In Table I all counting rates are in counts/sec. The quantity P_c is the percentage discrepancy of C_{calc} from C_{obs}. For the thicknesses 1.26 cm and 2.54 cm, the discrepancies of 1.6 percent and 1.7 percent are very likely within the experimental error. For 5.08 cm the discrepancy of 4.8 percent might also be within the experimental error, but the increase from 1.7 to 4.8 and the fact that all the calculated values are low lead one to believe that photons scattered more than twice begin to be important in aluminum at a thickness of two inches.

APPENDIX

Since $\sum C_0$ is the major constituent of C_{calc}, the smallness of the percentage discrepancies of C_{calc} from C_{obs} does not guarantee the accuracy of the calculated values of $\sum C_1$ and C_2. On the other hand, the smallness of σ_{ph} relative to σ_c and its computation with the satisfactory Sauter-Stobbe formula, and use of the Bronwin formula for the n_2-integrations, would appear to take care of some of the possible weak points in the above calculations. The outstanding possibility for error, however, occurs in the counter efficiency $e(\rho)$. We have tried to minimize this possibility by adjusting the Bradt efficiencies so that the theoretical and observed counting rates agree exactly at zero penetration. This procedure makes $\sum_{\rho 0} e(\rho_0)$ correct and thus practically eliminates any possibility of error from $e(\rho)$ in $\sum C_0$. There remains the possibility of error in $\sum C_1$ and C_2 from error in the shape of the $e(\rho)$ curve. More reliable theoretical predictions of the contributions of the various orders of scattering could be made for experiments involving detectors with a flat spectral response, as measured by dosage rate, such as ionization chambers. No such data appeared to be available, however, for cases involving multiple scattering at the time when these calculations were made.

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The Decay of a Neutral *V* Particle into Two Mesons*

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An unusual example of the decay of a neutral V particle has been observed in a multiplate cloud chamber operated at 10 600 feet. From this event, it is uncertain if the decay is a two- or three-body process, though in either case neither of the charged decay products can be as heavy as a proton. If we assume a two-body decay, the event may be completely and consistently described according to either of the following decay schemes: $V_2^0 \rightarrow \pi + \pi + Q$, $V_2^0 \rightarrow \pi + \mu + Q$. The corresponding Q values are approximately 185 Mev and 150 Mev, respectively.

An example of the decay of a neutral V particle into two mesons has been observed in a multiplate cloud chamber operated at Echo Lake, Colorado. One of the three available stereoscopic views is reproduced in Fig. 1. A fast charged particle (presumably a π-meson which originated in the nuclear interaction that triggered the cloud chamber) enters the chamber from above $(O'O)$ and causes a nuclear interaction at point O in plate 4. Out of this interaction there emerge three charged particles and a neutral V particle which decays at point P into an upward-going particle (No. 1) and a downward-going particle (No. 2). The directions of particle No. 1 and particle No. 2 with respect to the line of flight of the neutral particle are designated by the angles φ_1 and φ_2, respectively. The entire trajectory of each of the decay products is within the well-illuminated region of the cloud chamber.

The orientation of the plane of the V with respect to the origin O provides a test as to whether or not the decay is a two-body process. However, the large opening angle of the V, $\varphi = \varphi_1 + \varphi_2$, and the lack of adequate track lengths between plates 4 and 5 make it difficult to determine whether or not the origin O lies in the plane of the V. A geometrical reprojection discloses no definite lack of coplanarity, but neither can it be regarded as confirming coplanarity to better than about ten degrees. Another test as to whether or not the event is a two-body decay is the balance of the transverse momentum in the plane of the decay. It will be shown, however, that particle No. 2 very probably undergoes a nuclear interaction in plate 10, so that its momentum cannot be determined independently. Thus our experimental evidence will not give us a definite answer about the mode of decay, though it will be shown that the assumption of a two-body decay process leads to a completely consistent interpretation of the event.

