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The Mean Lifetime of the Meson

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Measurements of the lifetime of mesons which have traversed varying distances in air have been made and show that the value of $\tau/\mu c^2$ is constant. The existence of a spectrum of lifetimes is therefore excluded. The most probable value of $\tau/\mu c^2$ from our measurements is $2.6 \pm 0.3 \times 10^{-14}$ sec./ev.

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MEASUREMENTS during recent years have shown with certainty that the meson is unstable with a mean lifetime of 2 to 3 microseconds. Discussion now turns chiefly on questions of the exact value of the mean life and on whether it is the same for different mesons.

Recently Weisz[1] from an analysis of the results of various authors concluded that they could be brought into harmony by assuming that the value of $\tau/\mu c^2$ (τ, mean lifetime of meson at rest; μ, rest mass of meson) increases as the path traversed by the meson increases. This could be accounted for by assuming that in the upper reaches of the atmosphere not just one type of meson is generated but that the mesons produced have a spread either in mean lifetime, rest mass or both. If the mass is assumed constant, the mean lifetime would decrease with decreasing path traveled.

Because of the importance of this matter we maintain that before concluding that $\tau/\mu c^2$ varies with the path length of the meson in air, as previous measurements have somewhat indirectly indicated, measurements designed specifically to test this point should be carried out.

Juilfs' tested the variation of $\tau/\mu c^2$ by varying the zenith inclination and reported an increase in $\tau/\mu c^2$ with increasing θ. We have repeated Juilfs[2] calculations using careful zenith measurements at Passo Sella (2200 m above sea level) by one of us[3] and found no variation of $\tau/\mu c^2$.[4] This ratio remained constant within experimental error from $\theta=0°$ to $60°$.

In any case the values of $\tau/\mu c^2$ deduced from measurements of this type are uncertain, above all because of the uncertainty in our knowledge of the energy spectrum of the mesons. We have held it important therefore to do experiments from which it would be possible to deduce the

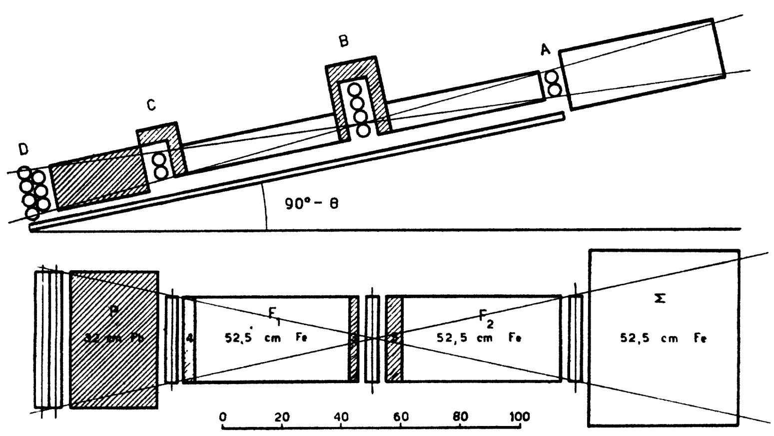

Fig. 1. Arrangement of counters and absorbers.

[1] P. Weisz, Phys. Rev. **59**, 845 (1941).
[2] J. Juilfs, Naturwiss. **30**, 584 (1942).
[3] V. Tongiorgi, Nuovo Cimento **1**, 96 (1943).
[4] G. Cocconi and V. Tongiorgi, Naturwiss. **31**, 108 (1943).

TABLE I. Essential data involved in the measurements.

1 Series	2 Type of meas.	3 θ	4 Absorb. $A+B$ g/cm²	5 g/cm² Pb in P	6 g/cm² Fe in F_1	7 g/cm² Fe in F_2	8 g/cm² Fe in Σ	9 $\frac{1020}{\cos\theta}$	10 E total ev	11 E mean ev	12 Km in air
I	20 *CP*	20° 00′	140	358	404	404	404	1085	5.25×10^9	4.97×10^9	18.6
	20 *SP*	20° 00′	140	0	404	404	404	1085	4.70×10^9		
	43 *CP*	43° 52′	140	358	404	404	0	1415	5.26×10^9	4.99×10^9	27.2
	43 *SP*	43° 52′	140	0	404	404	0	1415	4.72×10^9		
II	54 *CP*	54° 16′	140	358	0	0	404	1745	5.26×10^9	4.99×10^9	36.2
	54 *SP*	54° 16′	140	0	0	0	404	1745	4.72×10^9		
	60 *CP*	60° 32′	140	358	0	0	0	2075	5.29×10^9	5.01×10^9	45.4
	60 *SP*	60° 32′	140	0	0	0	0	2075	4.74×10^9		

value of $\tau/\mu c^2$ for mesons belonging to the same energy band but which have traveled over widely varying path lengths.

