The Intensity and Masses of Cosmic-Ray Particles*

T. C. MERKLE, JR., E. L. GOLDWASSER, AND ROBERT B. BRODE
Department of Physics, University of California, Berkeley, California

(Received June 12, 1950)

Measurements have been made of the relative numbers of mesons and protons in the sea level cosmic radiation. The measurements include those particles that have ranges in lead between 4.0 and 13.0 cm. The masses were determined by observing the range and momentum of each particle. No evidence was found for any particles except positive protons (mass $=1893\pm 50\ m_e$) and positive and negative μ-mesons (mass $=196\pm 3\ m_e$). The low value of the μ-meson mass reported here may be due in part to the uncertainty of the range-energy relations in copper. As many protons as μ-mesons were observed in the range interval from 4.0 to 13.0 cm of lead. The intensity of protons decreased with increasing range.

I. INTRODUCTION

THE penetrating component of the cosmic radiation is usually interpreted as that part of the radiation which would remain when the electrons and gamma-rays have been removed. Experimentally, the penetrating and non-penetrating radiations are often separated by the assumption that 10 to 15 cm of lead will remove the electrons and gamma-rays. The use of such an absorber removes those protons and mesons which have ranges in lead less than the thickness of the absorber.

From cloud-chamber observations of the curvature of a particle's track in a magnetic field and the subsequent range of the same particle in a chamber filled with absorbing plates, it is possible to identify the penetrating character of the particle and to determine its mass. The frequency of occurrence of mesons and protons has in this way been observed for the cosmic radiation at sea level for particles with ranges between 4 and 13 cm of lead. Because the effective time of operation of the apparatus was not accurately known, an absolute flux could not be determined. The total number of penetrating particles with ranges in excess of 13 cm was, however, observed for the same time interval so that the relative number of slow mesons and protons to the penetrating radiation is known.

Previous experiments[1,2] in this laboratory have determined the masses of particles capable of penetrating 25 to 45 cm of lead. With a lead absorber of 45 cm thickness above the mass measuring equipment, an increase in the rate of collection of data was obtained. The differential range spectrum of sea level cosmic-ray mesons is known to have a maximum at about 38 cm of lead.[3] The presence of the lead above the mass measuring equipment in previous experiments eliminates the slow mesons and protons as well as any other particles with ranges less than the absorber thickness. In the present experiment, the lead absorber above the equipment has been removed so that the character of the low energy sea level radiation could be observed.

The possibility of observing particles with masses different from the more abundant mesons and protons depends on the intensity of these particles and on the resolving power of the mass spectrograph. An improvement of the resolving power over that previously used is essential in settling the question of the existence of any appreciable intensity of mesons with masses between those of the π-meson and proton. The improvements made on the apparatus in these measurements have increased the resolving power by about a factor of two.

The masses of the particles were calculated from observation of the deflection of the particles' trajectory in a magnetic field of 4700 gauss and the observation of the range of the particles in lead and copper plates. The absolute value of the magnetic field was determined to about 0.5 percent by calibrations based on the proton magnetic resonance.

II. EXPERIMENTAL PROCEDURE

The magnetic field was uniform within a few percent over the 12-inch diameter of the cloud chamber and corrections were made for the deviation from the central field. The error due to magnification and to non-uniformity of the field in the direction normal to the illuminated plane of the cloud chamber contribute together about ± 1.6 percent probable error in the value of $B\rho$. Errors which might have been introduced into the curvature measurements by shrinkage or distortion of the photographic film were checked by means of straight lines etched on the inside surface of the front glass of the cloud chamber. Track distortions due to turbulence in the cloud chamber were observed by operating the equipment for several periods during each day of observation with the magnetic field off. The cloud chamber was thermally insulated from the magnet and its temperature was closely controlled by a water circulating system regulated to ± 0.05°C.

