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APPENDIX

To evaluate the integral

$$I=\int_0^1 (1-v^2)^{-\frac{1}{2}}J_1{}^2(\alpha v)(dv/v),$$

we introduce the representation

$$J_1{}^2(z)=(1/\pi)\int_0^\pi J_2(2z\sin\vartheta)d\vartheta$$

and obtain, with the change of variable $v=\sin\varphi$,

$$I=(1/2\pi)\int_0^\pi \sin^{-1}\varphi d\varphi\int_0^\pi J_2(2\alpha\sin\vartheta\sin\varphi)d\vartheta.$$

Regarding ϑ, φ as the polar angles of a point on a unit sphere, we may write

$$I=(1/2\pi)\int_{x\geq 0} x^{-1}J_2(2\alpha x)d\omega,$$

where $x=\sin\vartheta\sin\varphi$, $d\omega=\sin\vartheta d\vartheta d\varphi$, and the integration extends over the surface of the hemisphere on which x is positive. The replacement of x by $z(=\cos\vartheta)$ corresponds to a rotation of the coordinate system and does not affect the value of the integral. Hence

$$I=(1/2\pi)\int_{z\geq 0} z^{-1}J_2(2\alpha z)d\omega$$

$$=\int_0^1 \mu^{-1}J_2(2\alpha\mu)d\mu$$

$$=-\int_0^1 d(J_1(2\alpha\mu)/2\alpha\mu)=\tfrac{1}{2}[1-(J_1(2\alpha)/\alpha)],$$

which allows the verification of Eq. (4.6) in the text.

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The Energy Spectrum of the Decay Particles and the Mass and Spin of the Mesotron*

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Energy values determined from curvature measurements of 75 cloud-chamber tracks of decay particles of cosmic-ray mesotrons at sea level, in a magnetic field of 7250 gauss, are here reported. The observed spectrum extends from 9 Mev to 55 Mev with an apparently continuous distribution of intermediate energy values and a mean energy of 34 Mev. The shape of the spectrum and the value of its upper limit are strong evidence that the mesotron disintegrates into an electron and two neutrinos. It is concluded that the mesotron has half-integral spin. The value of the observed upper limit of the energy spectrum corresponds to a mass value of the mesotron equal to 217±4 electron masses.

I. INTRODUCTION

Measurements of the energy of the particles resulting from the decay of mesotrons have previously been made in three ways. In a very few cases, the energies have been determined directly by measurement of the curvature of cloud-chamber tracks of the decay particles in a magnetic field.[1] In other experiments, the energies of the decay particles have been inferred from measurement of their absorption in various materials,[2] and recently, from measurement of their scattering in photographic emulsions.[3] The very small number of cases available for measurement, and the difficulty in making precise energy measurements, have made it impossible so far to distinguish between a continuous spectrum of energies and two or three discrete energies for the decay particles. Thus, the basic nature of the spectrum has so far not been established.

The measurements of the energies of decay particles that are here reported were made on 75 cases obtained in a cloud chamber operated in a magnetic field. The precision of the measurements and the number of cases provide strong evidence for a continuous decay spectrum, and yield some information as to its shape.

* Assisted by the joint program of the ONR and AEC.

[1] (a) Adams, Anderson, Lloyd, and Rau, Phys. Rev. **72**, 724 (1947); (b) Adams, Anderson, Lloyd, Rau, and Saxena, Rev. Mod. Phys. **20**, 344 (1948); (c) R. W. Thompson, Phys. Rev. **74**, 490 (1948).

[2] Fowler, Cool, and Street, Phys. Rev. **74**, 101 (1948); Zar, Hershkowitz, and Berezin, Phys. Rev. **74**, 111 (1948); J. Steinberger, Phys. Rev. **74**, 500 (1948); E. P. Hincks and B. Pontecorvo, Phys. Rev. **74**, 697 (1948); M. H. Shamos and A. Russek, Phys. Rev. **74**, 1545 (1948); Kan-Chang Wand and S. B. Jones, Phys. Rev. **74**, 1547 (1948).

