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.

REVIEWS OF MODERN PHYSICS VOLUME 21, NUMBER 1 JANUARY, 1949

# 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 $6.48\pm0.34$, and for electrons in helium $8.13\pm0.51$ ion pairs per cm of track at N.T.P. In argon the minimum ionization was found to be $53.1\pm2.8$. 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).

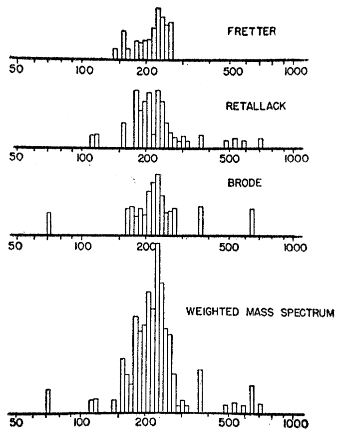



FIG. 1. Weighted mass spectrum.

cases above, the values are: hydrogen $1.02\pm0.03$, helium $1.005\pm0.02$, argon $1.017\pm0.03$.

Hazen[3] has measured the minimum ionization for electrons and mesotrons in air, and finds the value of the specific ionization to be $42\pm2$ for electrons and $45\pm3$ for mesotrons. This gives a value of $1.04\pm0.04$ for the probable value of the charge. All of these observations indicate that within the accuracy of experiments, that is, to about 2 percent, the charge on the mesotron is identical with that on the electron.

The ionization along the path of a high speed particle of known charge can be used to determine its velocity. Additional measurements relating mass and velocity are required to determine the mass of the ionizing particle. The curvature of the path of an ionizing particle as it passes through a magnetic field enables one to compute the momentum of the particle, since

$$\mu_0\beta c/(1-\beta^2)^{\frac{1}{2}} = B\rho, \qquad (2)$$

where $\mu_0$ is the rest mass of the mesotron, $B$ the magnetic induction, and $\rho$ the radius of curvature. By integrating Eq. (1), it is possible to obtain a relation between the range and the energy of a particle. Graphical relations between range and momentum and range and energy obtained in this way have been published by Wheeler and Ladenburg.[1] The relations between the observable quantities, that is, ionization, range, $B\rho$, and rate of change of $B\rho$, and the mass of the ionizing particle, has been discussed by Corson and Brode,[4] and a nomograph published that gives a convenient method of estimating the mass. A somewhat similar nomograph has been published by Hughes.[5] Although some of the earlier estimates of the mass of the mesotron were obtained by relations between ionization and momentum, this method has given very few measurements of the mesotron mass, as it is unusual to find a mesotron in a cloud chamber whose momentum is low enough to make possible a reasonably accurate mass determination.

To investigate the possible existence of mesotrons with different rest masses, it is desirable to use an experiment from which a large number of mass determinations could be obtained in a reasonable time. The observations of Fretter[6] on the momentum and range in lead of mesotrons indicated that this method is capable of sufficient accuracy to enable one to make a survey of the mesotron masses in a reasonable time. In the experiments of Fretter, the momentum of the particles was measured in a cloud chamber between the poles of an electromagnet giving a field induction of 5300 gauss. Below the cloud chamber in the magnetic field there was placed a second cloud chamber sixteen inches in diameter, which had 8 one-half-inch plates of lead placed horizontally with a little over one inch between each plate. Using the graphical relations

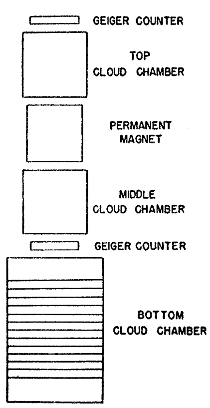



FIG. 2. Arrangement of apparatus for mesotron mass measurement.

[3] W. E. Hazen, Phys. Rev. **67**, 269 (1945).

[4] D. R. Corson and R. B. Brode, Phys. Rev. **53**, 773 (1938).

[5] D. J. Hughes, Phys. Rev. **69**, 371 (1946).

