event is apparently increased by the lead in s_1, since anticoincidences accompanied by side showers are more frequent with than without lead. This can be explained by the multiplication of shower particles in the lead.

Most of the "singles" observed without lead are probably due to a small lack of efficiency of the counter battery A. The "singles" obtained with lead in s_1 are more frequent than without lead, so that only part of them may be accounted for by lack of efficiency. The rest of the "singles" under lead and the "showers from the lead" are apparently due to secondary effects produced in the lead either by penetrating non-ionizing rays traversing the absorber Σ without encounter, or by photons missing the absorber Σ, or by electrons missing both the absorber Σ and the counter battery A. There is little doubt that the "singles" accompanied by side showers (see Fig. 7) are the result of secondary effects of electrons or photons. This is likely to be the case also for the remainder of the pictures, so that we do not find in our photographs any conclusive evidence for the existence of penetrating non-ionizing particles in the cosmic radiation. Furthermore these photographs show that most of the anticoincidences are due to spurious effects, especially to showers coming from the side.

The present experiments were initiated in the spring of 1939 in the Physical Laboratory of the University of Manchester, England, and were completed after the departure of the first-named author (B. R.) during the summer of the same year. The publication has been delayed by the recent European events. The writers express their appreciation to Professor P. M. S. Blackett for the facilities made available and for helpful discussions of the problem. One of us (B. R.) acknowledges with thanks the financial support granted to him by the Society for the Protection of Science and Learning.

NOVEMBER 1, 1940 PHYSICAL REVIEW VOLUME 58

The Mean Lifetime of the Mesotron from Electroscope Data

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(Received August 16, 1940)

In order to eliminate some experimental difficulties found in detecting the mesotron decay with Geiger counter apparatus, an experiment which consisted of the measurement of cosmic-ray intensity at various depths in two lakes of widely different altitude but of the same geomagnetic latitude was performed. One of our self-recording electroscopes which has been used in other cosmic-ray work was used. In the higher lake, about 12,000 ft. above the lower, readings were taken at depths of 4.9, 5.9 and 6.9 meters and in the lower lake at 1.3, 2.3 and 3.3 meters, the difference in depth being about equal in mass to the air between the lakes. On the basis of the most recent theory, air and water were assumed to be gram for gram equivalent absorbers for the mesotrons involved. The ratio of intensities at equivalent points in the two lakes was theoretically calculated and by matching this with the observed ratios a mean rest lifetime, τ_0, of 2.8×10^{-6} sec. was found for a rest mass of 160 times that of the electron.

I. Introduction

At the Cosmic-Ray Symposium during the summer of 1939, B. Rossi[1] summarized the then existing evidence for the postulated decay of the mesotron. He pointed out that the temperature effect and the greater absorption of air compared with more dense materials resulted in a mean rest life of the order of 3.0×10^{-6} sec. Other experimental facts gave no evidence for mesotron disintegration although they were not contrary to such a theory. At that time no experiments showed that the mesotron was beta-radioactive. It was concluded that the disintegration evidence was incomplete.

Since the Symposium a number of experiments have been designed specifically to detect the

[1] B. Rossi, Rev. Mod. Phys. 11, 296 (1939).

mesotron decay and to measure its mean rest life. As the first direct evidence that the mesotron was beta-radioactive, Williams and Roberts[2] published a cloud-chamber photograph of a positive mesotron at the end of its range emitting a positron with energy approximately half the rest energy of the mesotron. The mesotron lifetime obtained from the temperature effect is in the same range as the value from other experiments although the effect is not as clear. Blackett[3] first explained the negative temperature effect by assuming the formation level of the mesotrons is extended upwards for a warmer atmosphere so that there was a greater time for decay before reaching sea level. This view has been furthered by other observers although recently Hess[4] in analyzing five years of electroscope data concluded that the normal negative temperature effect was not completely explainable on the mesotron disintegration hypothesis.