[3] Brown, Camerini, Fowler, Muirhead, Powell, and Ritson, Nature **163**, 47 (1949).

Preliminary results of the present experiments have been reported.[4]

II. APPARATUS

Tracks were photographed in a cloud chamber of 30-cm inside diameter and 11-cm depth, operating in a magnetic field of 7250 gauss. The chamber was filled with argon to an absolute pressure of 1.25 atmospheres; a mixture of 35 percent water and 65 percent ethyl alcohol was used, giving an expansion ratio of 1.08. The gross weight of the magnet is 3300 pounds and it consumes a power of 10 kw. The cloud chamber is of the freely falling type.[5] This type of cloud chamber is employed in order to obtain a stronger and more uniform magnetic field for a given power consumption and magnet weight, to simplify the illumination, and to study the characteristics of a freely falling chamber with respect to track distortions arising from convection currents in the gas. In the present apparatus, the cloud chamber falls freely for a distance of 45 cm between the time the particle enters the chamber and the time the photograph is made. The tracks are illuminated by light projected from the rear of the cloud chamber through the front and rear walls which consist of glass plates. Four condensers, each of 23 μf charged to 1500 volts, are discharged through four FT-422 (General Electric Company) lamps to provide the illumination, and stereoscopic photographs are made on linagraph orthofilm with a lens setting of $f/14$. By means of a thermostated water jacket, all portions of the cloud chamber are maintained at constant temperature to within ± 0.1°C.

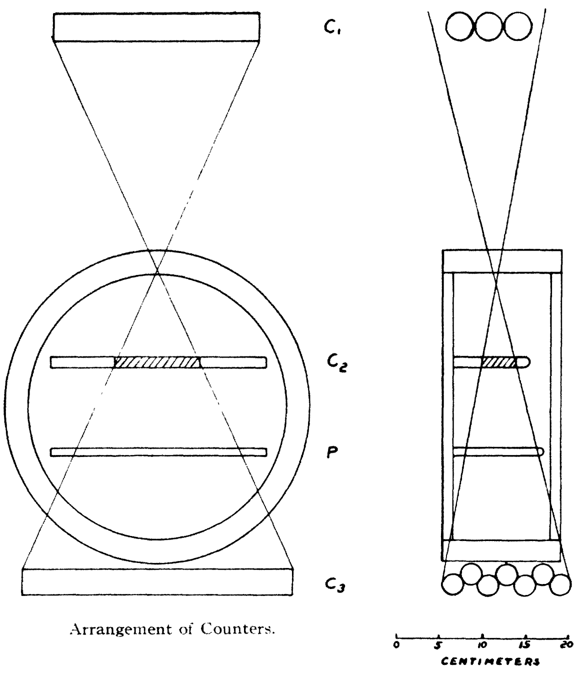

FIG. 1. Schematic diagram of cloud chamber and arrangement of Geiger counters.

The disposition of the Geiger counters which control the chamber is shown in Fig. 1. A lead absorber of 10-cm thickness has been placed directly below the upper coincidence tray. The chamber is actuated when a coincidence occurs between a counter in the tray C_1 above the chamber, and the counter C_2 mounted inside the chamber, if this coincidence is not accompanied by the discharge of a counter in the lower tray C_3. In this way the relative yield of slow particles, which stop inside the chamber, is increased. The total counting rate is approximately ten per hour.

The counter C_2 inside the chamber is rectangular in shape, having flat top and bottom surfaces consisting of copper sheet of 0.87-mm uniform thickness. The counter is mounted inside a flat copper jacket whose wall thickness is 0.63 mm. The counter also acts as an absorber for the determination of the mass of the mesotron by measurements of its momentum before and after it traverses the 3.0 mm of copper in the counter and jacket. A carbon plate P, 2.0 g/cm^2 in thickness, is mounted in the lower part of the chamber and provides an additional absorber for mass determinations and for the observation of decay particles.

