Discussion on the Disintegration and Nuclear Absorption of Mesons

Introductory Remarks

B. ROSSI, *Massachusetts Institute of Technology, Cambridge, Massachusetts:* Many experiments have been performed in recent years to investigate the phenomena which accompany the disappearance of ordinary mesons.

The results published to this date lead to the following conclusions. Both positive and negative mesons undergo spontaneous decay while in flight. Their mean lifetimes are believed to be identical and certainly do not differ by more than a few percent. When mesons stop in matter, they behave in a different manner depending on their sign, as first shown by the work of Conversi, Pancini, and Piccioni. Positive mesons undergo spontaneous decay in all substances with a mean lifetime of approximately 2.15 microseconds. Negative mesons undergo spontaneous decay with the same lifetime when brought to rest in very light elements. No delayed emission of decay electrons is observed when negative mesons come to rest in heavy elements (iron). In elements of intermediate atomic number (for instance, aluminum), negative mesons undergo disintegration but with a considerably shorter lifetime than positive mesons (Ticho, Valley). The following questions need further investigation:

A. *Products of the Spontaneous Decay of Mesons.* Past experiments indicate that when a meson decays a single electron is produced. This result needs to be tested more conclusively. If true, the principles of conservation of momentum and energy require that at least one neutral particle be produced simultaneously with the electron. The following questions then arise: Is only one neutral particle or are several neutral particles produced when a meson disintegrates? What is the nature of the neutral particles arising from the disintegration of mesons?

Useful information bearing on the above questions can be obtained by studying the energy distribution of decay electrons. If the disintegration is accompanied by the production of only one neutral particle, the decay electron must always have the same energy, E, given by the equation

$$E=(\mu^2c^4-\mu_0{}^2c^4)/2\mu c^2, \qquad (1)$$

where c is the velocity of light, μ is the mass of the meson, and μ_0 is the mass of the neutral disintegration product. If, instead, the disintegration of a meson gives rise to more than one neutral particle, then one should expect a spread in energy for the decay electrons. Equation (1) in this case gives the maximum energy of the decay electron, if μ_0 is understood as the sum of the masses of the neutral particles emitted in each disintegration process.

B. *Behavior of Negative Mesons.* The difference in behavior of positive and negative mesons which come to rest in matter depends on the fact that a negative meson, after being slowed down by inelastic collisions, is captured into a Bohr orbit in the neighborhood of a nucleus, while a positive meson, because of electrostatic repulsion, never reaches the vicinity of atomic nuclei, and it wanders about until it disintegrates.

The question then arises whether the shortening of the lifetime of negative mesons is due to a competition between nuclear absorption and spontaneous decay or by an acceleration of the natural decay process caused by the strong electric field which exists in the vicinity of atomic nuclei. If the first hypothesis is correct, the following relation should exist between the mean lifetime of negative mesons, τ^-, and the fraction, f, of negative mesons which undergo spontaneous decay

$$f=\tau^-/\tau, \qquad (2)$$

where τ is the mean lifetime of free mesons.

C. *Effects of the Nuclear Absorption of Negative Mesons.* If it turns out that some of the negative mesons undergo nuclear absorption after coming to rest in matter, the question arises as to what happens to the rest energy of mesons which is thereby set free.

Remarks by Anderson

C. D. ANDERSON, *California Institute of Technology, Pasadena, California:* In a series of 9000 cloud-chamber photographs in a magnetic field of 7500 gauss made at 30,000-ft. altitude, we have observed one[1] and probably two[2] cases

[1] Anderson, Adams, Lloyd, and Rau, Phys. Rev. 72, 724 (1947).

[2] Adams, Anderson, Lloyd, Ray, and Saxena, Rev. Mod. Phys. 20, 334 (1948).