The anomalous absorption of cosmic rays reported by Ehmert[5] and others, which was explained by Euler and Heisenberg[6] by the mesotron decay hypothesis, has been considerably investigated. Most results of this method lead to a mean lifetime of 2.6×10^{-6} sec. or higher. Rossi, Hilberry and Hoag[7] reported a lower value of 2.0×10^{-6} sec. for a mesotron rest mass of 160 times the electron rest mass. Fermi, in a pre-publication letter,[8] thought that the anomalous absorption could be explained by a correction in the absorption theory rather than by mesotron decay. When the effect of the field of the ionizing particle on surrounding electrons was taken into account the energy loss in dense materials was lessened. The order of magnitude of that correction was the same as that used to indicate mesotron decay. However, when the complete analysis[9] was published, Fermi indicated that only half or less of the anomalous absorption could be accounted for by this polarization effect.

All previous experiments to obtain the mesotron lifetime employed the Geiger counter cosmic-ray telescope as recording mechanism to compare the absorption of mesotrons in more dense materials such as lead, carbon, earth, to the absorption in air. In order to eliminate some of the corrections and inherent difficulties in Geiger counter measurements such as the correction for showers produced in the more dense absorber and the increased shower production in the air at higher altitudes, Professor J. R. Oppenheimer suggested the present experiment. The object was to compare the mesotron absorption in air and water by highly accurate electroscope data. For all points of measurement, the electroscope was surrounded by the same medium, water. Care was taken at all times to preserve the symmetry of the surroundings of the instrument.

Examining past experiments which compared the cosmic-ray absorption of air and water, those of Millikan and Cameron[10,11] stand out. In the first of these experiments, in 1926, these experimenters compared absorption curves in Arrowhead and Muir lakes with an altitude difference of about 2040 meters. The slight discrepancies from the mass absorption law for air and water were within the experimental error. In 1928, using more accurate pressure electroscopes, Millikan and Cameron performed a similar experiment in Arrowhead and Gem lakes, with an altitude difference of only 1200 meters. In this latter experiment the mass absorption law was found to hold.

II. Experimental Work

The experiment herein reported consisted in measurement of cosmic-ray intensities at various depths in two lakes of widely differing altitude. The intensities were measured by an accurate recording electroscope of the type used and described by Millikan and Neher.[12] Lake Tulainyo at 3921 meters above sea level was the higher lake and Kerchkoff Reservoir at 305 meters was the lower lake. These were chosen

[2] E. J. Williams and G. E. Roberts, Nature **145**, 102 (1940).
[3] P. M. S. Blackett, Phys. Rev. **54**, 973 (1938).
[4] V. F. Hess, Phys. Rev. **57**, 781 (1940).
[5] A. Ehmert, Zeits. f. Physik **106**, 751 (1937).
[6] H. Euler and W. Heisenberg, Ergeb. d. exakt. Naturwiss. (1938).
[7] B. Rossi, N. Hilberry and J. B. Hoag, Phys. Rev. **57**, 461 (1940).
[8] E. Fermi, Phys. Rev. **56**, 1242 (1939).
[9] E. Fermi, Phys. Rev. **57**, 485 (1940).
[10] R. A. Millikan and G. H. Cameron, Phys. Rev. **28**, 851 (1926).
[11] R. A. Millikan and G. H. Cameron, Phys. Rev. **31**, 921 (1928).
[12] R. A. Millikan and H. V. Neher, Phys. Rev. **50**, 15 (1936).