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With the counter telescope illustrated in Fig. 1 we have registered the difference $D=T-Q$ between triple ($T=A+B+C$) and quadruple ($Q=A+B+C+D$) coincidences. The counters in groups A, B, C had brass walls 1 mm thick and had an effective area 4.3×30 cm². They were filled with argon and alcohol. The tubes of group D were similar to those of A, B, C but had an area 4.3×45 cm². The solid angle of the telescope was $8°\times27°$. As shown in Fig. 1 lead and iron absorbers could be placed between and in front of the counters. The absorbers (of Pb, 140 g/cm²) around the counters B and C were present in all measurements and served to protect the system in large part from the effect of lateral showers and to eliminate the electronic component in the absence of the other absorbers.

The counters and absorbers were mounted on a mobile support which could turn on a horizontal axis to give to the telescope different zenith inclinations.

All measurements were carried out at the Physical Institute of the University of Milan (average barometric pressure 1020 g/cm²) before a large window which left the solid angle of the telescope completely unobstructed in all positions used in the experiments.

The conditions of the series of measurements are given in Table I. In column 9 is shown the path length to the top of the atmosphere (measured in g/cm²). We assume that the mesons are not generated at the top of the atmosphere but only after the primary cosmic radiation which generates them has passed through a distance s in air about equal to 100 g/cm². We shall see later the importance of taking for the path length of the meson the value ($1020/\cos\theta-s$). In column 10 are given the values of the energy which a meson must have to traverse the absorbing materials given in columns 4–9 and thus reach counters D. These values of meson energy are taken from the charts given by Wick.[5] Wick's calculations were made under the assumption that μc^2 for the meson is 10^8 ev but even assuming a variation of ±20 percent in the mass of the meson the values of the energy would not be seriously altered.

The first series of measurements was carried out in early 1942. The positions of absorbers and telescope were changed each day. A daily check was made of the operation of the counters and coincidence equipment. At each position of telescope and for each disposition of absorbers the difference between the triple and quadruple coincidence frequency was measured. The results are given in Table II.

The difference of the frequency differences $20\,CP-20\,SP$ is proportional to the frequency with which mesons in the energy range 4.70 to

[5] G. C. Wick, Nuovo Cimento **1**, 302 (1943).

TABLE II. Differences between triple and quadruple coincidence.

I Series	20 *CP*	20 *SP*	43 *CP*	43 *SP*
$\frac{T-Q}{\text{min.}}$	$\frac{3283}{30844}=0.105\pm0.0019$	$\frac{512}{14186}=0.0361\pm0.0016$	$\frac{2825}{37897}=0.0746\pm0.0014$	$\frac{344}{13862}=0.0248\pm0.0014$
II Series	54 *CP*	54 *SP*	60 *CP*	60 *SP*
$\frac{T-Q}{\text{min.}}$	$\frac{885}{18369}=0.0481\pm0.0016$	$\frac{71}{5349}=0.0132\pm0.0015$	$\frac{627}{21227}=0.0295\pm0.0012$	$\frac{106}{8306}=0.0128\pm0.0013$
$\frac{T-Q}{\text{min.}}$	$\frac{2624}{45307}=0.0519\pm0.0012$	$\frac{231}{9777}=0.0236\pm0.0016$	$\frac{1901}{52903}=0.0359\pm0.0008$	$\frac{147}{7016}=0.0209\pm0.0017$

5.25×10^9 ev (average energy 4.97×10^9 ev) reach the telescope within its effective solid angle around its inclination to the zenith. Similarly for the difference $43\ CP-43\ SP$ except that the energy range is from 4.72 to 5.26×10^9 ev (average energy 4.99×10^9 ev). Aside, therefore, from the completely negligible energy difference and assuming the space isotropy of cosmic radiation the ratio

$$R_1=\frac{43\ CP-43\ SP}{20\ CP-20\ SP}$$

gives the relative probabilities that mesons of average energy 4.98×10^9 ev will reach sea level with the above inclinations.

