The Instability of the Meson*

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Values of the proper lifetime of the meson have been deduced from a comparison of the intensity of mesons in an inclined direction under air with that in the vertical under a superposed lead shield equivalent in absorbing power to the difference between the masses of air traversed by the mesons before reaching the apparatus in the two directions. The required mass of lead was calculated from the Bethe and Bloch formula. The reliability of this use of the formula has been verified by an experimental determination of the relative stopping powers of water and lead. We calculate from our experimental data that the average proper lifetime of all mesons having energies exceeding 6.1×10^8 ev upon reaching the apparatus is equal to 3.9 ± 0.3 microseconds, and the average proper lifetime of all mesons with energies exceeding 11.9×10^8 ev upon reaching the apparatus is equal to 3.8 ± 0.4 microseconds. From the same data, the proper lifetime of only those mesons having about 9×10^8 ev energy upon reaching the apparatus is equal to 2.6 ± 0.8 microseconds. With the theory of Euler and Heisenberg, the proper lifetime has also been calculated from measurements of the number of disintegration electrons and their secondaries in equilibrium with the mesons in air. The value obtained by this method is roughly equal to 6 microseconds.

I. INTRODUCTION

THE observations of Ehmert,[1] and of Auger, Ehrenfest, Fréon and Fournier[2] originally indicated that the intensity of the cosmic radiation depends not only upon the quantity of matter traversed by the rays, but also upon the density of the absorbing medium. As an explanation of this effect, Kulenkampf, and Euler and Heisenberg[3] have pointed out that the instability of the meson,[4] predicted theoretically by Yukawa,[5] would result in a lower intensity as the time required for the secondary mesons[6] produced in the upper atmosphere to reach the detecting apparatus is increased. Interpreting Ehmert's results in this manner, Euler and Heisenberg calculated that the proper lifetime, τ_0, of the meson, i.e. the mean life of the meson in its rest system, is of the order of several microseconds. As a further test of the instability hypothesis, Euler[7] assumed that the soft component at sea level consists almost exclusively of electrons arising from the disintegration of mesons, and from the ratio of the intensities of the soft and hard component, he deduced a value of τ_0 of the same order of magnitude. Montgomery and Montgomery determined the proper lifetime from the frequency of occurrence of large bursts produced by the disintegration electrons. Ehrenfest and Fréon[8] compared the intensity of cosmic rays in an inclined direction at a high elevation with that in the vertical at a lower elevation, and calculated τ_0 from this data. Blackett[9] invoked the instability of the meson to account for the temperature coefficient of the cosmic-ray intensity as a change in height of the layer at which mesons are produced. The difference between the coefficient of the barometer effect and the absorption coefficient was given an analogous interpretation by Rathgeber,[10] and by Kolhörster and Matthes.[11] Barnóthy and Forró[12] applied the instability hypothesis in discussing the barometric and temperature effects on the intensity of the soft component. Rossi[13] calculated τ_0 from the differ-

* A preliminary report of the results of these investigations was presented at the University of Chicago Symposium on Cosmic Rays, June 30, 1939.

[1] A. Ehmert, Zeits. f. Physik **106**, 751 (1937).

[2] P. Auger, P. Ehrenfest, A. Fréon and A. Fournier, Comptes rendus **204**, 257 (1937).

[3] H. Euler and W. Heisenberg, Ergeb. d. Ext. Natur. (1938).

[4] For a resumé of the experiments leading to the discovery of the meson see E. E. Witmer and M. A. Pomerantz, J. App. Phys. **9**, 746 (1938).

[5] H. Yukawa, Proc. Phys. Math. Soc. Jap. **17**, 48 (1935).

[6] For arguments favoring the secondary nature of mesons see T. H. Johnson and J. G. Barry. Phys. Rev. **56**, 219 (1939); see also L. W. Nordheim and M. H. Hebb, Phys. Rev. **56**, 494 (1939).

[7] H. Euler, Zeits. f. Physik **110**, 692 (1938).

[8] P. Ehrenfest and A. Fréon, Comptes rendus **207**, 853 (1938); J. de phys. et rad. **12**, 529 (1938).

[9] P. M. S. Blackett, Phys. Rev. **54**, 973 (1938); Nature **142**, 992 (1938).

[10] D. Rathgeber, Naturwiss. **26**, 842 (1938).

[11] W. Kolhörster and I. Matthes, Physik. Zeits. **40**, 142 (1939).

[12] J. Barnóthy and M. Forró, Phys. Rev. **55**, 868 (1939).

[13] B. Rossi, Nature **142**, 992 (1938).

ence in the absorption in equivalent masses of lead and air, and Johnson and Pomerantz[14] independently determined the proper lifetime from the difference in the absorption of mesons in air and water. Although these methods have yielded concordant values of τ_0 of the order of 2×10^{-6} second, the calculations in all cases are based upon more or less arbitrary assumptions and limited experimental data, and the results can be considered only as indicating the correct order of magnitude.

An accurate comparison of the absorption of mesons in lead and air has been undertaken for several reasons. This experiment has the advantage that all measurements are made at a single station, and frequent interchanges of position can be made for the purpose of detecting any possible change of sensitivity in the apparatus itself. Thus, the data are of sufficient accuracy that the uncertainty in the value of τ_0 deduced therefrom resides principally in the assumptions regarding the mass of the meson and the height at which mesons are produced. It was also the purpose of this experiment to ascertain whether the stability of a meson increases in proportion to its energy, as is predicted by the Lorentz dilatation of the time scale. Finally, in order to achieve greater accuracy, it was expedient to discard the mass-absorption law, generally assumed for mesons, in favor of the more accurate theory. It was, however, considered important to check the theoretical absorption law by subsidiary experiments in which the stopping powers of water and lead were compared.