for their low horizon which was about 82° from the vertical in both cases. Since the intensity falls off approximately as $\cos^2\theta$, it is clear that not more than a small fraction of a percent of the total intensity was lost in either lake. Both lakes were at approximately 43° north geomagnetic latitude, well above the equatorial dip, and within 70 miles of each other longitudinally so that no difference of intensity due to the earth's magnetism entered. The instrument was placed well away from shore and from the bottom of the lakes. In Kerchkoff, measurements were made at depths 1.31, 2.31, and 3.31 meters below the surface; in Tulainyo at 4.88, 5.88, and 6.88 meters. The readings were taken first in Kerchkoff and then in Tulainyo after which the Kerchkoff readings were repeated. Table I gives a summary of the results. N, the number of ions per cubic centimeter per second, has been corrected for barometric pressure variation and for residual radioactivity of the instrument. The instrument had a negligible temperature coefficient for the range of temperatures encountered. Each N is an average of about 14 discharges of the electroscope which corresponds to 24 hours of measurement. The probable error of each reading was computed from the deviation from the mean of these 14 discharges. The 3.57 meters of water difference in depth of reading in the lakes corresponds approximately in stopping power to the 3.62×10^5-cm column of air at an average density 0.00094 g/cm^3. In Fig. 1, the logarithm of N is plotted against the total absorber, both air and water, in meters of water equivalent. Air and water are taken as gram for gram equivalent in stopping power.

TABLE I. *Corrected readings for both lakes.*

Date	Lake Altitude in meters	Depth in Lake in meters	Total Absorber in M H_2O	Ions/cc/sec. N
Sept. 1	Kerchkoff	1.31	11.29	2.209 ± 0.014
2	305	2.31	12.29	1.938 ± 0.007
3		3.31	13.29	1.736 ± 0.009
9	Tulainyo	4.88	11.38	2.501 ± 0.007
10	3921	5.88	12.38	2.217 ± 0.007
11		6.88	13.38	1.982 ± 0.002
17	Kerchkoff	1.32	11.30	2.242 ± 0.007
18	305	2.32	12.30	1.936 ± 0.007
19		3.32	13.30	1.747 ± 0.007

III. Relative Mesotron Stopping Power of Air and Water

Previous to the recent modification of the absorption theory by Fermi,[9] the energy loss per unit path in an absorber of n electrons per cubic centimeter by a high energy mesotron of energy E and velocity $v=\beta c$ was given by the Bethe-Bloch formula,[13,14]

$$-\frac{dE}{dy}=\frac{2\pi ne^4}{m_ec^2\beta^2}\,\mathrm{Log}\,\frac{m_ec^2\beta^2W}{(13.5Z)^2(1-\beta^2)},\qquad(1)$$

where m_e is the rest mass of the electron and e is the electronic charge. W is the maximum energy which may be imparted to an electron in a direct collision with a mesotron of mass m.

$$W=\frac{E+2mc^2}{1+m_ec^2(1+m/m_e)^2/2E}.$$

Fermi subtracts from (1)

$$\frac{2\pi ne^4}{m_ec^2\beta^2}\,\mathrm{Log}\,\epsilon\quad\text{for}\quad\beta<\frac{1}{\sqrt{\epsilon}}\qquad(2)$$

or

$$\frac{2\pi ne^4}{m_ec^2\beta^2}\left[\mathrm{Log}\,\frac{\epsilon-1}{1-\beta^2}+\frac{1-\epsilon\beta^2}{\epsilon-1}\right]\quad\text{for}\quad\beta>\frac{1}{\sqrt{\epsilon}},\qquad(3)$$

where ϵ is the effective dielectric constant for the polarization effect.

From the Bethe-Bloch formula, the ratio of the energy loss in one gram of air per square centimeter to the loss in a similar amount of water is about 0.9. When, however, the Fermi correction is applied to the case of water the ratio of energy losses is just 1.0 if an average mesotron energy of a few Bev and the value given by Fermi for ϵ are used. From these considerations it is concluded that points in the two lakes under equal masses of absorbing materials may be compared in intensity, the difference of intensity being just due to the mesotrons which have decayed in the 3.62×10^5-cm air column.