A total of 315 no-field tracks indicated a turbulent curvature of $+0.0118\ M^{-1}\pm 0.02\ M^{-1}$. Corrections to curvature measurements were made for the systematic portion of this distortion. The improvement in the no-field tracks in this series of observations was due to the careful temperature control and to the re-design of the cloud chamber. The expansion valves were equipped

* Assisted by the joint program of the ONR and the AEC.
[1] W. B. Fretter, Phys. Rev. **70**, 695 (1946).
[2] J. G. Retallack and R. B. Brode, Phys. Rev. **75**, 1716 (1949).
[3] L. S. Germain (to be published).

with pads calculated to restrict the flow velocity of the gas behind the rubber diaphragm, and thus prevent shock wave disturbance in the chamber. Each valve had an aperture of seven square inches so that although the velocity was slow, the expansion time was not long.

The ranges were observed in a second cloud chamber placed below the curvature cloud chamber. Eleven copper plates and three lead plates were used. These plates were graduated in thickness in such a way that the probable error in range was about 3.5 percent for any particle stopping in the chamber. Pictures were taken with a stereo-camera so that estimates of the track location and direction of travel could be made.

The chambers were expanded by signal from a three-tube Geiger counter telescope arranged with one tube above the curvature chamber and two tubes between the curvature and range chambers. The Geiger counter tubes were one inch in diameter and eight inches long.

The curvature and range measurements were reduced to masses by means of a chart relating these quantities, prepared by Wheeler and Ladenburg.[4] Conversion of the copper range to the equivalent lead range was calculated from range-energy relations tabulated by Aron, Williams, and Hoffman.[5]

III. RESULTS

During 1169 hours of operation, 8545 events were photographed. Each event was recorded in a set of three photographs, one of the upper chamber and two of the lower. A total of 1155 events were photographed with the magnetic field off. Single penetrating particles with ranges in excess of 13 cm of lead accounted for 5993 events. Soft particles and showers appeared in 681 pictures. There were 101 particles observed whose ranges were greater than 4 cm and less than 13 cm of lead. The masses of of these particles have been calculated and a histogram showing the distribution of masses in equal curvature intervals is shown in Fig. 1. This histogram indicates two well-defined groups of masses. In order to make an estimate of the average mass of each group, it is necessary to assign proper weights to each measurement. The masses as calculated are not the quantities which are subject to symmetrical random variation. Using range and curvature in unit magnetic field as variables, a family of curves can be drawn relating mass, range and curvature. The best mass value will be determined by that curve of constant mass that best fits the observed values of range and curvature.[6]

If an analytical expression is known for the relation between mass, range, and curvature, the graphical solution is not necessary. The values of the individual mass measurements, m_i, from each pair of range, R_i, and curvature, c_i, observations are calculated by the Wheeler-Ladenburg chart. The weight to be attached to each of these mass values can be derived from an approximate analytical function relating range, mass, and curvature. For mesons stopping in the apparatus, the relation $m=\text{const}/c^2R$ gives a good fit to the relation between the mass, curvature, and range. For protons, a suitable function is $M=\text{const}/c^3R$. A constant can be chosen for each of these equations so that the analytic expression for the mass does not differ from the value given by the Wheeler-Ladenburg charts by more than 2 percent of the mass values for particles with ranges between 4 and 13 cm of lead.

Errors in range are limited in the sense that deviations greater than one-half a plate thickness are not probable. Since the mass values vary inversely as the range, the probable error of 3.5 percent in range will introduce an error in mass of the same magnitude. The probable errors in the measurement of curvature and magnetic field are of the order of 9 percent. Because the error in range is limited in magnitude and is small in comparison to the errors in curvature, the range error has been neglected in assigning weights to the mass observations.

Since the curvature decreases as range increases, the fractional error in mass due to a constant uncertainty in curvature increases with increasing range. Minimizing the squares of the residuals in curvature in unit magnetic field, one obtains as the resulting mean mass value ($\bar{m}$) from a series of individual mass and range measurements:

$$(\bar{m})^{-\frac{1}{2}}=\frac{\Sigma_i m_i^{-\frac{1}{2}} R_i^{-1}}{\Sigma R_i^{-1}}.$$

For the proton group, the expression becomes:

$$(\bar{M})^{-\frac{1}{3}}=(\Sigma_i M_i^{-\frac{1}{3}} R_i^{-\frac{2}{3}})/\Sigma_i R_i^{-\frac{2}{3}}.$$

The 23 positive mesons and 25 negative mesons give a value $\bar{m}=196\pm3\ m_e$. The 52 protons give a value of $\bar{M}=1893\pm50\ m_e$.