[14] T. H. Johnson and M. A. Pomerantz, Phys. Rev. **55**, 104 (1939).

II. The Relative Meson Stopping Power of Water and Lead

Because of the large mass of the meson, the loss of energy by radiation may be neglected, and, as far as we now know, ionization is the only important process by which mesons dissipate their energy prior to their disintegration. From the theory of Bethe[15] and Bloch,[16] the average energy lost per gram per square centimeter in a substance with N atoms per cm^3 by a meson with the velocity $v=\beta c$ and energy E may be expressed in the form:[17]

$$S\equiv-\frac{dE}{\rho dx}=\frac{2\pi NZe^4}{mc^2\beta^2\rho}\left[\log\frac{mc^2\beta^2W}{(1-\beta^2)\bar{I}^2}\right], \quad (1)$$

where m is the rest mass and e the charge of the electron, $\bar{I}$ is the mean ionization energy of the atom equal to $13.5Z$, and W represents the maximum energy which can be transferred in a direct collision from the meson to a free electron. The latter[18] is given by

$$W=(E+2\mu c^2)/[1+mc^2(1+\mu/m)^2/2E], \quad (2)$$

where μ is the rest mass of the meson. S_1/S_2, the relative stopping powers of equal masses of two media, may be calculated from Eq. (1).

An experimental value of S_{H_2O}/S_{Pb} which can be compared with that calculated from Eq. (1) was obtained in the following two experiments. In the first experiment, the quadruple coincidence counting rate of a train of four trays of counters (Fig. 3) was obtained as a function of interposed

[15] H. Bethe, *Handbuch der Physik*, Vol. 24, 1.
[16] F. Bloch, Zeits. f. Physik **81**, 363 (1933).
[17] Several additional terms appear between the brackets in the more exact expression, but these are negligible in the present considerations.
[18] T. H. Johnson, Phys. Rev. **45**, 580 (1934).

Table I. *Resumé of data used for comparing the stopping powers of water and lead. The data of experiment 1 is to be compared with that of experiment 2 only insofar as the intensity in arbitrary units is concerned, inasmuch as the sensitivity of the apparatus was adjusted between experiments.*

Exp. No.	Zenith Angle	Superposed Shield, M_1, in g/cm^2	Interposed Shield, M_2, in g/cm^2	Total Number of Quadruple Coincidences	Total Time in Hours	Coincidences per Hour	Intensity, $j_0(M_1+M_2)/j_{60}(M_2)$	(M_1+M_2) in g/cm^2
1	60°	0	403 Pb	2366	46	51.43±1.06		
	0°	1045 Pb	202 Pb	3296	26	126.77±2.22	2.46±0.10	1247
	0°	1045 Pb	403 Pb	4246	37	114.76±1.77	2.23±0.08	1448
	0°	1045 Pb	666 Pb	2023	20	101.15±2.31	1.97±0.09	1711
	0°	1045 Pb	868 Pb	3950	42	94.04±1.54	1.83±0.07	1913
2	0°	890 H_2O	403 Pb	2961	20.17	146.40±3.00	1.76±0.10	
	60°	0	403 Pb	1150	13.82	83.40±3.00		

lead thickness when the counters were beneath a superposed shield of 1045 g/cm^2 of lead, and in the second experiment, the counting rate of the same arrangement of counters was recorded under 890 g/cm^2 of superposed water, and with 403 g/cm^2 of interposed lead. The data are recorded in Table I. Since the experiments were run at different times, the effect of changes of sensitivity have been avoided by expressing all intensities in terms of that measured at the same time by the same arrangement inclined 60° from the vertical (without the superposed shields). Thus, the intensities given in the eighth column of Table I are comparable between the two experiments. The results of the first experiment are plotted in Fig. 1, which shows the cosmic-ray intensity as a function of the sum of the masses of superposed and interposed lead. The abscissa of the point on the lead absorption curve having as ordinate the intensity observed in the second experiment represents the amount of lead which reduces the intensity to the same extent as 890 g/cm^2 of water and 403 g/cm^2 of lead. This is found to be 1950 g/cm^2, and, subtracting the 403 g/cm^2 of interposed lead, the result indicates that 890 g/cm^2 of water has the same effect in absorbing mesons[19] as 1547 g/cm^2 of lead. It follows that these masses have the same stopping power, and hence the ratio of the relative stopping powers per g/cm^2, S_{H_2O}/S_{Pb}, is equal to 1.72 ± 0.22. The theoretical ratio of the stopping powers per g/cm^2 is obtained from Eq. (1). The result is not sensitive to the value of the energy E, and with E equal to 10^9 ev, a reasonable average value for the rays as they are passing through the superposed lead and water, and μ equal to $200m$, Eq. (1) gives S_{H_2O}/S_{Pb} equals 1.82, in agreement with the experimental result. Further experimental confirmation of the validity of Eq. (1) has recently been provided by Wilson's[20] cloud-chamber investigations of the specific energy loss in lead of mesons with energies of 2 to 7×10^8 ev. We may conclude, therefore, that Eq. (1) affords a suitable method for determining what thickness of one absorber is equivalent in stopping power to a given thickness of any other, in the experiments to be discussed.