The identification of particle No. 1 does not depend upon an assumption as to the mode of decay. Track No. 1 is at about minimum ionization (as judged by

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comparison with the adjacent fast primary track $O'O$) until after its third traversal of a lead plate. There the specific ionization appears to be between 2 and 4 times the minimum value. If the ionization is taken to be 3 times minimum, and if the particle is either a π- or a μ-meson, the residual range is about one-half of the plate thickness.[1] Using the upper limit of ionization we assign a lower limit to the range R_1 which corresponds to a penetration of 2 g/cm^2 into plate 1, and in the belief that the particle does not emerge from this plate, we assign an upper limit to R_1 which corresponds to a penetration of 8.4 g/cm^2, the full effective plate thickness at the observed angle of incidence.

There is a dense track in the space above plate 1 which might be taken to be a continuation of track No. 1, though it should be noted that it is considerably displaced; the nearby primary track $O'O$ shows no such lateral displacement as would be expected if there were a cross wind in the space above plate 1. Thus the two tracks are probably unassociated, though it is possible that a large double scattering could account for the misalignment. In any event the question is immaterial, for the track above plate 1 is so dense that if it is due to a meson the residual range could not be more than 1 g/cm^2.

TABLE I. Summary of the data for a two-body decay under the assumption that particle No. 2 is a π-meson and particle No. 1 is either a π- or a μ-meson.

$R_1 = (26.9-33.3)$ g/cm^2 of Pb
$\varphi_1 = 95.0 \pm 5$ degrees
$\varphi_2 = 33.5 \pm 3$ degrees

(a) If particle No. 1 is a π-meson:
$p_1 = (145\text{–}158)$ Mev/c
$p_2 = (261\text{–}285)$ Mev/c
$Q = (173\text{–}198) \pm 11$ Mev

(b) If particle No. 1 is a μ-meson:
$p_1 = (123\text{–}135)$ Mev/c
$p_2 = (222\text{–}243)$ Mev/c
$Q = (140\text{–}163) \pm 11$ Mev

The observed multiple scattering *vs* range of track No. 1 in three traversals is appropriate to that of a meson,[2] as is the rate of change of ionization before stopping. The ionization *vs* range is definitely inconsistent with a particle as heavy as 900 electron masses. Therefore, if particle No. 1 is a known particle, it must be a π- or μ-meson, though we cannot distinguish between the two possibilities.

From the measured range R_1 and the published[3] momentum-range curves we find the momentum p_1 in the cases (a) that particle No. 1 is a π-meson, and (b) that it is a μ-meson. Because of the slow dependence of momentum on range in this region ($p \sim R^{0.4}$), the 10 percent accuracy in range corresponds to a 4 percent accuracy in momentum (see Table I).

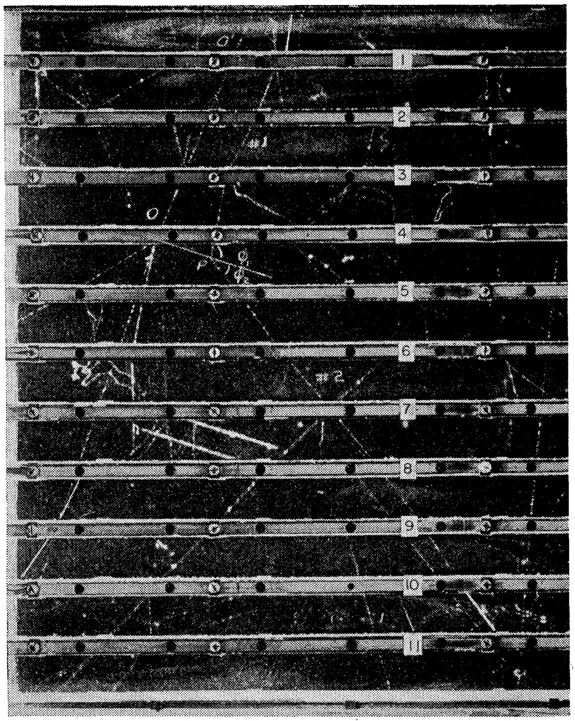

FIG. 1. Cloud-chamber photograph of a neutral V particle decaying into two mesons. The V particle originates at O and decays at P into particles No. 1 and No. 2. The chamber has an illuminated volume $20 \times 20 \times 6\frac{1}{2}$ inches. The plate assembly consists of 11 Pb plates, each of 7.74 g/cm^2 thickness.

