead in their chamber to select penetrating secondary particles, that about half of the penetrating secondary particles observed by them are protons, and that between 25 and 50 percent of all penetrating shower particles are probably protons.

In addition, all singly-occurring particles observed in this experiment, or particles not appearing to come from a single point of nuclear interaction and therefore rejected in the first selection have been analyzed for sign of charge. All photographs containing an identifiable electronic component were again rejected. Two hundred-ninety particles of measurable sign and having momenta greater than 125 Mev/$c$ are included in this group (Table III). The ratio of positively charged particles to negatively charged particles in this case is 1.84, which is remarkably close to the corresponding value of 1.83 in the much more stringently selected group. This provides strong evidence that the penetrating shower detector is much more efficient for selecting penetrating shower events than the 20 percent figure given in Sec. III would indicate.

TABLE II. Analysis of the collimated secondary particles in definite penetrating shower events.

| | |
|---|---|
| Total number of penetrating showers: | 120 |
| Total number of secondaries from penetrating showers: | 378 |
| Total number of secondaries with measurable sign of charge: | 235 |
| Total number of positive secondaries: | 152 |
| Total number of negative secondaries: | 83 |
| Excess of positive particles: | 69 |
| Ratio of positive secondaries to negative secondaries: | 1.83 |
| Ratio of protons to mesons and electrons: | 0.42 |

TABLE III. Analysis of singly-occurring particles and groups of particles that are not collimated.

| | |
|---|---|
| Particles with measured sign of charge: | 290 |
| Total number of positive particles: | 188 |
| Total number of negative particles: | 102 |
| Excess of positive particles: | 86 |
| Ratio of positive to negative particles: | 1.84 |
| Ratio of protons to mesons and electrons: | 0.42 |

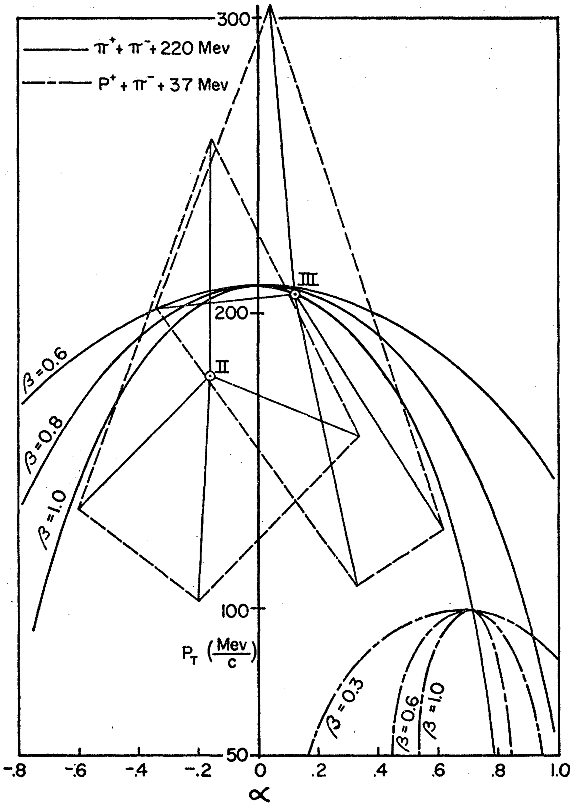

FIG. 3. Graph of $\alpha$ *versus* $P_T$ for the neutral $V$ particles shown in Fig. 2 and listed as II and III in Table I. $\alpha \equiv (P_+^2 - P_-^2)/P_0^2$ where $P_+$, $P_-$, $P_0$ are momenta of the positive, negative, and neutral particles, respectively. $P_T$ is the component of momentum of either of the charged particles perpendicular to the direction of travel of the neutral particle. The dashed trapezoids represent the possible range of the plotted points, due to errors in the momenta of the decay products.

## VI. CONCLUSIONS[4]

1. Five decays of neutral $V$ particles have been observed and analyzed. One of these is a decay of a $V_1^0$ particle, three of $V_2^0$ particles, and one does not permit definite identification.

2. A single photograph shows the decay of two $V_2^0$ particles that probably originated in a single nuclear interaction.

3. The proton component of the proton-plus-meson secondary particles in the penetrating showers observed in this experiment has been determined to be 30 percent. This figure is a lower limit, but is probably close to the actual value.

4. The positive-to-negative ratio of the singly occurring particles and uncollimated particles provides evidence that a large fraction of these originate in penetrating showers. The penetrating shower detector is therefore probably more efficient for selecting penetrating shower events than the 20 percent figure of Sec. III would indicate.

**ACKNOWLEDGMENTS**

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# Density of Extensive Air Showers at Airplane Altitudes*

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The exponent $\gamma$ in the density spectrum of extensive air showers has been measured at 25 000-ft, 30 000-ft, and 33 000-ft pressure altitude, by observing the threefold coincidence rate of counter trays as a function of tray area. Areas of the individual trays were varied by factors up to eight. The measured mean values of $\gamma$ are 1.45 at 25 000 ft, 1.5 at 30 000 ft, and 1.56 at 33 000 ft.