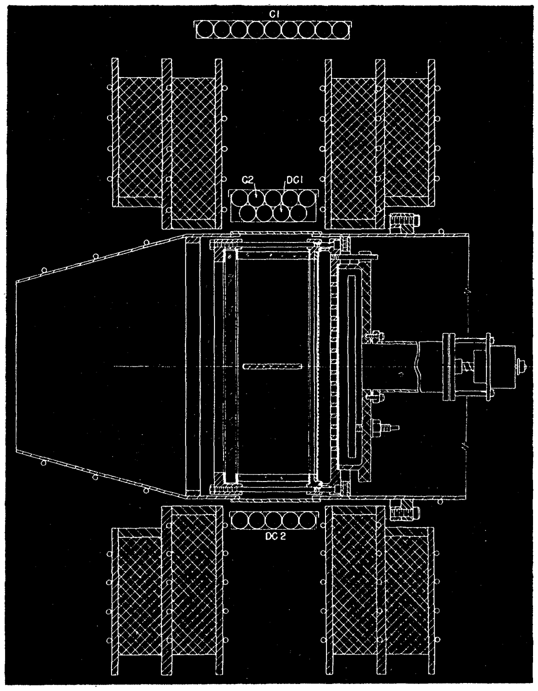

FIG. 1. Experimental arrangement used by Thompson for measuring the energy of decay electrons.

which seem to represent an electron resulting from the decay of a mesotron. Both of these cases represent the decay of mesotrons of positive charge, and the energies of the decay positrons in the two cases are 24 and 25 Mev, respectively. Now in recent experiments at M.I.T., I understand the energies of the decay electrons observed are approximately 40 Mev, and therefore it will be worth while to consider the magnitude of the errors in our measurements and to see whether there might not be some other interpretation of our photographs.

Our first case shows a heavily ionizing particle entering the cloud chamber and coming to rest very near one edge of the illuminated region, and a lightly ionizing track which is accurately copunctal with the heavily ionizing track. The radius of curvature of the lightly ionizing track is readily measured and corresponds to an energy of 24 Mev if the particle is assumed to be a positron. Considering the inhomogeneity of the magnetic field, the effect of scattering in the gas, and the errors of measurement of the curvature of the track, one would assign limits to the energy of 21 and 27 Mev.

The question has been raised that this photograph might represent the disintegration of a π-mesotron into a μ-mesotron, and that the lightly ionizing track represents the μ-mesotron. This possibility, however, can be entirely eliminated because the secondary particle ionizes very near or at the minimum value, which fact, if considered together with the observed range of the particle, precludes the possibility that the secondary particle could have a mass greater than 25 electron masses, and thus cannot represent a μ-mesotron.

If one measures the radius of curvature of the upper half of the heavily ionizing track and then determines its residual range by measuring the distance the particle goes from the midpoint of the upper half of the track to the end, the mass of the heavily ionizing particle can be computed to be about 100 electron masses. This is just the value of mass which corresponds to a decay electron energy of 24 Mev, if the particle is assumed to disintegrate into an electron and a neutrino. Such an interpretation should not be ruled out, particularly when one recalls that our two disintegrations were observed at an altitude of 30,000 ft. while the M.I.T. experiments which lead to higher decay electron energies were made

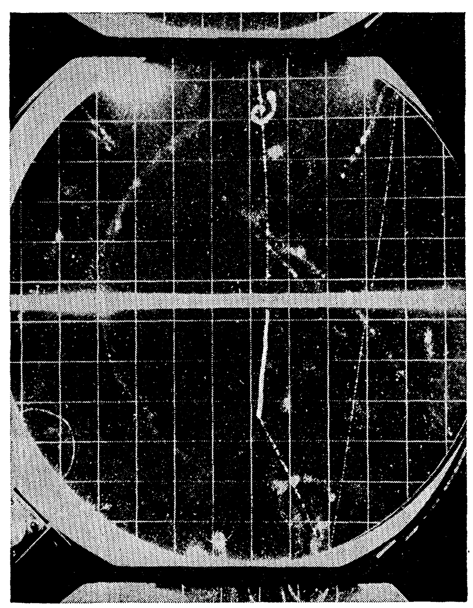

FIG. 2. Cloud-chamber picture of a meson decay process occurring in the gas.