IV. Theory of Mean Lifetime Determination and Application to Experimental Results

Consider high energy mesotrons of velocity, $v=\beta c$, where $\beta\approx1$. In the coordinate system

[13] H. Bethe, *Handbuch der Physik*, Vol. 24, p. 1.
[14] F. Bloch, Zeits. f. Physik **81**, 363 (1933).

stationary with respect to the earth, the energy is given by $E=kmc^2$ where $k=1/(1-\beta^2)^{\frac{1}{2}}$ and the mean lifetime is $\tau=k\tau_0$ where τ_0 is the mean rest lifetime of the mesotron. Let P be the probability that a particle will survive for a time t so that the probability for disintegration in the time interval t to $t+dt$ is

$$-dP=Pdt/\tau. \quad (4)$$

For a mesotron incident at any angle θ from the vertical and having an energy, $E=kmc^2$, at $y=0$, where y is the vertical distance measured downward, with a uniform loss of energy, imc^2, per unit path, (4) may be written

$$-dP=\frac{Pdt}{\tau_0(k-iy\sec\theta)}=\frac{Pdy}{\beta c\tau_0(k/\sec\theta-iy)}. \quad (5)$$

Integrating (5) from $y=0$ to $y=y_0$, the probability, $P(E,\theta)$, that the mesotron will reach a vertical distance y_0 below $y=0$ is

$$P(E,\theta)=\left[\frac{E-imc^2y_0\sec\theta}{E}\right]^{1/i\beta c\tau_0} \quad (6)$$

It is important to note that $P(E,\theta)=P(E',0)$ where $E'=E/\sec\theta$ or in words the probability that a particle of energy, E, traveling at an angle θ will reach a vertical distance, y_0, downward is the same as the probability that a particle of energy, $E/\sec\theta$, traveling vertically will reach y_0.

Assume that the energy distribution, $f(E)$, is of the form, B/E^γ for mesotrons above some minimum energy. This is a valid assumption for Blackett's[15] energy distribution curve at sea level is of that form with γ between 2 and 3. The total intensity incident at an angle θ at y_0 is

$$J_{y0}(\theta)=\int_{E_0}^{\infty}P(E,\theta)\frac{B}{E^\gamma}dE, \quad (7)$$

where E_0 is the energy just sufficient to penetrate the air column and the layer of water above the instrument in the lower lake. By inserting a new variable $E'=E/\sec\theta$ in (7) it is seen that

$$J_{y0}(\theta)=(\cos\theta)^{\gamma-1}J_{y0}(0). \quad (8)$$

This last result shows that the total intensity, N_{y_0}, which is the integral of (8) over the hemispherical solid angle, is just proportional to the vertical intensity, the constant of proportionality being the same for all y_0. With that in mind, the ratio of intensities at points in the two lakes under equal total absorber may be written

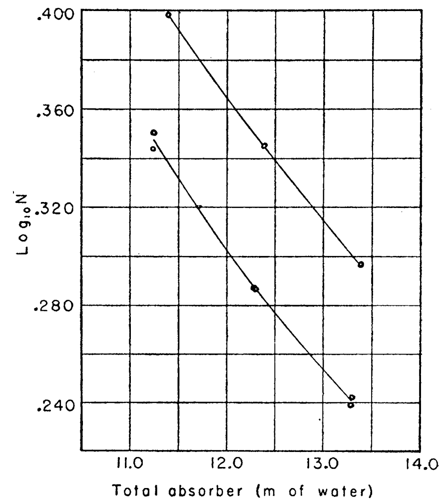

FIG. 1. The logarithm of N, the number of ions per cubic centimeter per second, is plotted against the total absorbing matter from the top of the atmosphere to the electroscope expressed in meters of water equivalent. The upper curve represents the absorption in the upper lake (elevation 3921 meters); the lower curve is the curve for the lower lake (elevation 305 meters).

$$N_u/N_L=\int_{E_0}^{\infty}f(E)dE\Big/\int_{E_0}^{\infty}P(E,0)f(E)dE. \quad (9)$$