KNOWLEDGE of the density spectrum of large air showers at airplane altitudes is helpful in checking theories of their origin and development. Calculations[1] based upon a purely electromagnetic cascade model have predicted that the relative number of less dense showers should increase with altitude, and that $\gamma$, the exponent in the integral density spectrum,[2] should increase from 1.4 near sea level to about 1.9 near 30 000 feet. This prediction conflicts with measurements by Maze *et al.*,[3] by Biehl and Neher,[4] and by Hodson,[5] who have found values of $\gamma$ at airplane altitudes which are not much different from the sea-level values. The method used in most cases was to observe the change of counting rate of a coincidence detector when the counter area was changed (method $B$). Early measurements of this author,[6] obtained by varying the number of counters in coincidence (method $A$), indicated that $\gamma$ increases with altitude, in qualitative agreement with the predictions of the above theory. However, it has been pointed out[7] that method $A$ is unreliable, because it is susceptible to density gradients in the showers, which become more serious at high altitudes. Therefore, I have remeasured $\gamma$ in a series of airplane flights during the summer of 1951, using method $B$. The counter areas were varied by factors as high as eight. Curves of counting rate *versus* counter area were plotted from which the applicability of the power law to the density spectrum was ascertained and the values of $\gamma$ were determined. This procedure differs from other reported measurements at these altitudes, in which the power law was assumed, and the value of $\gamma$ was deduced by comparing the counting rates for two different counter areas.

The data reported here were taken in a B-29 airplane during two round trips at constant altitude between Rome, New York, and Lima, Peru. The variation in latitude, which was required by other experiments carried out in the airplane, did not adversely affect these measurements, since the extensive shower rate is constant with latitude.[4,6]

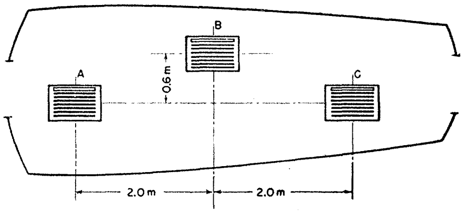

FIG. 1. Top view of rear pressurized compartment of B-29 airplane, showing location of shower counter trays. Each tray was connected to a channel of a threefold coincidence circuit.

The location of the counter trays in the airplane is shown in Fig. 1. The active dimensions of the cylindrical counters were 2.4 cm×32 cm. A space of one inch was provided between adjacent counters in each tray, to avoid overlapping of their areas for showers incident from angles other than the zenith. In this way, a tray of several counters is made to have the same effective shape as a single counter. Calculations by Biehl and

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* The work was supported in part by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.

[1] M. M. Mills, Ph.D. thesis, California Institute of Technology, 1948 (unpublished).

[2] $N=K\Delta^{-\gamma}$, where $N$ is the number of showers with density greater than $\Delta$, and $K$ and $\gamma$ are constants.

[3] R. Maze and A. Frèon, J. phys. radium **10**, 85 (1949).

[4] A. Biehl and H. V. Neher, Phys. Rev. **83**, 1169 (1950).

[5] A. L. Hodson, Proc. Phys. Soc. (London) **A66**, 49 (1953).

[6] H. L. Kraybill, Phys. Rev. **76**, 1092 (1949).

[7] J. Ise and W. Fretter, Phys. Rev. **76**, 993 (1949).

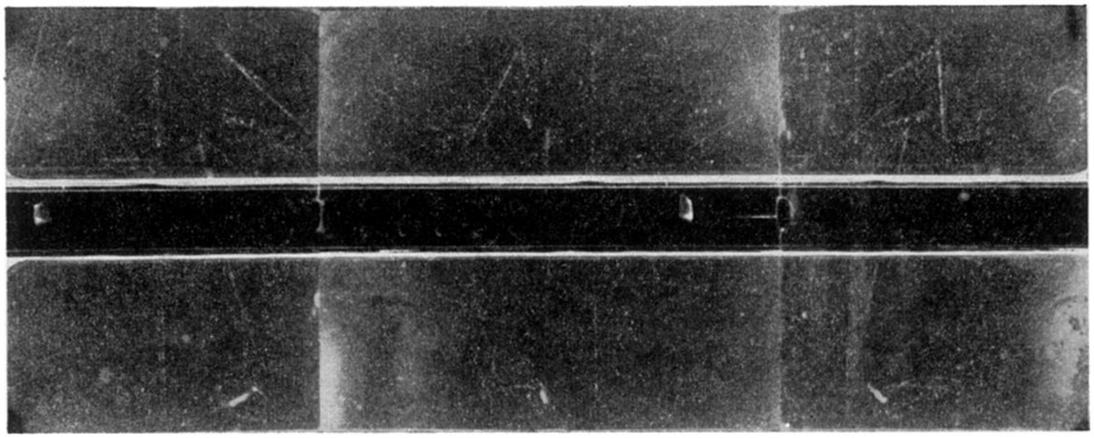

FIG. 2. Two neutral $V$ particles which are apparently produced in the same event. From their momenta and angles these particles are tentatively classified as $V_2^0$ particles.