[6] W. B. Fretter, Phys. Rev. **70**, 625 (1946).

between range and momentum given by Wheeler and Ladenburg,[1] Fretter obtained the masses of 26 mesotrons. The probable error in mass assigned to each of these measurements was deduced from the probable error in momentum and the probable error in range. Treating this set of data statistically, Fretter obtained a mean value for the mass of the mesotron of 202±5 electron mass units. The errors in range are statistical in the sense that they represent a symmetrical distribution with plus and minus deviations equally probable about a mean value. The errors in curvature due to chamber turbulence and nuclear scattering represent errors that are also symmetrical in the same sense. The resulting errors in the deduced mass value are not symmetrically distributed about the mean. When properly averaged, the most probable value of Fretter's 26 observations is 212±5 electron mass units. Linear displacements normal to the parameter curves of constant mass correspond rather closely to the log of the mass. Taking the weighted mean of the log of the mass values gives essentially the same value as the more accurate statistical analysis.

To increase the accuracy with which the range can be observed, Retallack and Brode[7] have placed a cloud chamber below the electromagnet with fifteen plates each $\frac{1}{4}$ inch thick. The volume of this chamber was large enough, $20\times20\times10''$, so that even particles with appreciable deflections in the lead plates could still be followed to the end of their range. Special care was taken to keep the chamber at constant temperature to avoid initial turbulence in the chamber. Forty-one mass determinations have been made with this arrangement. The probable errors in range were assigned from the thickness of the absorbing plates and the angle of entrance into the plate. The probable errors in curvature were computed from a least squares analysis of the curvature of each track. To this curvature error was added the probable error in curvature observed from a series of measurements on tracks taken with no magnetic field. These latter measurements introduced the largest errors in the momentum measurement, and studies are now under way to reduce the errors due to cloud chamber turbulence. Tracks that should be straight in a zero magnetic field cloud chamber had a probable curvature of about 25-meters radius.

As noted in the analysis of Fretter's data, the average of the logarithm of the observed masses weighted inversely as the square of the percent probable error represents a more nearly correct handling of the data. Figure 1 gives a histogram of the 41 observations of Retallack and Brode.

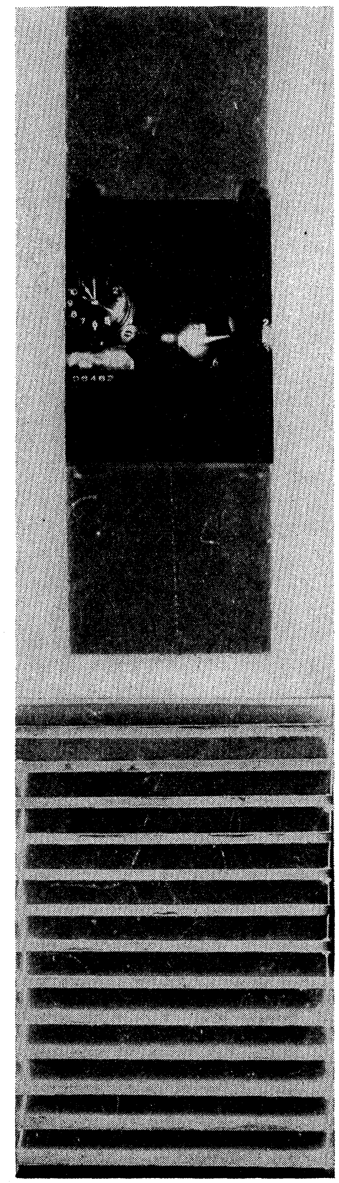


FIG. 3. Negative mesotron with a measured mass of 225±20.

[7] J. G. Retallack and R. B. Brode, to be published.

In addition to the pronounced group at about 200, there are 2 observations at about 100 and 4 observations between 500 and 800 that seem to be either anomalous from the probable error theory, or to indicate the existence of particles of mass different from that of the usual cosmic-ray mesotron. Omitting the two low and four high mass particles, the remaining 35 particles indicate a value for the mass of the mesotron of 215±4.