at sea level. In this connection, however, it should be emphasized that the measurement of mass as indicated above actually means very little because the particle is near the end of its range where the probability of scattering in the gas is very high. In fact, the probability that the mass is 200 electron masses or more in this case is about 20 percent, so we have no real evidence here that the particle does not have a mass of about 200 electron masses. It might also be mentioned that among the 9000 photographs made in this series of flights there are several cases of mesotron tracks whose ionization and curvature are consistent with mass values of 200 or 300 but are not consistent with a mass as low as 100 electron masses.

Our second case shows a heavily ionizing track which crosses the cloud chamber and apparently comes to rest just outside the illuminated region. An electron track which seems to be associated with the heavily ionizing track is also present. Stereoscopic observation shows that these two tracks, when projected, actually do pass through the same point or within a very small distance of one another. The heavily ionizing track is highly scattered in the gas, indicating it has a very low energy. The electron track in this case has an energy of 25 Mev, which value is subject to the same error as in the previous case. An attempt to determine the mass of the heavily ionizing particle by measurement of its range and curvature leads to a value of about 450 electron masses, but this value is subject to such a large error, because of scattering in the gas, that the track could almost equally well be ascribed to a proton or to a particle of mass 200 electron masses.

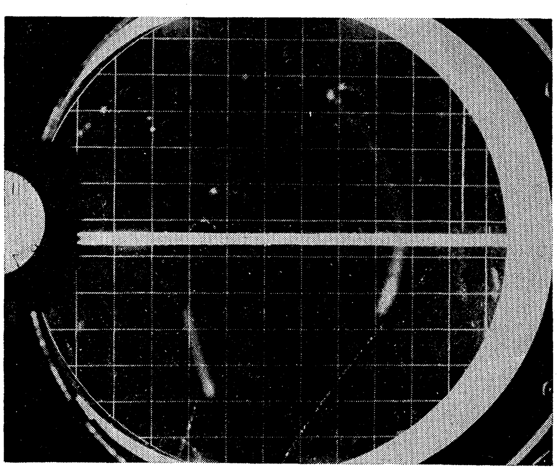

FIG. 3. Cloud-chamber picture of a meson decay process occurring in an aluminum plate.

It is quite possible in either of the photographs here discussed that an additional charged particle could have been produced and could have escaped detection by going into the non-illuminated portion of the chamber. In this case, however, we should expect the production of two additional charged particles in order that charge may be conserved in the disintegration. That two such particles should have escaped detection seems unlikely, and previous evidence all indicates that only one electron results from a mesotron decay.

ROSSI: Is there a possibility that the disintegration may have occurred in the glass of the chamber?

ANDERSON: The glass is very near the illuminated region. In the first case this hardly looks possible but it may well be a possibility in the second case.

ROSSI: Then the electron might have lost some energy in coming out of the glass.

ANDERSON: I think the loss of a small amount of energy is possible. The mesotron is obviously so near the end of its range, as indicated both by its heavy ionization and by the large amount of scattering in the gas, that it is very difficult to see how it could have penetrated enough glass to correspond to more than a very few Mev energy loss on the part of the electron.

To sum up I might say that it is extremely difficult to interpret our photographs except in terms of decay electrons whose energies lie in the range between 21 and 28 Mev.

Cloud-Chamber Measurements of the Energy of Decay Electrons

B. ROSSI: An experiment specifically designed for the purpose of obtaining pictures suitable for the measurement of the energy of the decay electrons is being carried out by R. W. Thompson. The apparatus is shown in Fig. 1. It includes a cloud chamber placed in a magnetic field of 1680 gauss and four trays of G-M counters ($C1$, $C2$, $DC1$, $DC2$). A $\frac{1}{4}$-inch thick aluminum plate is placed across a diameter of the chamber to act

TABLE I. Energies of decay electrons. The last five pictures were obtained under improved conditions and are therefore more reliable.