[19] The mesons concerned are those which have sufficient energy after emerging from the superposed shield to just penetrate 403 g/cm^2 of lead.

[20] J. G. Wilson, Proc. Roy. Soc. **172**, 517 (1939).

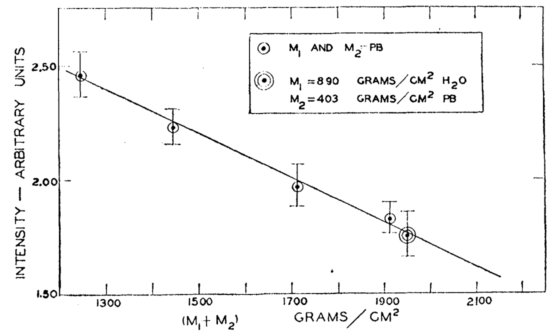

FIG. 1. Lead absorption curve for mesons. The intensity in arbitrary units *vs.* M_1 g/cm^2 of superposed lead $+M_2$ g/cm^2 of interposed lead is plotted from the data of Exp. 1, Table I. The abscissa of the point on the lead absorption curve whose ordinate is the intensity found in Exp. 2 is $(M_1+M_2)=1950$ g/cm^2. As $M_2=403$ g/cm^2, $M_1=1547$ g/cm^2 of lead. Actually, M_1 in Exp. 2 was 890 g/cm^2 of water. Therefore 890 g/cm^2 of water is equivalent in stopping power to 1547 g/cm^2 of lead.

III. Theory of the Determination of the Proper Lifetime

By inserting lead above the coincidence counter system in the vertical direction in an amount equivalent in absorbing power to $H(\sec\zeta-1)$ atmospheres, the vertical path through the air and the lead differs from that through the atmosphere at angle ζ only in regard to the time required for the rays to traverse it. When the cosmic rays traverse equivalent thicknesses of absorbing materials, the ratio of the intensity from the inclined direction to that from the vertical, j_ζ/j_0, is a function merely of the probabilities of disintegration of the rays during the times required to traverse the two paths. Since the disintegration probability is a function of the energy, the total intensity in each orientation must be expressed as an integral extending over the energy distribution. On the other hand, the ratio of the differences of the intensities recorded with two thicknesses of interposed lead, $\Delta j_\zeta/\Delta j_0$, is a function of the disintegration probability of rays whose energies are within a certain narrow range determined by the difference in lead thickness. Calculations of the mean lifetime can therefore be carried out by invoking either of these procedures, which shall be designated as the integral and differential method, respectively.

A. The integral method

It is assumed that mesons attaining sea level, incident at a zenith angle ζ, have originated as

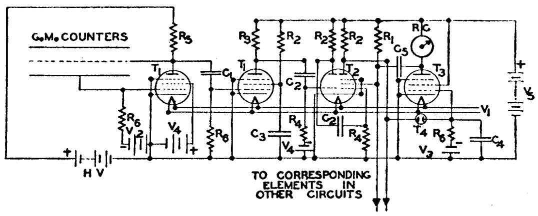

FIG. 2. The three-stage circuit associated with each of the trays of counters in the quadruple coincidence train, and the neon-tube coupled multivibrator delay circuit which recorded quadruple coincidences.

R_1 = 40,000 ohms	C_1 = 6 $\mu\mu$f
R_2 = 0.1 megohm	C_2 = 0.00025 μf
R_3 = .3 megohm	C_3 = .01 μf
R_4 = .5 megohm	C_4 = .005 μf
R_5 = 2.0 megohm	C_5 = .25 μf
R_6 = 10.0 megohm	
V_1 = 6.3 v a.c.	T_1 = RCA. 6C6
V_2 = 4.5 v	T_2 = RCA. 6F7
V_3 = 33.0 v	T_3 = RCA. 89
V_4 = 45.0 v	T_4 = G.E. S-4½
V_5 = 180 v	R.C. = Recording dial

secondaries at an atmospheric depth

$$h = fH \cos \zeta, \tag{3}$$

where H is the depth of the homogeneous atmosphere (8×10^5 cm), and f is the fraction of the homogeneous atmosphere traversed by the primaries prior to the generation of the mesons. The actual height x above sea level corresponding to this depth in an isothermal atmosphere is given by

$$h = He^{-x/H} \tag{4}$$

or

$$x = H \log (\sec \zeta / f). \tag{5}$$

In consequence of the relativistic transformation, the apparent stability should increase with the energy,[21] and for energies large compared with the rest energy, μc^2, the mean life of a meson of energy $\epsilon\mu c^2$ is $\tau=\epsilon\tau_0$, where τ_0 is the proper lifetime, or the mean life of the meson in the coordinate system with respect to which the particle is at rest. If a ray loses energy by ionization at the constant rate $i\mu c^2$ per cm in normal air, the probability $P(\epsilon,\zeta)$ that a ray of initial energy $\epsilon\mu c^2$ will attain sea level without disintegrating can be derived in the following manner. If P is the probability that a ray will survive for a time t, then the probability for disintegration in time t to $t+dt$ is

$$-dP = Pdt/\tau \tag{6}$$

or

$$-dP = P\frac{dx \sec \zeta}{\beta c \tau_0(\epsilon - ih \sec \zeta)}. \tag{7}$$