III. EXPERIMENTAL RESULTS

Out of a total of 15,000 photographs, 75 photographs were obtained which show slow mesotrons which are observed to produce decay particles whose tracks are suitable for measurement. In these cases the mesotron stops either in the gas of the chamber, in the counter C_2 inside the chamber, in the carbon plate, or in the Bakelite or glass walls of the chamber. On the basis of evidence presented in Section IV of this paper, the decay particles are assumed to be electrons. Figures 2 and 3 are examples of electrons produced in the decay of mesotrons. The energy of the electron was determined in each case from measurement of the track curvature in the magnetic field. Each energy measurement was corrected for the angle between the electron track and the magnetic field, and for the energy lost by the electron before it appeared in the cloud chamber. The latter correction was made by calculating the distance of penetration of the incoming mesotron into the absorber, using for this purpose the momentum of the mesotron as determined from the observed curvature of its track, and assuming that the mass of the mesotron in each case is 220 m_e (m_e = electron mass); then, with the

[4] Leighton, Anderson, and Seriff, Phys. Rev. **75**, 1466 (1949). See also: R. W. Thompson, Phys. Rev. **75**, 1279 *et seq.* (1949); J. Steinberger, Phys. Rev. **75**, 1279 *et seq.* (1949).
[5] C. T. R. Wilson and J. G. Wilson, Proc. Roy. Soc. **148A**, 523 (1935).

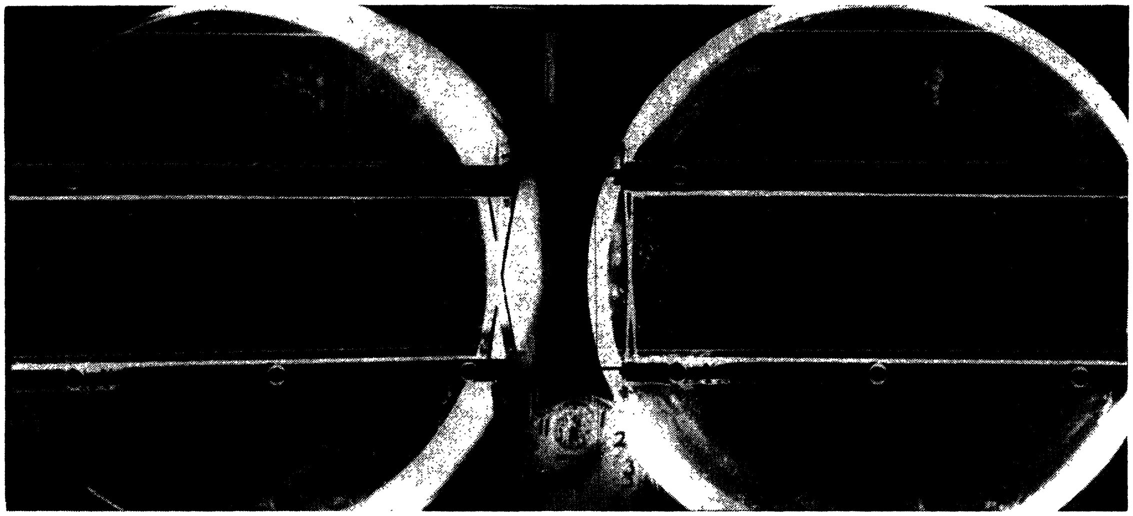

FIG. 2. A mesotron of positive charge passes downward through the counter in the cloud chamber, comes to rest in the carbon plate, and produces a decay electron whose energy, after correction for energy loss in the plate is 37 ± 1.5 Mev. The momentum of the mesotron upon entering the carbon plate is 72 Mev/c. A magnetic field of 7250 gauss, directed toward the observer, is present. Two stereoscopic views are shown.