Film number	Sign of meson	Place of disintegration	Sagitta of track in mm	$E=Pc$ in Mev
77	+	plate	1.2	(20–50)
78	+	plate	3.3	42 ± 12
84	−	glass	1.0	(70(?))
87	+	glass	3.5	53 ± 15
89	+	gas	0.7	(20–50)
104	+	plate	3.5	43 ± 9
106	+	plate	2.5	40 ± 8
110	+	glass	1.5	(40 ± 12)
111	+	plate	4.0	48 ± 10
112	+	plate	4.0	42 ± 8

as a meson absorber. The chamber is expanded whenever a simultaneous discharge in trays $C1$ and $C2$ is followed, with a delay larger than 0.7 microsecond, and smaller than 4.7 microseconds, by a discharge in either tray $DC1$ or tray $DC2$. This triggering arrangement favors the recording of mesons which decay in the cloud chamber, even though most of the delayed coincidences are produced by mesons which stop in the walls of the chamber or in the coils and produce decay electrons which reach the delayed counters without traversing the illuminated volume of the chamber. With this arrangement ten pictures of meson decays were obtained, from which the energy of the decay electrons could be estimated. In one case the meson came to rest in the gas, in 6 cases in the aluminum plate, in 3 cases in the glass wall. For the last three pictures the interpretation of the observed event as a meson decay is somewhat less certain than for the other seven pictures because the end point of the meson track is not conveniently located for observation. However, the appearance of the tracks (e.g., density of ionization, presence of δ-rays) and the selection by the delayed coincidence arrangement lend considerable assurance against spurious events. Some of the pictures obtained are shown in Figs. 2, 3, and 4. Table I gives the observed energies of the decay electrons, corrected for the energy loss in the absorber (which amounts to less than 8 Mev/c in all cases). This table shows a preponderance of decay electrons with energies between 40 and 50 Mev. In fact, Thompson's results would be consistent with the assumption of a unique energy, in the neighborhood of 45 Mev, for *all* decay electrons. However, the measurements are not yet sufficiently accurate and extensive to prove such an assumption. It may be pointed out that in the experiment described the decay electron has to traverse a certain minimum amount of absorbing material before reaching the delayed counters $DC1$ or $DC2$. This sets a lower limit of about 15 Mev to the energy of decay electrons which can be detected.

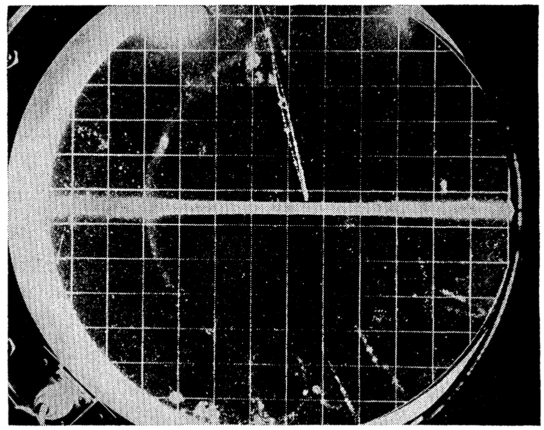

FIG. 4. Cloud-chamber picture of a meson decay process occurring in an aluminum plate.

Remarks on μ-Decay

J. R. OPPENHEIMER, *Institute for Advanced Study, Princeton, New Jersey:* There would be one element of sanity in the picture if the normal process of μ-meson decay led to both a neutral meson and a neutrino—if it were a ternary decay involving also an electron. That is this: if we compare, let us say, the neutron going to a proton plus an electron plus a neutrino (or hydrogen 3 or carbon 11 or any of the other radioactive materials) with μ^+, let us say, going to μ°, plus e^+, plus a neutrino, and try to think of these as parallel processes, the lifetime of the former is some 25 minutes, the lifetime of the latter is 2 microseconds. These are consistent with a reasonable dependence of lifetime on available energy, if the mass of μ° is about 90 electron masses. This is not an argument that this is right; this is an argument that, if it were right, one might have at least one cross connection within the field of beta-decay, very different from the one proposed by Yukawa, but perhaps true. That is why I would feel that it might not be too arbitrary to have a ternary decay of μ-mesons paralleling that of all nuclear matter.