Making use of Eqs. (4) and (5), and integrating (7) over the path to sea level, we obtain:

$$P(\epsilon,\zeta) = \exp[-(H \sec \zeta/\beta c\tau_0\epsilon) \times\log\{(\epsilon/ifH-1)/(\epsilon/iH \sec \zeta -1)\}]. \tag{8}$$

Let $j(\epsilon)d\epsilon$ represent the number of mesons per second per square centimeter per unit solid angle whose initial energies lie in the interval $d\epsilon$ at ϵ, a function which is assumed to be independent of the direction. The total vertical intensity of the penetrating component at sea level may thus be expressed as

$$j_0(t) = \int_{E_0}^{\infty} j(\epsilon)P(\epsilon, 0)d\epsilon, \tag{9}$$

where $E_0 = \alpha(t) + iH(1-f) + \alpha'$, t is the thickness of lead interposed in the counter system for eliminating the soft radiation, $\alpha(t)$ is the energy required to just penetrate the interposed lead, and α' is that lost in penetrating the superposed shield. The intensity which would be measured by an apparatus inclined at a zenith angle ζ with no superposed lead shield filling its solid angle is

$$j_\zeta(t) = \int_{E_\zeta}^{\infty} j(\epsilon)P(\epsilon, \zeta)d\epsilon, \tag{10}$$

where $E_\zeta = \alpha(t) + iH(\sec \zeta - f)$. From counter experiments such as those performed by Wilson[22] and Ehmert,[1] and the cloud-chamber observations of Blackett,[23] the energy distribution at sea level and below is of the form (Energy)$^{-\gamma}$, where $2<\gamma<3$. Consequently, in terms of ϵ,

$$j(\epsilon)P(\epsilon,0) = A/[\epsilon - iH(1-f)]^\gamma, \tag{11}$$

and carrying through the integration expressed by Eq. (9),

$$j_0(t) = A/(\gamma-1)[\alpha(t)+\alpha']^{\gamma-1} = A/K. \tag{12}$$

Combining (10) and (11),

$$j_\zeta(t) = \int_{E_\zeta}^{\infty} \frac{AP(\epsilon, \zeta)d\epsilon}{[\epsilon - iH(1-f)]^\gamma P(\epsilon, 0)}, \tag{13}$$

[21] H. J. Bhabha, Nature **141**, 117 (1938).

[22] V. Wilson, Phys. Rev. **53**, 337 (1938).

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

and finally

$$\frac{j_\zeta(t)}{j_0(t)}=K\int_{E_\zeta}^{\infty}\frac{P(\epsilon,\zeta)d\epsilon}{P(\epsilon,0)[\epsilon-iH(1-f)]^\gamma}. \quad (14)$$

For the determination of τ_0, the ratio of the intensities $j_\zeta(t)/j_0(t)$ is measured and compared with the values obtained from Eq. (14) when various values of τ_0 are introduced. It is, of course, necessary to select specific values of μ, f, and γ. The values thus calculated for $\mu=200m$, $f=0.1$, and $\gamma=2$ and 3 are represented as functions of τ_0 in Fig. 5. The calculated values are least sensitive to γ when $E_\zeta=E_0$, and, in the experimental work, ζ has been selected to fulfil this condition.

B. The differential method

In determining τ_0 by the differential method, we are concerned with the disintegration of only those rays possessing sufficient energy to penetrate an initial thickness t_1 of interposed lead, but without enough energy to pass through a larger thickness t_2 of lead. This calculation has the advantage that it is independent of the energy distribution, and, when $E_\zeta=E_0$, it gives the proper lifetime of rays of initial energy

$$\epsilon_1=iH(\sec\zeta-f)+\bar{\alpha}, \quad (15)$$

where $\bar{\alpha}$ is the average of the minimum energies required for penetrating the two thicknesses of lead. In this instance,

$$\eta\equiv\frac{j_\zeta(t_1)-j_\zeta(t_2)}{j_0(t_1)-j_0(t_2)}=\frac{P(\epsilon,\zeta)}{P(\epsilon,0)} \quad (16)$$

and τ_0 is determined by comparing the observed value of η with those calculated from Eq. (8) with various values of τ_0 (Fig. 6).

IV. Experimental Procedure

A. Apparatus

The intensities of the penetrating component were measured with a quadruple coincidence counter train of large area, but relatively small angular aperture. Each tray consisted of twelve parallel-connected G-M counters with copper cylinders 8″ long and $\frac{3}{4}$″ in diameter. These overlapped in such a manner that the tray presented an unbroken sensitive area of approximately 440 cm². The distance between extreme trays was 132 cm. Provision was made for interposing up to 90 cm of lead between the counter trays. In these experiments, a 6 percent Sb-Pb alloy was used, cast in plates 10″×10″ ×$\frac{3}{8}$″, each weighing about 10 g/cm². The counters were filled with a mixture of hydrogen at a pressure of 5 cm of Hg, and argon at a pressure of 33 cm of Hg. The individual counters had a constant counting rate over a range of 200 volts. The operating potential was approximately 1250 volts.

The three-stage circuit diagrammed in Fig. 2 amplified the pulses, and selected coincidences by means of the usual Rossi parallel-plate connection. Neon-tube coupling to a multivibrator output stage[24] was employed, and an automatic mechanism provided photographic records of the counts obtained during hourly intervals. The counters were quenched by the conventional Neher-Harper[25] arrangement, and the stabilized high voltage was supplied by Gingrich's[26] modification of the Street-Johnson[27] voltage control circuit.