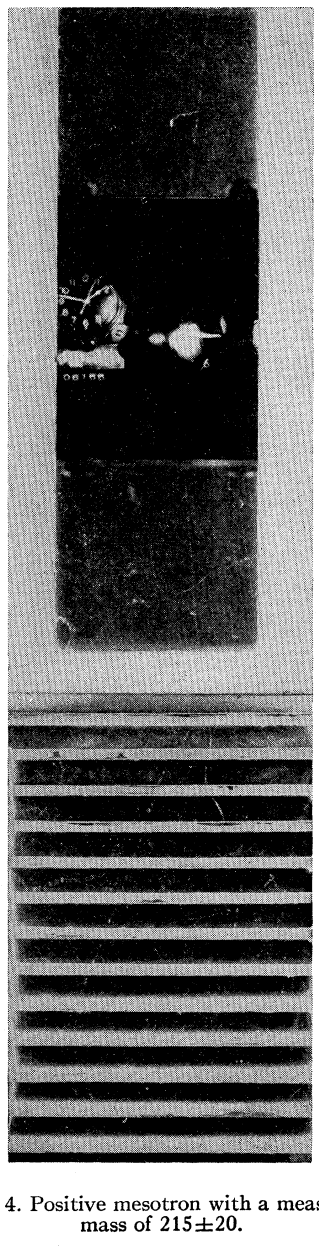


FIG. 4. Positive mesotron with a measured mass of 215±20.

One of the sources of error in the mass measurement has been the fluctuation of the magnetic field in the electromagnet used by Fretter, Retallack, and Brode. The heat from the 25 kilowatts expended in the magnet has also been a cause of turbulence which disturbed the curvature measurements. To avoid these troubles, new mass measuring equipment has been constructed in which the electromagnet has been replaced by a permanent magnet. The cost of electricity is such that the permanent magnet saved its cost in two months of operation. The apparatus has the further advantage of portability. The general arrangement of the apparatus* is shown in Fig. 2. Between the top and middle cloud chamber, the cosmic-ray particles pass through the gap of the permanent magnet, where the field is slightly over 5000 gauss. The momentum of the particles passing through this field is inversely proportional to the angle of deflection in the magnetic field. Errors in angle due to scattering in the walls of the chamber were reduced by making a window in the bottom of the top chamber and in the top of the middle chamber of berillium foil 10 mils thick. The space between the poles of the permanent magnet was filled with helium to further reduce the possible scattering. The range of the particles in lead is observed in the bottom cloud chamber where there are 13 lead plates each 0.6 cm in thickness. The top and middle chambers are photographed with one camera. Forward or backward scattering could be detectable by mirror images at each side of the central picture. The lower chamber is photographed by a stereoscopic camera, so that the motion of the particle can be studied with a stereoscopic viewer. Figures 3 and 4 show the tracks of mesotrons that are deflected between the top and middle chambers and stop in the lead plates of the lower chamber.

Figure 1 shows the results of a preliminary survey of some mass measurements made with this apparatus. Again, there is some evidence for the existence of particles of mass less than 100 and of mass between 500 and 800. The 18 mass determinations between 150 and 350 appear to be statistical fluctuations in the measurement of

* A more detailed description of this apparatus will be published elsewhere.

a unique mass. The mean value of this group gives $218\pm5$ times the mass of the electron.

The combination of the three groups of measurements is also shown in Fig. 1. The mean of the combined series of measurements leads to a value of $215\pm2$ for the mass of the mesotron. The probable error of $\pm2$ is entirely that due to the statistical errors in range and curvature of the particles. Systematic errors in the magnetic field calibration might cause even larger errors. The magnetic standards used in the field measurements were compared with the magnetic standards of the University of California Radiation Laboratory.** The magnetic field measurements by the radiation laboratory standards and by the Physics Department standards differed by less than 1 percent.

The 78 determinations used in deriving the mean value of 215 are a consistent set of observations on a particle with a unique mass as judged by the rules of external and internal consistency.[8]

If the decay of the $\pi$-mesotron into the $\mu$-mesotron[9] takes place with the ejection of a neutrino which shares the momentum and energy, one can calculate the mass of the $\pi$-mesotron. The kinetic energy of the $\mu$-mesotron has been observed to be about 4 Mev. Taking this value of the kinetic energy and the mass of the $\mu$-mesotron as $215\pm5$, the mass of the $\pi$-mesotron is computed as $283\pm7$.