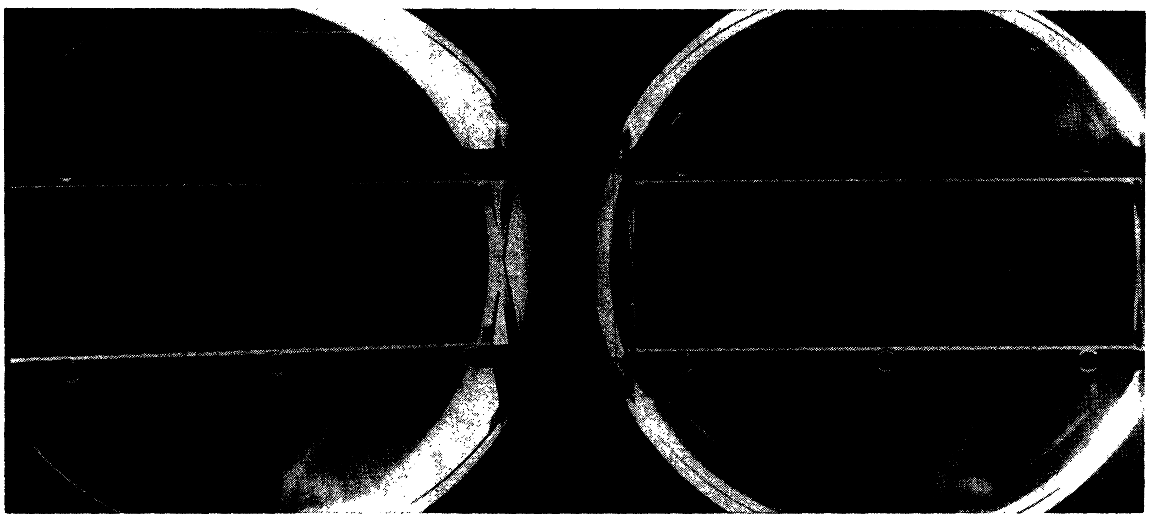

FIG. 3. A mesotron of negative charge passes through the counter in the cloud chamber and comes to rest in the gas (argon). A decay electron of 13.0 ± 1 Mev is produced. The decay electron is projected in a direction almost normal to the front glass of the cloud chamber, thus producing only a short track. The increase in ionization and the scattering of the mesotron near the end of its range is apparent in the photograph.

aid of stereoscopic observation of the tracks, the thickness of material traversed by the electron and the corresponding loss in energy of the electron were determined. The largest of these corrections is 11 Mev, and in the great majority of cases, the corrections are only 2 to 5 Mev. Since these corrections could be made with considerable accuracy, the error they introduce into the final energy of the decay electron is only 1 to 2 Mev.

It is possible that electrons of very low energy may have escaped detection by their failure to emerge from the walls of the chamber or from the carbon plate. However, the effect of such cases on the observed energy distribution should be small, and should be limited almost wholly to electrons of energy less than about 10 Mev. It is also possible that electrons of high energy may have escaped detection by entering the bank of anticoincidence counters below the cloud chamber. The combined thickness of the lower wall of the cloud chamber, and the anticoincidence counter wall is about 7 g/cm^2, which corresponds to the total range of an electron of about 15 Mev. Geometrical considerations, which include the effect of the curvature of the electron

TABLE I. Energies of decay electrons. List of observed decay electrons arranged in order of increasing energy. The sign of charge is indicated and the region of the chamber in which the decay occurred.