Decay of Mesons in Aluminum

G. E. VALLEY, *Massachusetts Institute of Technology, Cambridge, Massachusetts:* Our most extensive measurements concern the decay of slow mesons in aluminum. A reason for this choice of element was that in our apparatus the walls of the delay counters must be considered as part of the specimen material in which mesons can decay. We found it possible to make Geiger-Müller tubes with aluminum walls and were thus able to study an intermediate element for which our data need not be corrected for those mesons which decay in the counter walls.

Our apparatus differs from that of other experimenters in that a cloud chamber equipped with a magnetic field in the usual manner is used instead of a ferro-magnetic lens. Above and below the cloud chamber is a triple coincidence telescope which defines a beam of penetrating particles passing through the cloud chamber. Beneath the cloud chamber and the lower counter tray of this telescope is an aluminum slab in which mesons can decay. Surrounding this slab on two sides and bottom are three banks of delay counters. The cloud chamber is triggered whenever these counters indicate a delayed coincidence longer than 0.5 and shorter than 15 microseconds. The actual delay time is recorded for each event by a ballistic galvanometer which is photographed on the cloud-chamber picture.

In addition, indicator lamps are photographed which show which of the three banks of delay counters has fired in order that we can see if there is evidence for the emission of more than one decay particle. The advantage of this method is that both positive and negative mesons are registered during its operation. The "background" of spurious negative particles is, in addition, rather low. We have not yet analyzed all the pictures which we have taken with this apparatus. Thus far, however, our results are: for the ratio of lifetimes (negative to positive), 0.35 ± 0.04; for the ratio of the total numbers of mesons which decay (negative to positive), 0.435 ± 0.05; for the mean lifetime of negative mesons, 0.7 ± 0.1 μsec; for the mean lifetime of positive mesons, 2.0 ± 0.15 μsec. We find no evidence that more than one decay particle is emitted by mesons of either sign.

The Capture and Disintegration of Sea-Level Mesons*

R. D. SARD, *Washington University, St. Louis, Missouri:* A. *The 2.2-Microsecond Meson Decay Process Does Not Involve Production of a High Energy Photon.* During the past winter, Hincks and Pontecorvo at Chalk River,[3] and Althaus and I at Washington University,[4] have independently carried out experiments designed to decide whether or not the μ-meson disintegrates into a photon and an electron. In both experiments delayed coincidences were sought between the arrival of a meson that stopped in a solid absorber and the subsequent emission of a 50-Mev photon, detected by its materialization in a lead sheet. As the time available for this talk is short, I shall only say that both experiments gave clean-cut negative results, indicating that the 2.2-microsecond decay process does not involve production of a photon more energetic than about 15 Mev.[5] This not only rules out the

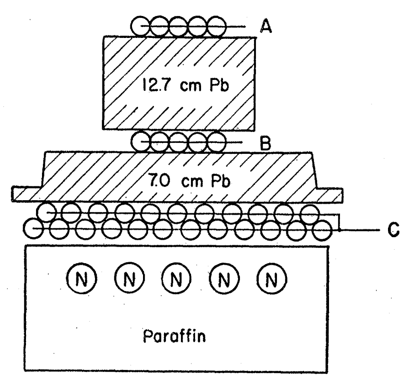

FIG. 5. Counter arrangement. Search for fast neutron associated with meson stopping.

* This work has been supported by the Office of Naval Research.

[3] E. P. Hincks and B. Pontecorvo, Phys. Rev. **73**, 257 (1948).

[4] R. D. Sard and E. J. Althaus, Phys. Rev. **73**, 1251 (1948). A complete account of this experiment is being submitted to The Physical Review.