Since the energy distribution, $f(E)$, for the upper lake is not known, it is necessary to write an expression similar to (9) for the lower lake where Blackett's sea level energy curves hold to very good approximation, the lower lake being only 305 meters above sea level. It is to be remembered that the energy E in $P(E,\theta)$ in expression (6) is the energy at the upper lake. In terms of E', the energy at the lower lake, letting $f'(E')$ represent the lower lake energy distribution,

$$\frac{N_u}{N_L}=\int_{E_0'}^{\infty}\frac{f'(E')dE'}{P(E'+iy_0mc^2,0)}\Big/\int_{E_0'}^{\infty}f'(E')dE'. \quad (10)$$

E_0' is the energy necessary to penetrate to the instrument through the water in the lower lake. Expression (10) is integrated graphically for various values of m/τ_0 using Blackett's energy

[15] P. M. S. Blackett, Proc. Roy. Soc. **159**, 1 (1937).

distribution at sea level for $f'(E')$ and expression (6) for $P(E'+iy_0mc^2, 0)$. For the point at 3.3 meters under the surface of the lower lake E_0' has a value 0.75×10^9 ev. A value of 78 ion pairs per cm with 32 ev per ion pair in atmospheric air was used for the energy loss per unit path. The value of the ratio of mesotron intensities N_u/N_L from (10) is plotted against m/τ_0 and then the experimental value of N_u/N_L is used to find the experimental value of m/τ_0 from the plot. From Fig. 1 the experimental N_u/N_L is 1.15 which gives a value for m/τ_0 of 58 in m_e/microsecond units where m_e is the electron mass. Thus for a mass 160 times the electronic mass, the value of the mean rest lifetime is $\tau_0=2.8\times10^{-6}$ sec.

V. Discussion of Results and Sources of Errors

Experimentally the intensity, N, is made up of mesotrons, knock-on electrons, soft primary component and decay electrons. In the above determination of m/τ_0, it was assumed that the intensity measured by the electroscope was made up of mesotrons or a component proportional to the mesotron. Of the three soft components, the knock-on electrons are proportional to the mesotrons so they introduce no error. The soft primary component which is only 4 percent or 5 percent of the total intensity at sea level is negligible at the point in question 3 meters below sea level. In an accompanying paper, Mr. Nelson finds, using cascade theory, that at the lowest depth in the lower lake, the decay electrons are of negligible intensity. From these considerations it may be concluded that $N_u/N_L=1.15$ is the correct ratio of mesotron intensities.

It should be pointed out that, for the points at 1.3 and 2.3 meters below the surface of the lower lake and their corresponding points in the upper lake, the experimental ratios N_u/N_L are about the same as for the point at 3.3 meters. From expression (10), since E_0' is lower with a greater probability of decay, it might be expected that the ratio would be greater. However, the decay electron intensity is greater for the shallower depths in the lower lake so that the two effects approximately cancel. Nelson's quantitative results taking into account the decay electrons are in excellent agreement with the experimental intensities found. This is good evidence that the mesotron decay, detected in this and other experiments, is a beta-decay with the decay electron producing cascades.

The data herein presented were taken with well-tested dependable apparatus and the method used eliminated many errors inherent in other experiments. The chief error in the ratio m/τ_0 found here is not due to the experimental data but rather to the inaccuracies in the energy distribution and other approximations used in the derivation of expression (10). Naturally the value of τ_0 depends on an accurate mesotron mass determination, and until such is made the ratio m/τ_0 is the only constant determined by this experiment.

In conclusion appreciation for the funds used for this work is extended to the Carnegie Corporation of New York. Mr. T. Smith, Mr. H. Bradner and Mr. R. Hog generously assisted on location. Especially we thank both Professor Oppenheimer for pointing out several finer points in the results and Mr. Nelson for his accompanying article.