Sign of charge	Material	Energy in Mev
+	Carbon	9.0±2.0
+	Carbon	11.0±1.5
−	Carbon	11.8±0.5
+	Carbon	12.5±2.0
−	Gas (argon)	13.0±1.0
+	Bakelite	16.0±3.0
+	Carbon	17.0±1.0
−	Carbon	18.0±1.0
+	Copper	18.0±1.0
+	Carbon	19.0±1.0
−	Carbon	20.5±1.0
−	Copper	21.0±2.0
−	Bakelite	21.5±0.5
+	Bakelite	22.0±1.0
+	Bakelite	22.5±2.0
+	Copper	23.0±5.0
+	Bakelite	24.0±2.0
+	Carbon	25.5±2.0
−	Bakelite	27.0±2.0
+	Glass	27.5±1.5
−	Carbon	27.5±1.5
−	Glass	28.0±3.0
+	Copper	28.5±3.5
+	Carbon	29.0±1.0
−	Carbon	29.0±2.0
−	Carbon	29.0±6.0
+	Brass	30.0±1.0
+	Bakelite	30.0±1.0
−	Carbon	30.5±1.5
+	Copper	31.0±4.0
+	Bakelite	31.5±2.0
+	Carbon	32.5±1.5
+	Copper	32.5±1.5
+	Copper	33.0±3.0
−	Carbon	34.0±2.0
+	Carbon	35.0±1.5
−	Carbon	35.0±3.0
−	Carbon	36.0±2.0
−	Carbon	36.0±2.0
+	Carbon	36.5±2.0
+	Carbon	37.0±1.5
−	Carbon	37.0±4.0
−	Copper	38.0±5.0
−	Copper	38.5±3.0
+	Glass	38.5±5.0
+	Glass	38.5±5.0
+	Carbon	39.0±2.0
+	Copper	39.0±4.0
−	Glass	39.0±4.0
−	Carbon	40.0±2.0
+	Copper	40.0±2.0
+	Carbon	40.0±2.0
−	Carbon	40.0±4.0
−	Glass	41.0±1.5
+	Carbon	41.0±1.5
+	Carbon	41.0±2.0
−	Carbon	42.0±3.0
−	Carbon	43.0±2.0
−	Carbon	43.0±3.0
+	Bakelite	43.0±4.0
−	Carbon	43.0±4.0
+	Carbon	43.5±2.0
+	Carbon	44.0±1.5
+	Carbon	45.5±1.0
+	Carbon	45.5±3.0
+	Bakelite	46.5±3.0
−	Carbon	46.5±3.0
+	Carbon	47.0±2.0
−	Carbon	48.5±2.5
−	Carbon	51.5±2.0
−	Glass	52.0±2.0
−	Copper	52.0±4.0
−	Carbon	52.5±2.0
−	Bakelite	53.0±2.0
+	Bakelite or brass	54.9±1.0

trajectories, indicate, however, that not more than 10 percent of the electrons should have escaped detection in this way.

In Table I are listed the energies of all the decay electrons observed. The estimated uncertainties in the energy values, the sign of charge, and the material in which the mesotron decayed are also given.

It will be noted that in the case of mesotrons which decay in carbon and Bakelite, positive and negative electrons occur in almost equal numbers, while positive electrons predominate when the mesotron decays in copper. The average energy of all the decay electrons is 34 Mev.

In Fig. 4 is shown the integral distribution of the observed energies of the decay electrons, where the ordinate of each point corresponds to the total number of decay electrons having an energy less than, or equal to, the energy indicated by the abscissa.

In Fig. 5 is shown the differential energy spectrum where each point represents the observed number of electrons per energy interval of 10 Mev. Points corresponding to two sets of overlapping energy intervals, displaced from one another by 5 Mev, are plotted.

The energy spectrum of mesotron decay electrons may be compared with the distribution found in the case of nuclear β-decay. In the case of mesotron decay, the most probable electron energy is about 40 Mev, which corresponds to about three-fourths of the observed maximum energy, whereas the most probable energy in the case of nuclear β-decay is usually about equal to, or even less than, one-half of the maximum energy. The present data are not sufficient to establish the behavior of the curve at the upper and lower energy limits. The relatively large number of cases observed in the vicinity of the upper energy limit, however, indicates that the energy spectrum of mesotron decay electrons falls to zero at the upper energy limit more abruptly than does the spectrum of nuclear β-particles.