Track No. 2 traverses five lead plates at approximately minimum ionization and with small scattering, but out of the next (plate 10) there emerges a spatially associated track which is very dense and is sharply inclined towards the front of the chamber. (The angle is not apparent from Fig. 1, but from the stereoscopic views this angle is found to be 50° with respect to the preceding section of track.) Taking into account the observed ionization, range, and scattering one cannot consistently ascribe track No. 2 to a particle of any mass which comes to the end of its range by ionization losses alone. That is, the low scattering rules out a light particle while the abrupt change in ionization density in traversing plate 10 rules out a heavy particle.

For example, let us assume that particle No. 2 is a π-meson which comes nearly to rest in plate 10 by ionization losses alone. In order that this π-meson should emerge from plate 10 with the heavy ionization observed, its ionization above the plate would have to be somewhat more than twice minimum, whereas the actual ionization above plate 10 appears to be about minimum. However, considering the uncertainties in the measurement of ionization, we cannot by this argument completely rule out the possibility that the particle is a π-meson which stops from ionization loss

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[1] The chamber contained 11 lead plates, each 7.74 g/cm^2 in thickness.

[2] Annis, Bridge, and Olbert, Phys. Rev. **90**, 1216 (1953).

[3] See, for example, B. Rossi, *High Energy Particles* (Prentice-Hall Inc., New York, 1952).

alone. Certainly, though, it could not be much heavier than a π-meson.

On the other hand, the observed rms projected scattering angle for track No. 2 is 3.5°, which is only one-half of the most probable value for a π-meson[4] of the range in question. The probability for a rms angle of scattering in five plates equal to or less than one-half of the most probable value is 4 percent. Thus on the basis of scattering and range it is unlikely that track No. 2 is a π-meson which stops from ionization losses alone and even more unlikely that it is a lighter particle.

It is therefore difficult to avoid the conclusion that particle No. 2 undergoes an inelastic nuclear collision in plate 10. (If it has geometric cross section for interacting with a lead nucleus, the observed track length of particle No. 2 is 0.4 mean free paths, and so a nuclear interaction is not unlikely.) In this event the particle could have lost any amount of energy in the encounter, and its momentum cannot be determined from the observed range. On the basis of the ionization density and the multiple scattering,[2] a rough upper limit may be obtained for the mass of particle No. 2. If we place an upper limit of twice minimum to the inoization, we conclude that this particle could be as heavy as 1000 electron masses, but that it is almost certainly lighter than a proton.

This is as much information as can be obtained without the assumption of a specific decay process. In the rest of this paper we shall develop the consequences of the assumption that the decay process involves only two particles as decay products. However, it should first be pointed out that if track No. 2 were a π-meson which stopped from ionization loss only, a two-body decay process would be impossible: the transverse momentum unbalance in this case (39 Mev/c if particle No. 1 is a π-meson and 16 Mev/c if it is a μ-meson) is beyond the limit of error in the momentum measurement. (Notice that since φ_1 is close to 90°, the transverse component of p_1 is known to an accuracy which is practically independent of φ_1.)

Under the assumption of a two-body decay process the transverse momentum of particle No. 1 can be used to compute the momentum of particle No. 2; values of the momentum p_2 computed under the assumptions that particle No. 1 is either a π- or a μ-meson, and that particle No. 2 is a π-meson, are given in Table I. If both particles are π-mesons, p_2 is between 261 and 285 Mev/c, and the most probable value of the rms scattering angle is about 3 degrees. This is perfectly consistent with the observed value. By using the upper limit of the momentum and considering that the ionization is certainly less than twice minimum, one concludes that the mass of particle No. 2 is less than 850 electron masses. Thus if the decay is a two-body process and if particle No. 2 is a known particle, it is almost certainly a π-meson; the momentum balance and ionization exclude a heavy particle, and the momentum balance requires that the particle have a nuclear interaction to explain the observed range. Because of this last fact it is unlikely that the particle is a μ- meson.