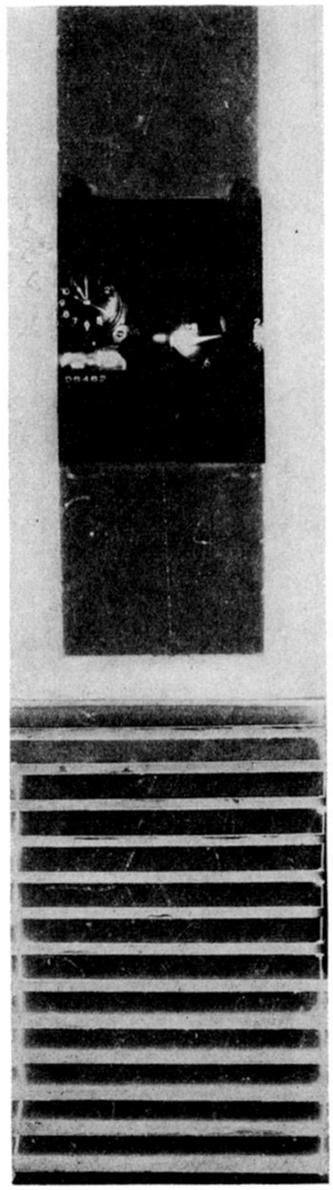
In the three groups of mass measurements discussed here, there are 78 determinations that appear to be statistical fluctuations of a unique mass. In addition to these observations, there are 8 particles whose apparent masses lie between 500 and 800. These particles do not appear to be light mesotrons that have been stopped by some nuclear process when they still had a few cm of residual range in lead. The increased ionization above more than one lead plate and the noticeably smaller scattering confirms the observation of greater mass for these particles. No evidence was found for the presence of $\pi$-mesotrons in the sea-level cosmic radiation. If a heavy mesotron of mass 283 were present in an intensity of even 10 percent, it is doubtful if its presence would noticeably distort the observed distribution of mass values found in this research.

This research has been supported in part by the Atomic Energy Commission and the Office of Naval Research.

** We are indebted to Professor W. M. Powell for his generous assistance in the comparison of magnetic standards.

[8] R. T. Birge, Phys. Rev. **40**, 207 (1932).

[9] C. M. G. Lattes, G. P. S. Occhialini, and C. F. Powell, Nature **160**, 453, 486 (1947).



Fɪɢ. 3. Negative mesotron with a measured mass of $225\pm20$.

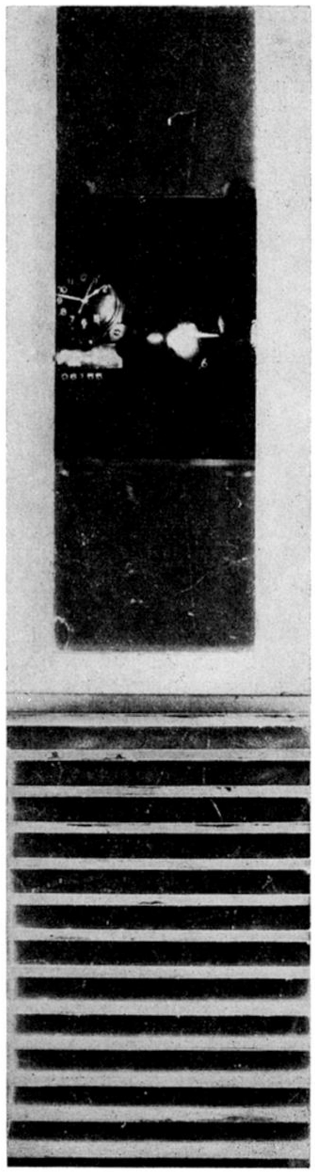


FIG. 4. Positive mesotron with a measured mass of 215±20.