Adjacent to a window in the laboratory a scaffold was erected upon which was placed an inverted truncated pyramid of lead 67.7 cm high filling the solid angle of the counter train. The remaining portion of the absorbing shield was

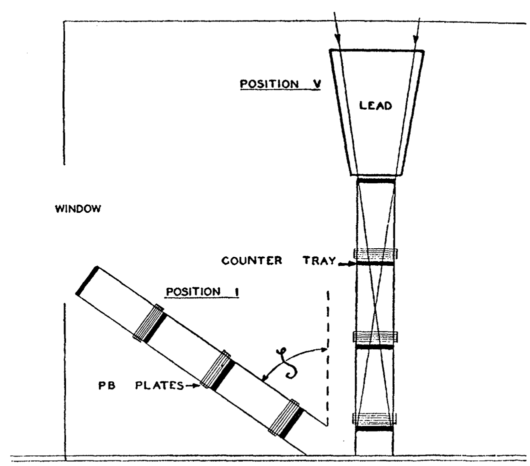

Fig. 3. Scale diagram of the geometry of the experiment.

[24] T. H. Johnson, Rev. Sci. Inst. **9**, 221 (1938).
[25] H. V. Neher and W. W. Harper, Phys. Rev. **49**, 940 (1936).
[26] N. S. Gingrich, Rev. Sci. Inst. **7**, 207 (1936).
[27] J. Street and T. H. Johnson, J. Frank. Inst. **214**, 155 (1932).

provided by the building itself. In position V, the apparatus was placed vertically under the pile, and in position I it was inclined toward the window at an angle ζ from the vertical (Fig. 3).

B. Determination of lead equivalent of building

In order to evaluate α', (Eq. (9)), the amount of lead equivalent in stopping power to the building was determined in the following manner. The counting rate was recorded with the apparatus in a vertical position under the scaffold with the superposed lead removed, but with 42 lead plates interposed. The apparatus was then transferred to a shack on the roof of the building, and the additional quantity of lead required to reduce the counting rate to that recorded in the basement was ascertained. The results are listed in Table II and Fig. 4. The building was found to be equivalent to 32.6±2 lead plates.

In order to determine the angle ζ for which $E_0=E_\zeta$, the mass of air equivalent in stopping power to the superposed shield was calculated by means of Eq. (1). Inasmuch as the Pb plates utilized in these experiments were a 6 percent Sb-Pb alloy, the total shield thickness (building +pile) amounted to 40 g/cm^2 of Sb and 1060 g/cm^2 of Pb. Assuming the average energy of the rays during their traversal of the shield to be of the order of a billion ev, Eq. (1) gives the equivalent amounts of air as 28 g/cm^2 for the antimony, and 670 g/cm^2 for the lead, yielding a total of 698 g/cm^2 as the quantity of air equivalent in stopping power to the superposed shield. This assigns the angle of inclination for which $E_0=E_\zeta$ as $\zeta=\sec^{-1}(1.7)\approx 54°$.

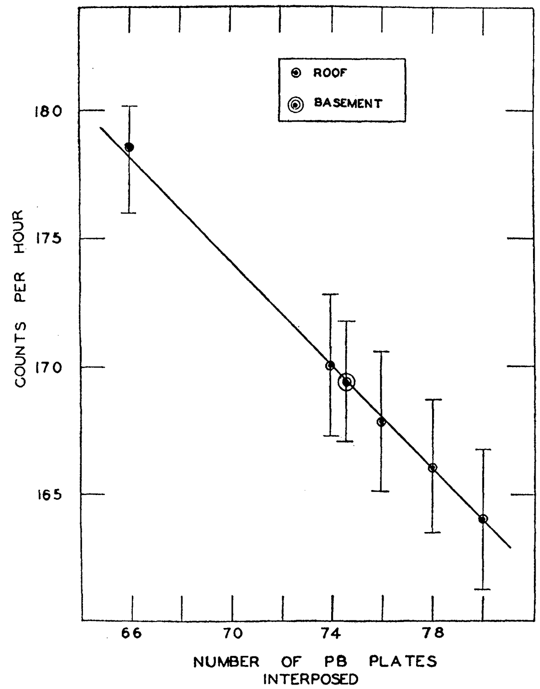

FIG. 4. Plot of the data of Table II used for the determination of the lead equivalent of the building. The points obtained on the roof give the lead absorption curve for mesons. The point obtained in the basement, with no Pb overhead, but with 42 plates of lead interposed in the counter system, is plotted on the curve with ordinate corresponding to the observed intensity. The lead equivalent of the building is the corresponding abscissa less the 42 plates of interposed lead.