[5] O. Piccioni (Bull. Am. Phys. Soc. **23**, 3, 42 (1948)) has recently reported the negative result of an experiment designed to detect high energy photons resulting from the nuclear capture of μ-mesons. He points out that his experiment should also have brought to light decay photons, so that his negative result presents an independent confirmation of this conclusion.

hypothesis of disintegration into a photon and an electron, but also shows that if the meson disintegrates into an electron and neutral meson, the latter then disintegrating into two photons, the mean life of the neutral meson against this process must be greater than about 10^{-10} sec.[6]

B. *Neutrons Are Produced in the Stopping of Sea-Level Mesons in Lead.* In another experiment,[7] Ittner, Conforto, Crouch, and I have recently detected neutrons correlated in time with the stopping of mesons in lead. These neutrons result most probably from the capture of negative μ-mesons by lead nuclei, though the measurements carried out thus far do not exclude the possibility that the neutrons result in some way from the disintegration of positive μ-mesons.

The arrangement used is shown in Fig. 5. Geiger tube trays A and B select a cone of charged particles capable of penetrating 12.7 cm Pb. Some of these stop in the 7-cm Pb absorber, resulting in failure of tray C to discharge except in the small (2 percent) fraction of the cases in which a decay electron reaches C. Tray C more than covers the cone defined by A and B. Underneath C is placed a group of slow neutron counters, N, surrounded by paraffin. These are proportional counters, whose cathodes are coated on the inside with boron enriched in B^{10}.[8] The circuit records coincidences (AB), anticoincidences $(AB-C)$, neutron counts (N), and delayed coincidences $(AB-C:N)$ between a Geiger tube anticoincidence and a neutron count occurring 4 to 84 microseconds later. The last is realized by having the $(AB-C)$ pulse initiate a gate 80 microseconds long; this gate pulse is placed in coincidence with the N pulse. As it takes several microseconds for a fast neutron to be slowed down to thermal speed and the mean life once thermal is estimated to be about 150 microseconds, the 4-microsecond delay causes no appreciable loss in neutron coincidence counts; it serves to protect against spurious N pulses due to charged particles or photons associated with (AB). The dimensions of the neutron moderating and detecting system were determined empirically to give maximum neutron counting rate for the fission neutrons from a tray of uranium oxide placed at the level of the middle of the Pb absorber.

Measurements of $(AB-C)$ with and without the Pb absorber gave a rate of 0.86 meson stopping per minute in the absorber. Measurements of $(AB-C:N)$ with and without Cd shields around the N counters gave a neutron coincidence rate of 0.34 ± 0.04/hour. This is 300 times the expected accidental rate of 1.1×10^{-3}/hr. given by the product of the $(AB-C)$ rate (1.89/min.), the N rate (7.43/min.), and the gate length (80 microseconds).

It is clear then that there is a real correlation between $(AB-C)$ and N. But 55 percent of the anticoincidences are due to the inefficiency (3.5 percent) of the anticoincidence arrangement, so the $(AB-C:N)$ coincidences could as well be due to penetrating particles as to stopped ones. In order to settle this point, we took data with no voltage on the counters C. The $(AB:N)$ rate so obtained should be almost thirty times greater than the $(AB-C:N)$ rate if the effect is due entirely to penetrating events, as the (AB) rate is 28.4/min. It should be equal to the $(AB-C:N)$ rate if the neutrons result only from meson stoppings in the Pb. The $(AB:N)$ cadmium difference turned out to be 0.70 ± 0.09/hour. We take this to mean that the $(AB-C:N)$ coincidences are due almost entirely to stopped mesons.

The excess of $(AB:N)$ over $(AB-C:N)$, 0.36 ±0.10/hour, could be due to neutron production in the lead or paraffin by penetrating ionizing events or to neutron production by mesons stopped in the paraffin (neutrons produced in the paraffin would be detected with considerably higher efficiency). Experiments on this question are under way.

We are preparing to determine whether the neutrons from stopped mesons result from capture or decay by replacing the lead absorber with graphite; later we shall try to clinch the point by using magnetically separated positive and negative mesons.