In many cases, the curvature in the magnetic field and, therefore, the momentum of the incoming mesotron was measured before and after it traversed the known amount of material represented by either the flat counter or the carbon plate in the chamber. Computation of the mass of the mesotron from

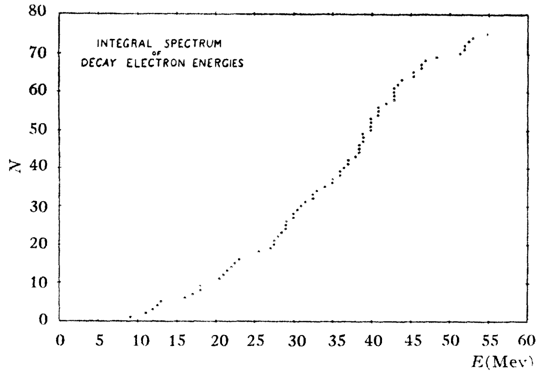

FIG. 4. Integral distribution of the energy of mesotron decay electrons.

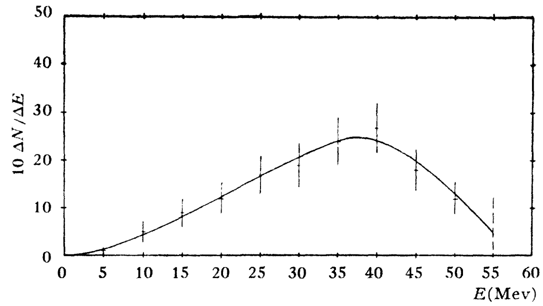

FIG. 5. Energy spectrum of mesotron decay electrons. Each point represents the number of electrons per energy interval of 10 Mev. The vertical lines indicate the expected statistical spread. A smooth curve is drawn through the observed points.

these data lead to values usually ranging from about 175 to 300 m_e. The effects of gas distortions, the short length of track available for measurement, and the small curvature of the tracks did not permit the rather high precision of measurement needed to obtain mass values of small uncertainty. The observed mass values, however, are not inconsistent with a unique mass of about 220 m_e.

IV. THE DECAY PRODUCTS OF THE MESOTRON

It has been assumed throughout this paper that the observed ionizing decay particle is an electron. This, of course, has not actually been proved. It is possible, however, to estimate the charge and to set an upper limit to the mass of the particle. Visual estimates of the minimum ionization of the decay particles indicate that their charge is certainly less than twice that of an electron. In one photograph the decay particle was deflected by the magnetic field so that it made four traversals of the carbon plate before coming to rest within the plate. The successive values of the momentum of this particle, after each traversal of the plate, were measured. From these momenta and the corresponding amount of carbon traversed, it is possible to set an upper limit to the mass of the decay particle equal to 15 m_e. Comparison with its own ionization at higher momenta, and with the ionization of the 90-Mev/c mesotron, gave 1.5 times minimum as an upper limit for the ionization of the decay particle, when its momentum was 5.5 Mev/c. This leads to a value of 10 m_e for the upper limit of its mass. The data are therefore wholly consistent with the assumption that the charged particle is an electron.[6]

Before any measurements had been made of the energy of the decay electrons, it was generally assumed that in the decay process an electron and a single neutrino are formed. If momentum and energy are conserved in the decay process, one would then expect to find decay electrons of a discrete energy equal to about 55 Mev for a mesotron whose mass is 220 m_e. The first accurate measurements,[7] however, of the energy of mesotron decay electrons consisted of two cases in each of which the energy of the decay electron was only 25 Mev, thus ruling out this hypothesis. The new data here reported serve to place further restrictions on the alternative modes of decay suggested at that time, and indeed, only one of these is entirely consistent with the present data; i.e., a decay resulting in the production of an electron and two neutral particles of very low mass.

If one excludes the possibility that the mesotron has a variable mass,** then, on the basis of conservation of energy and momentum, the observed broad energy spectrum is inconsistent with any mode of decay which results in the production of only two particles of discrete mass, e.g., an electron and neutrino, or an electron and a neutral mesotron. If we assume, therefore, that an electron and two neutral particles are produced, it is possible to compute an upper limit to the sum of the masses of the two neutral particles from the observed upper limit of the decay spectrum on the basis of the conservation laws. Assuming the mass of the mesotron to be 216 ± 4 m_e,[8] and taking the observed upper limit of the energies of the decay electrons to be 55 ± 1 Mev, one finds that the data are consistent within the given errors only with the emission of particles whose added masses are less than 30 m_e. The fact that the production of energetic photons is not observed in mesotron decay[9] leaves open only

[6] See also J. C. Fletcher and H. K. Forster, Phys. Rev. **75**, 204 (1949); E. P. Hincks and B. Pontecorvo, Phys. Rev. **75**, 698 (1949).