C. Results

Table III summarizes in chronological order the data used for the determination of τ_0. Runs with the two thicknesses of interposed lead ($t_1=36$ plates, $t_2=86$ plates) were conducted alternately in the two positions I and V. There was satisfactory evidence that no changes of sensitivity occurred during this experiment. In

TABLE II. *Resumé of vertical runs for determination of stopping power of building. Run No. 131 was made in the basement under scaffold with no superposed Pb. The remainder of the runs were made in the shack on roof.*

Run No.	Pieces of Interposed Lead	Total No. of Counts	Total Time, in Hours	Quadruple Coincidences per Hour
131	42	5252	31	169.42±2.34
132	66	4286	24	178.58±2.63
134	74	3742	22	170.00±2.78
135	80	3608	22	164.00±2.74
136	76	3860	23	167.83±2.70
137	78	4152	25	166.08±2.59

TABLE III. *Resumé of data for determination of τ_0. Position V: Apparatus vertical under superposed absorbing shield. Position I: Apparatus inclined toward window, principal axis of counter train 54° from vertical.*

Run No.	Position	Interposed Pb, t	Total No. of Counts	Total Time, Hours	Quadruple Coincidences per hour
210	I	t_1	640	9	71.11±2.82
212	I	t_2	798	12	66.50±2.36
213	I	t_1	520	7	74.29±3.29
214	I	t_2	1346	20	67.30±1.84
215	I	t_1	1688	23	73.43±1.79
216	I	t_2	834	13	64.15±2.23
217	V	t_1	990	8	123.75±3.94
218	V	t_2	1306	13	100.46±2.79
219	V	t_1	1096	9	121.78±3.67
220	V	t_2	2398	24	99.92±2.04
222	I	t_1	1700	24	70.83±1.72
223	V	t_1	708	6	118.00±4.43

all of the data presented herewith, the errors indicated are standard deviations. The statistical fluctuations in hourly values were in satisfactory agreement with the deviations expected from the total number of counts. An average correction for accidentals and showers was determined for each orientation and for each thickness of interposed lead by observing the counting rate with one tray displaced out of line. The values obtained were not sensitive to lead thickness, and the average values for the two thicknesses are given in Table IV.

Figure 5 shows the theoretical ratio $j_\zeta(t)/j_0(t)$ as a function of τ_0 calculated from Eq. (14) for the two values of t used in the experiment. A value of 10^8 ev, corresponding to a rest mass of the meson equal to $200m$ has been selected for μc^2 in these calculations, and the depth fH below the top of the homogeneous atmosphere at which mesons are produced is assumed as one-tenth of an atmosphere. The two curves in each instance represent two choices of the exponent γ in the energy distribution 2 and 3. In making the calculations based upon Eqs. (14) and (16) a value 20 of the energy iH lost in passing through the atmosphere has been used. This is consistent with 78 ion pairs per cm of air, and 32 ev per ion pair, and is the theoretical value given by Eq. (1) assuming an average energy for the mesons during their traversal of the atmosphere of the order of several billion ev. The calculations are not especially sensitive to the choice of the value of iH, and the severe test of changing the value by about 15 percent without compensating with the change of angle which would be entailed modifies τ_0 in the range of the experimental results by about half a microsecond. The energies required to just penetrate the interposed shield have been calculated from the range equation[28] based upon the $1/v^2$ law. The values used are $\alpha(t_1)=6.10$ and $\alpha(t_2)=11.8$. If the value of f is increased to 0.5, the value of τ_0 found from the data is decreased by less than a microsecond. The effect of a change in γ is indicated in Fig. 5. A small change in the angle ζ has a negligible effect upon the calculated values

TABLE IV. *Cumulative summary of data for determination of τ_0.*

Position	Interposed Pb, t	Total No. of Counts	Total Time, Hours	Quadruple Coincidences per Hour	Correction, Counts per Hour due to Showers and Accidentals	Corrected Data, Counts per Hour
I	t_1	4548	63	72.19±1.07	2.87	$j_\zeta(t_1)=$ 69.32±1.48%
I	t_2	2978	45	66.18±1.22		$j_\zeta(t_2)=$ 63.31±1.84%
V	t_1	2974	23	121.48±2.30	5.35	$j_0(t_1)=$116.13±1.90%
V	t_2	3704	37	100.11±1.65		$j_0(t_2)=$ 94.76±1.64%

$j_\zeta(t_1)/j_0(t_1)=0.596\pm0.021$; $j_\zeta(t_2)/j_0(t_2)=0.668\pm0.023$; $\dfrac{j_\zeta(t_1)-j_\zeta(t_2)}{j_0(t_1)-j_0(t_2)}=0.281\pm0.093$

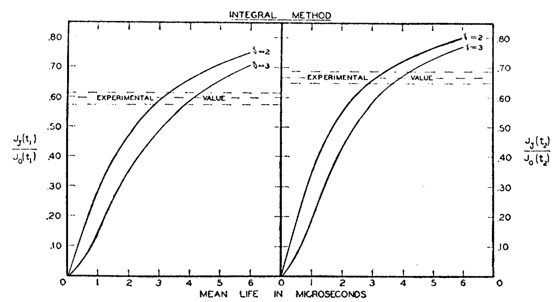

FIG. 5. The integral method for the determination of τ_0. The curves represent $j_\zeta(t)/j_0(t)$ *vs.* τ_0 calculated from Eq. (14) with $f=0.1$, $\mu c^2=10^8$ ev, $t_1=36$ lead plates, $t_2=86$ lead plates, and $\gamma=2$ and 3. The value of τ_0 corresponding to the experimental value of $j_\zeta(t)/j_0(t)$ lies between 3 and 4 microseconds.

of the ratio $j_\zeta(t)/j_0(t)$ in the region of the experimental results.

Figure 6 is a plot of the expected values of η *versus* τ_0, calculated from Eq. (16). In this case, ϵ_1 is equal to 41 μc^2, or about 4 Bev. This calculation is less sensitive than the integral method to variations in the choice of the parameters iH and α.