Dr. Tongiorgi has developed[9] a neutron coincidence technique very similar to ours. I understand that she has confirmed the production of neutrons by stopped mesons, using iron as

[6] This point has also been made by E. P. Hincks and B. Pontecorvo, Phys. Rev. **73**, 1122 (1948).

[7] Sard, Ittner, Conforto, and Crouch, Phys. Rev. **74**, 97 (1948).

[8] We are indebted to the Argonne National Laboratory for the loan of these counters.

[9] V. Tongiorgi, Phys. Rev. **73**, 923 (1948).

stopper. I hope that she can tell us here about her work.

Discussion

OPPENHEIMER: How many neutrons are there per stopped meson?

SARD: The ratio of the meson stopping rate to the $(AB-C:N)$ rate gives 152 mesons stopped per neutron coincidence detected. Assuming a 20 percent positive excess, we get one neutron coincidence per 68 negative mesons stopped. The solid angle subtended by the paraffin is about one-quarter of the sphere. If there is one neutron produced per negative meson captured, the efficiency of the neutron detecting arrangement is, therefore, 5.9 percent per incident neutron. A measurement of the efficiency for Po-Be neutrons will be made in the near future. It should make possible an estimate of the multiplicity of the neutron production.

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The Mass of the Mesotron

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WHEN the charge of an electron was experimentally determined, the mass could be deduced from the ratio of charge to mass. As in the case of the electron, the mass of the mesotron can only be observed by phenomena that give the ratio of the mass to the charge. The only method at present available to measure the charge depends on the ionization per cm of path. The rate of loss of energy per cm of path is given by the formula of Bohr for low velocities and by Bethe and Bloch[1] for relativistic velocities, as

$$dE/dx = (4\pi Ne^4z^2/mc^2\beta^2) \times(\ln(2mc^2\beta^2/I(1-\beta^2))-\beta^2). \quad (1)$$

The rate of loss of energy is a function of the material through which the particle passes and of the velocity $(\beta=v/c)$ of the ionizing particle, but it is not a function of the mass of the ionizing particle. The quantity, m, in the above formula is the mass of the electron that is ejected from the atom and not the mass of the ionizing particle. The rate of loss of energy per cm of path is directly proportional to the ionization per cm of path. This function has a minimum for the value of $1/(1-\beta^2)^{\frac{1}{2}}$ of about 3.5, that is, where the relativistic mass of the particle is 3.5 times the rest mass. The energy is then 2.5 times the equivalent energy of the rest mass, $(E_0=m_0c^2)$.

For electrons this corresponds to energies of about 1.5 Mev, and for protons about 3000 Mev. For mesotrons of mass 200 times the electron's mass, this corresponds to about 300 Mev. Protons of 3000 Mev are not conveniently available, and hence electrons have been used as the comparison particle.

Recent measurements by R. H. Frost[2] have given quite accurate values for the minimum in the electron ionization. Frost has observed the minimum specific ionization for electrons in hydrogen to be 6.48 ± 0.34, and for electrons in helium 8.13 ± 0.51 ion pairs per cm of track at N.T.P. In argon the minimum ionization was found to be 53.1 ± 2.8. The observations with mesotrons indicate that the minimum ionization for hydrogen is 6.78, for helium 8.20, and for argon 55. Since the ionization is proportional to the square of the charge carried by the ionizing particle, $(ze)^2$, the square root of the ratio of the minimum value for mesotrons to that for electrons gives the effective value of the charge carried by the ionizing mesotron. For these

[1] For a discussion of the validity of this equation and original references, see J. A. Wheeler and R. Ladenburg, Phys. Rev. 60, 754 (1941).

[2] R. H. Frost, Ph.D. thesis, University of California, Berkeley (1947).