In the light of these considerations we will compute the Q value for a two-body decay process assuming that particle No. 2 is a π-meson and that particle No. 1 is either a π- or a μ-meson. The Q value depends upon three parameters: R_1, φ_1, and φ_2. Considering each as an independent source of error, the errors in Q are characterized by the following coefficients:

$$dQ/dR_1 = 3.8 \text{ Mev per g/cm}^2,$$
$$dQ/d\varphi_1 = 1.2 \text{ Mev per degree},$$
$$dQ/d\varphi_2 = -3.0 \text{ Mev per degree}.$$

The uncertainty in the range R_1 is indicated in Table I by means of upper and lower limiting values within parentheses. The resulting errors in the momenta and the Q values are similarly represented. On the other hand, the errors arising from angular measurements are indicated by ± quantities (it being assumed that the angular errors have a Gaussian distribution). The errors in φ_1 and φ_2 are believed to be not greater than 5 and 3 degrees, respectively. The uncertainty in the initial directions of the two tracks account for 4 and 2 degrees, and the uncertainty in the line-of-flight of the V^0 particle accounts for another degree.

We conclude that the present event represents the decay of a neutral V particle into two charged particles, both of which are lighter than a proton. Particle No. 1 is very likely a π- or μ-meson. The identification of particle No. 2 depends upon whether or not the decay is assumed to be a two-body process. There is no definite evidence on this last question. However, if we do assume a two-body process, the event may be consistently interpreted according to either of the following schemes:

(a) $V_2^0 \rightarrow \pi + \pi + Q$, where $Q = (173-198) \pm 11$ Mev,[5]

(b) $V_2^0 \rightarrow \pi + \mu + Q$, where $Q = (140-163) \pm 11$ Mev.

There is no experimental evidence here which would allow one to distinguish between these two possibilities.

The authors wish to thank Professor B. Rossi, Dr. H. S. Bridge, Dr. C. Peyrou, and Dr. R. W. Safford for their very helpful participation in the interpretation of this event.

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[4] The computation of the probable rms scattering angle, including the ionization loss, is given by Bridge, Peyrou, Rossi, and Safford, Phys. Rev. 91, 921 (1953).

[5] R. W. Thompson *et al.* report a group of neutral V particles which give a best Q value of 214±5 Mev if one assumes that the only decay products are two charged π-mesons. (Private communication, and Proceedings of the Third Annual Rochester Conference, 1952.)

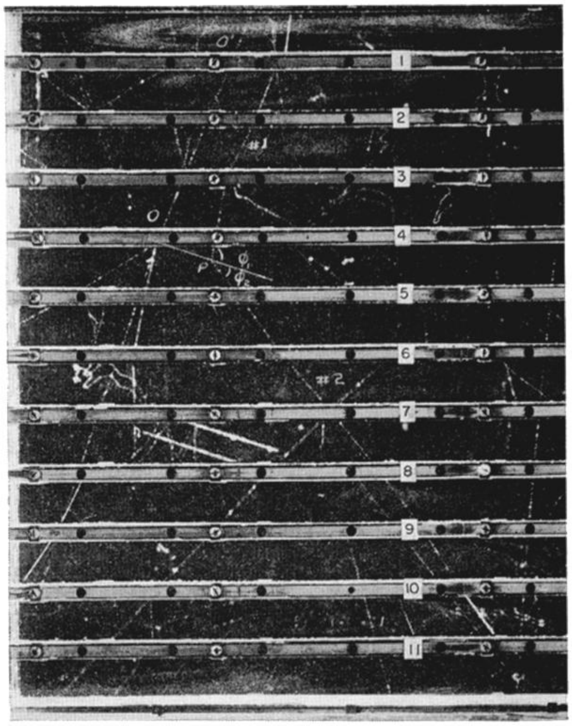

FIG. 1. Cloud-chamber photograph of a neutral *V* particle decaying into two mesons. The *V* particle originates at *O* and decays at *P* into particles No. 1 and No. 2. The chamber has an illuminated volume $20\times20\times6\frac{1}{2}$ inches. The plate assembly consists of 11 Pb plates, each of 7.74 g/cm^2 thickness.