During the first-half of the experiment some data were obtained which seemed to indicate the existence of particles of a mass of about 1000 m_e.

These observations now appear to be only large deviations of curvature for particles whose true mass is that of the proton. The resolving power of the apparatus is not adequate to separate a small number of 1000 m_e

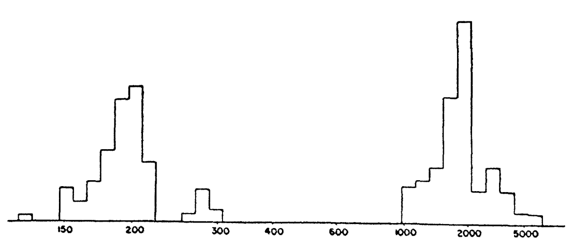

FIG. 1. Weighted mass spectrum of cosmic-ray particles at sea level with ranges between 4 and 13 cm of lead.

[4] Wheeler and Ladenburg, Phys. Rev. **60**, 754 (1941).

[5] Aron, Williams, and Hoffman, U. C. Radiation Laboratory (private communication).

[6] R. B. Brode, Phys. Rev. **75**, 904 (1949)

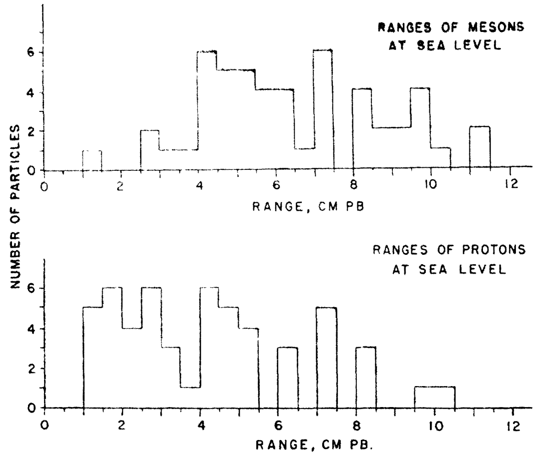

FIG. 2. Range spectrum of cosmic-ray protons and mesons at sea level. The ranges shown are the lead equivalent of the path below the curvature chamber. Material equivalent to 2 cm of lead is located above the curvature chamber.

particles from protons. None of the proton group of particles has a negative charge and none shows evidence of decay particles at the end of its range. No masses were found in the region between 300 and 1000 m_e.

The mesons which stop between 4 and 13 cm of lead constitute about one percent of the hard component. An equal number of protons stop in this same absorber. The observed range spectra of mesons and protons are shown in Fig. 2. The decrease in meson intensity above 7 cm range appears to be due in part to loss of particles from the illuminated region by scattering and insufficient illumination in the lowest section of the chamber. The number of protons with low ranges is definitely greater than the number of mesons in this same region. Since about 15 cm of wood were located above the apparatus, it is possible that at least a part of these protons may have originated in the wood. The total ranges of the particles have been calculated on the assumption that all of the particles have passed through about 15 cm of wood, the Geiger counter, and the chamber walls. Unfortunately, the wood thickness was not uniform throughout the solid angle above the chamber. Unlike the experiment of Germain,[3] no anticoincidence counters were located below the equipment so that stopping protons accompanied by fast particles were not automatically rejected. The experiment is being continued with various thicknesses of absorber above the curvature chamber to study more fully the range spectrum of protons.

The mass of the μ-meson obtained in this experiment is somewhat lower than currently reported values.[1,1] The mass calculated by the Wheeler and Ladenburg chart involves a comparison of the ranges of mesons and protons with corresponding velocities. Protons with suitable velocities would have energies of one Bev and are not readily available. The range-energy relationship has therefore been extrapolated from data at much lower energies. A small deviation in the extrapolated form of the range-energy curve could appreciably change the value of the result given here. In the mass measurements of artificially produced μ-mesons at the University of California Radiation Laboratory, protons are available with velocities comparable with the ranges of the low energy mesons and the calibration in those experiments will be much more certain.