V. DETERMINATION OF τ_0 FROM THE RELATIVE INTENSITIES OF THE SOFT AND HARD COMPONENTS[29]

An independent but less accurate value of τ_0 has been calculated from some measurements of the relative intensities of the soft and hard components, using the following formula derived by

[28] See e.g. reference 3, page 39.

[29] A preliminary report of this experiment was presented at the Washington meeting of the American Physical Society, April 27, 1939. A method similar in principle was proposed by J. Clay, K. Jonker, and J. Wiersma, Physica **6**, 174 (1939). In their experiment, they assumed that the ratio of the soft and hard components at a zenith angle of 60° provides a more correct value of κ.

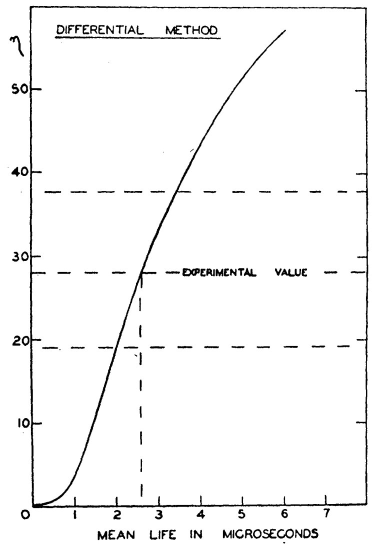

FIG. 6. The differential method for the determination of τ_0. The curve represents η *vs.* τ_0, calculated from Eq. (16), with the values of f, μc^2, and t used in the integral method. From the experimental value of η, $\tau_0=2.6$ microseconds for mesons with an initial energy $\epsilon_1=4$ Bev.

Euler and Heisenberg:[3]

$$\kappa\approx\frac{9X_0\mu c^2}{4\tau_0 c2E_j}+\frac{\mu c^2}{2aT}, \tag{17}$$

Here κ is the ratio of the number of disintegration electrons and their secondaries to the number of penetrating particles, X_0 is the unit of length characteristic of a particular absorber in the radiation theory and is equal to 27,500 cm in normal air, E_j is the energy at which an electron loses energy by ionization and by radiation at the same rate, and is equal to 15×10^7 ev in air, a is the rate of loss of energy by ionization of a meson in air, and T is the depth below the top of the atmosphere. The value of κ has been obtained by comparing the amount of soft component under the atmosphere and a meter of lead with that under an equal mass of air alone. The technique of the preceding experiment has been utilized for obtaining the data of Table V.

The decrease in the counting rate caused by the interposition of the first 20 lead plates in the arrangement of coincidence counters is due both to the partial absorption of mesons, and to the complete elimination of the soft radiation. Under the superposed pile of lead, the disintegration electrons are absent and the soft radiation consists of knock-on electrons produced by direct elastic impact of mesons with atomic electrons, and of the secondaries arising from these electrons according to the cascade process. When no dense medium fills the solid angle of the counter system, however, an additional soft radiation, consisting of the electrons together with their secondaries arising from the disintegration of mesons, is present. Data A' and B' of Table V show that, with the apparatus under the superposed lead, the interposition of the first 20 lead plates reduces the counting rate to 84.2 ± 2.7 percent of the original counting rate. Coincidences recorded when 20 lead plates are interposed in the system are due entirely to mesons. The data of Table I show that the subsequent interposition of 20 additional plates absorbs 8 ± 3 percent of the remaining radiation. Extrapolating to zero interposed lead thickness, we find that 91.5 ± 4.2 percent of the original counting rate was due to mesons. Therefore, the soft radiation here accounts for 8.5 ± 4.2 percent of the counting rate without interposed lead, or 9.4 ± 5 percent of the counting rate due to mesons. This agrees, within the experimental limits, with the cloud chamber, and counter observations of Trumpy.[30] However, the value obtained under these conditions is doubtlessly too small, since under the superposed shield, events may occur in which the simultaneous passage of a meson and its secondaries produces a single coincidence. We arbitrarily assume that the intensity of the soft component under lead is of the order of 1.5 times the observed value. Under air, on the other hand, the secondaries originate at a greater distance from the apparatus, and, because of their divergence, the simultaneous passage through the apparatus of the parent meson and one or more of its secondaries is less probable. Thus, the observed intensity of the soft component under air corresponds closely with the actual intensity.

According to Bhabha's[31] theory, which has been experimentally supported by the cloud-chamber observations of Lovell,[32] and by the experiments of Swann and Ramsey,[33] the number

[30] B. Trumpy, Zeits. f. Physik **113**, 582 (1939).
[31] H. J. Bhabha, Proc. Roy. Soc. **164**, 257 (1937).
[32] A. C. B. Lovell, Proc. Roy. Soc. **172**, 568 (1939).
[33] W. F. G. Swann and W. E. Ramsey, Phys. Rev. **56**, 378 (1939).

of knock-on electrons and subsequent secondaries accompanying a meson in air is roughly one-third of the number in lead, or $\frac{1}{3}\times\frac{3}{2}\times 9.4$ percent $=5\pm 3$ percent.