[7] See reference 1, (a) and (b).

** In several instances, both the mass of the mesotron and the energy of its decay electron were measured with sufficient precision to show that these quantities do not bear the relationship to one another to be expected on the basis of the conservation laws, if the mesotron decays simply into an electron and a single neutrino.

[8] A. S. Bishop, Phys. Rev. **75**, 1468A (1949).

[9] R. D. Sard and E. J. Althaus, Phys. Rev. **75**, 1251 (1948); E. P. Hincks and B. Pontecorvo, Phys. Rev. **73**, 257 (1948); O. Piccioni, Phys. Rev. **74**, 1754 (1948).

the possibility that the neutral particles are neutrinos or other neutral particles of low mass. In terms of generally accepted particles, the simplest decay process is thus one which results in the production of an electron and two neutrinos.

On the other hand, if the neutral particles have rest masses which are actually zero, then the mass of the mesotron, calculated from the upper limit of the energy spectrum, is equal to $217\pm4\ m_e$. Within experimental uncertainty this value is equal to the values, $216\pm4\ m_e$[8] and $215\pm4\ m_e$,[10] determined by other methods, and is in satisfactory agreement with 220 ± 35 Mev, the only mass measurement previously reported from this laboratory.[11]

The observed shape of the energy distribution curve and the observed average electron energy provide further support to the assumption that the decay results in the production of three particles and not more than three; for if the decay results in the production of three particles whose proper energy is small compared with the total available energy, and if the three particles play symmetrical roles in the decay process, then each particle should receive an average energy approximately equal to one-third of the total available energy or two-thirds of the maximum electron energy. Two-thirds of the maximum observed electron energy (55 Mev) is 37 Mev, which is in satisfactory agreement with the observed value of 34 Mev for the average decay electron energy. A decay resulting in the production of four or more particles seems unlikely as the average energy then to be expected would be 27.5 Mev or less.

If one adopts the view indicated above, that the decay of the mesotron results in the production of an electron and two neutrinos, $\mu^{\pm}\rightarrow e^{\pm}+2\nu$, then, in order that spin may be conserved in the decay, the spin assigned to the mesotron must be half-integral.

Electron energy distributions have been computed recently for several different types of fields.[12] In some cases these are in good qualitative agreement with the observed spectrum, but more data will be needed for a precise comparison.

We wish to acknowledge the assistance of Dr. E. W. Cowan who provided the counter circuits, and of Mr. Robert C. Hsiao who shared in the operation of the equipment and in the measurements.

[10] J. G. Rettallack and R. B. Brode, Phys. Rev., in press.

[11] S. H. Neddermeyer and C. D. Anderson, Rev. Mod. Phys. **11**, 201 (1939).

[12] J. Tiomno and J. A. Wheeler, Rev. Mod. Phys. **21**, 144 (1949).