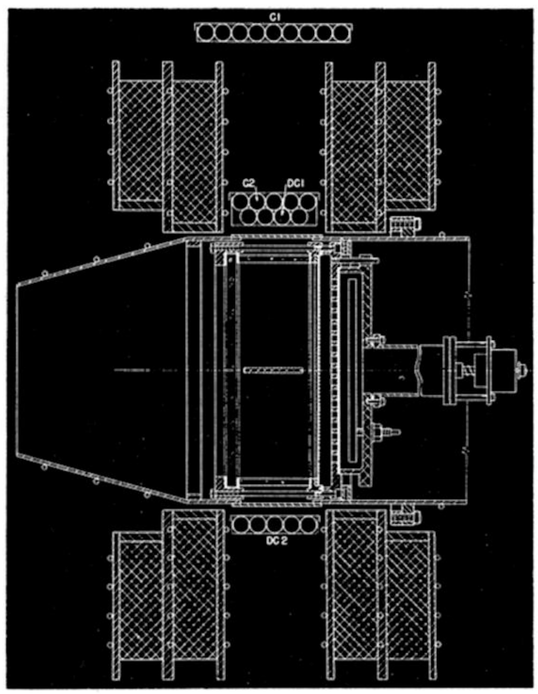


FIG. 1. Experimental arrangement used by Thompson for measuring the energy of decay electrons.

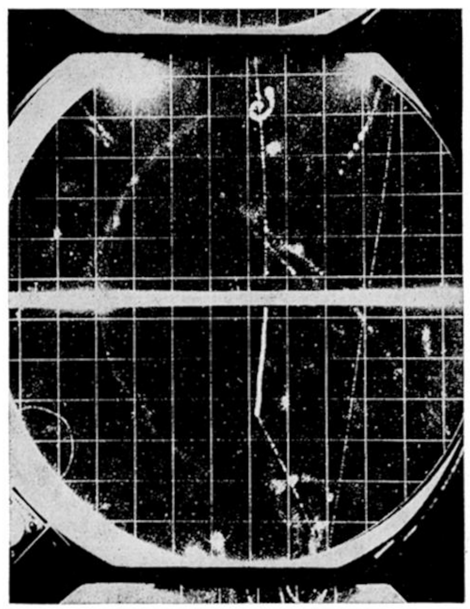


FIG. 2. Cloud-chamber picture of a meson decay process occurring in the gas.

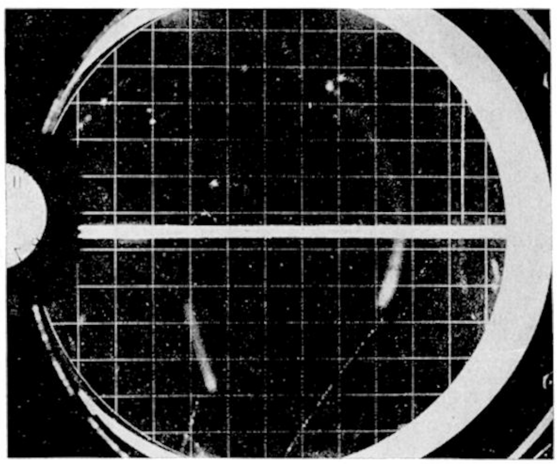
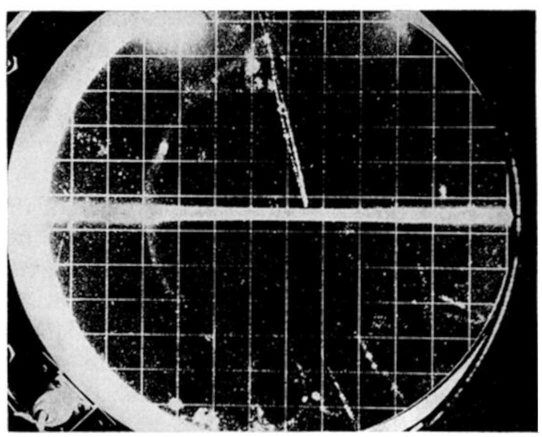


FIG. 3. Cloud-chamber picture of a meson decay process occurring in an aluminum plate.



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