Data A and B of Table V show that, under air, 77.7 ± 3.6 percent of the original counting rate is observed after the interposition of the first 20 lead plates. The percentage change of the remaining intensity, produced by the interposition of 20 additional plates, as already stated, is equal to 8 ± 3 percent. Again extrapolating to zero lead thickness, the counting rate due to mesons accounts for 84.5 ± 4.8 percent of the total counting rate with no interposed lead. From the above estimate of the number of coincidences per meson-produced coincidence, due to knock-on electrons and associated secondaries, we find that 3.9 ± 2.3 percent of the total counting rate with no interposed lead was attributable to this soft radiation. The contributions of the various components of cosmic radiation to the observed counting rate under air were therefore the following:

Mesons $=84.5\pm 4.8$ percent
Knock-on electrons and
subsequent secondaries $=3.9\pm 2.3$ percent
Disintegration electrons and
subsequent secondaries $=11.6\pm 5.4$ percent.

From this, the ratio of the intensity of disintegration electrons and their secondaries to the intensity of mesons, κ, is equal to 0.137 ± 0.062. Solving Eq. (17) with this value of κ and with μ equal to $200m$, we find that τ_0 is equal to 6 microseconds. However, this value may be too low, as there may have been more knock-on electrons in air than have been accounted for in the calculation. Furthermore, the experimental uncertainties alone are such that within the range of the probable error, τ_0 may have any value within the range from 4 to 12 microseconds. The value of τ_0 obtained from the intensity of the soft component is slightly higher than that found from the differential and integral methods, but the difference may not be significant in view of the rather large probable error.

TABLE V. *Data for determination of* κ.

Zenith Angle	No. of Pb Plates Interposed	Total No. of Quadruple Coincidences	Total Time in Hours	Quadruple Coincidences per Hour
60°	20	1644	105.8	$A=15.54\pm 0.50$
60°	0	1062	53.2	$B=20.00\pm 0.61$
0°	20	1686	48.0	$A'=35.12\pm 0.86$
0°	0	2566	61.5	$B'=41.73\pm 0.83$

$A/B=77.7\pm 3.6\%$; $A'/B'=84.2\pm 2.7\%$.

VI. Discussion

The data of Fig. 5 reveal that the proper lifetime of the meson, determined by the integral method, lies between 3 and 4 microseconds, depending upon the choice of the constant γ in the energy distribution. The results for the two thicknesses of interposed lead are indeed in striking agreement. This enables one, on the strength of the experimental evidence[1, 22, 23] indicating a value of γ of about 2.8 to assign a most probable value of about 3.8×10^{-6} second to τ_0 as determined by the integral method.

The data of Fig. 6 disclose that the proper lifetime of a meson of about 4 Bev initial energy, as determined by the differential method, is about 2.6×10^{-6} second. It is difficult to conclude that this value disagrees with the value obtained by the integral method, but there is some indication that the latter method yields a longer proper lifetime. Inasmuch as the mesons whose disintegration was considered in the differential experiment are those whose energies are near the lower limit included in the integral calculation, this possible discrepancy would imply that the lower energy particles are less stable relative to the higher energy particles than is accounted for by the relativistic effect alone. In the light of the present state of our knowledge, it is premature to stress the significance of this possible discrepancy.

The uniqueness of the rest mass of the meson has not yet been established, and the existence of a variable mass would obviously play an important role in these considerations. Inasmuch as the experiments are only capable of leading to a determination of the ratio μ/τ_0, the above values of the proper lifetime would be changed by an amount proportional to the change in μ, to the first approximation. More specific information regarding the height at which mesons originate is necessary for further limiting the range of possible values of τ_0. It is possible that the altitude of the layer at which mesons are produced varies with the energy of the particles, an assumption which has been made by Nordheim[34] in his theory of the production of mesons.

There are several arguments favoring the hypothesis that low energy mesons are less stable. The abrupt termination of meson tracks and the apparent absence of evidence for disintegration electrons in cloud chamber photographs[35] suggest that some process other than ionization and disintegration may be responsible for the removal of slow mesons from the cosmic radiation. This would also explain the failure of Montgomery, Ramsey, Cowie, and Montgomery[36] to detect disintegration electrons with their delayed coincidence counter arrangement. Moreover, despite the inaccuracy in the value of τ_0 determined from the relative intensities of soft and hard components, the fact that the value of the proper lifetime calculated on this basis is larger than those calculated by the other methods may be interpreted as indicating that slow mesons are disappearing by some process not resulting in the formation of an electron.* The high value of τ_0 equal to about 4 microseconds deduced from the analysis of the frequency of occurrence of large bursts by Montgomery and Montgomery[37] is also consistent with this hypothesis.

Finally, the existence of possible nuclear resonance effects, analogous to the selective absorption of slow neutrons, cannot be precluded, and investigations now in progress should elucidate this point. It is noted that if an effect of this nature is to account for the results, the effective cross section would have to be greater in air than in lead, and would have to be of the same order as that for disintegration, i.e., 10^{-5} per cm of air.

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[34] L. W. Nordheim, Phys. Rev. **56**, 502 (1939).

[35] S. H. Neddermeyer and C. D. Anderson, Phys. Rev. **54**, 88 (1938); H. Maier Leibnitz, Zeits. f. Physik **112**, 569 (1939).

[36] C. G. Montgomery, W. E. Ramsey, D. B. Cowie, and D. D. Montgomery, Phys. Rev. **56**, 635 (1939).

* *Note added in proof.*—H. Yukawa and T. Okayama have very recently published the results of calculations of the cross section for nuclear capture of mesons. (Scientific Papers of the Institute of Physical and Chemical Research **36**, 385 (1939).) For very slow mesons, their theory assigns a greater probability to this process than to disintegration.

[37] C. G. Montgomery and D. D. Montgomery, Rev. Mod. Phys. **11**, 255 (1939).