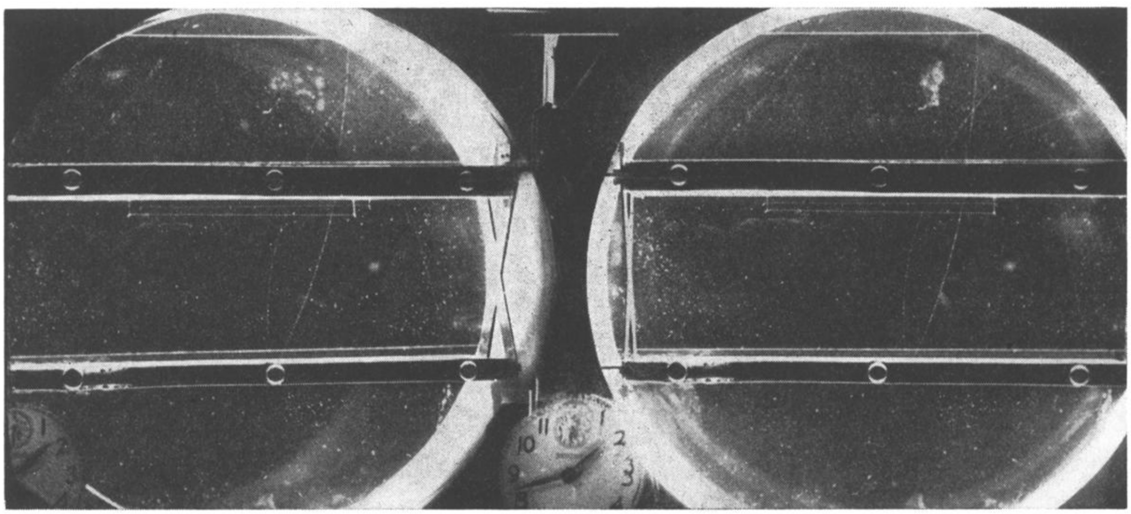

FIG. 2. A mesotron of positive charge passes downward through the counter in the cloud chamber, comes to rest in the carbon plate, and produces a decay electron whose energy, after correction for energy loss in the plate is 37 ± 1.5 Mev. The momentum of the mesotron upon entering the carbon plate is 72 Mev/c. A magnetic field of 7250 gauss, directed toward the observer, is present. Two stereoscopic views are shown.

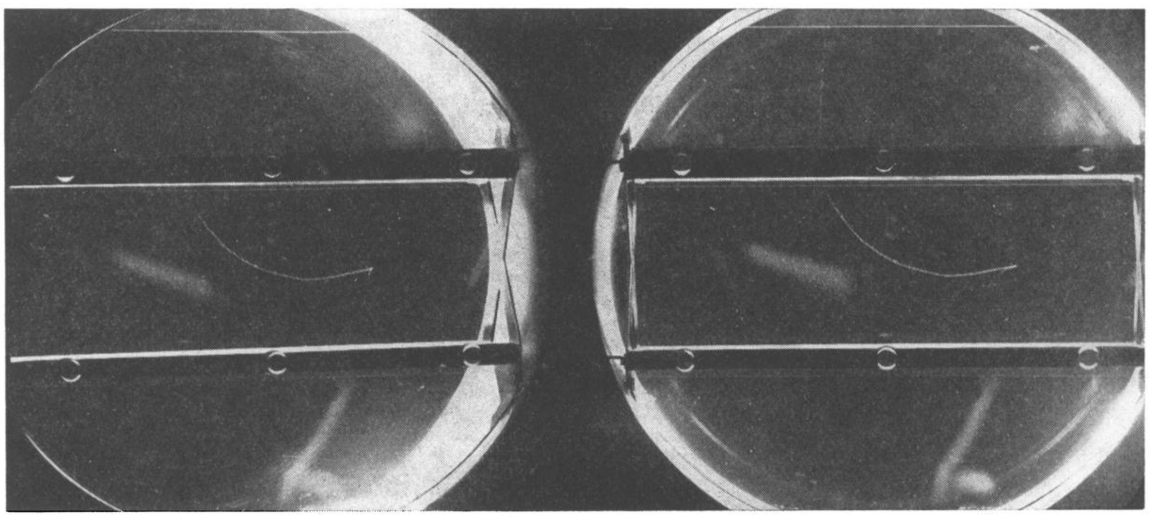

FIG. 3. A mesotron of negative charge passes through the counter in the cloud chamber and comes to rest in the gas (argon). A decay electron of 13.0±1 Mev is produced. The decay electron is projected in a direction almost normal to the front glass of the cloud chamber, thus producing only a short track. The increase in ionization and the scattering of the mesotron near the end of its range is apparent in the photograph.