As already stated the lead absorbers around counters B and C largely eliminated the effect of lateral showers. The residual effect of these have been observed by moving two counters out of alignment. It was found that their effect besides being small was equal in all dispositions of the telescope and absorbers used. They are therefore eliminated in taking differences $CP-SP$.

In column 12 of Table I are given the path lengths l of the trajectories of the mesons at the various inclinations to the zenith. In the calculation it is assumed that the mesons are generated after passing through a stratum of air of 100 g/cm². The values of l are calculated from the relation

$$l=\frac{17.0}{\cos\theta}\log\frac{10.2}{\cos\theta}\ \text{km} \quad \text{(isothermal atmosphere at } -20°\text{C).}$$

From the first series of measurements the value of $\tau/\mu c^2$ can be calculated for mesons which have traversed in the mean about 23 km.

In the second series similar measurements were made at 54° 16′ and 60° 32′ inclination to the zenith. Here again the average energy of the mesons stopped in P is practically the same as in the first series (5×10^9 ev). The lateral showers were also constant for all arrangements. From the ratio

$$R_2=\frac{60\ CP-60\ SP}{54\ CP-54\ SP}$$

the value of $\tau/\mu c^2$ may be computed for mesons which have traversed not 23 km but 42 km.

Comparison of the values for $\tau/\mu c^2$ from R_1 and R_2 will therefore show whether or not this quantity varies with the path length. It is to be noted that by this method we are measuring the values of $\tau/\mu c^2$ for mesons of the same energy and energy spread and therefore the results are independent of any assumption of the shape of the primary spectrum. This is one of the principal causes of differences between measurements carried out by different experimenters under different conditions.

The only uncertain quantity introduced in our calculations is the value of s, the mean path length in air (in g/cm²) for the creation of mesons by the primary cosmic radiation. It will be seen, however, that our conclusions are not critically sensitive to the value assumed for s.

The second series of measurements was repeated twice, once during the spring of 1942 and once during the winter of 1943.

From Table II

$$R_1=\frac{0.0498}{0.0689}=0.724\pm0.039,$$

$$R_2=\frac{0.0167}{0.0349}=0.479\pm0.054,$$

$$R_3=\frac{0.0150}{0.0343}=0.439\pm0.062.$$

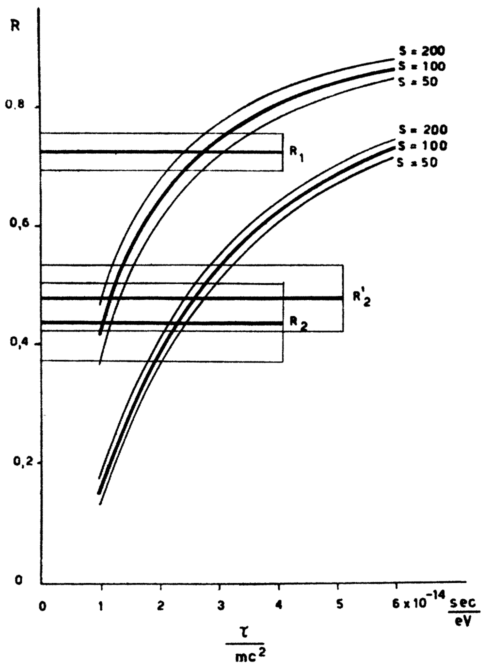

FIG. 2. Calculated relation between R and $\tau/\mu c^2$ together with the three measured values of R and their statistical errors.

If τ is the mean lifetime of the meson, μ its mass, the probability that it will disintegrate in a vertical distance dz is

$$-d\Pi=\frac{\mu c^2}{\tau c W}\frac{dz}{\cos\theta},$$

where W is the meson energy and θ is the inclination of the path of the meson to the zenith. This formula takes account of relativistic corrections and is a sufficiently close approximation for values of $W>10^8$ ev.

In terms of pressure change

$$dp=(p/p_0)\delta dz,$$

where δ is the density of normal air at p_0. Substitution gives

$$-d\Pi=\frac{\mu c^2}{\tau}\frac{p_0}{c\delta}\frac{dp}{pW\cos\theta}.$$

If we designate by $\Pi(p, W, \theta, s)$ the probability that a meson generated by a primary cosmic ray after passing through a stratum s of air will reach a level in the atmosphere of pressure p with energy W and inclination θ, Π will satisfy the differential equation

$$\frac{-d\Pi(p, W, \theta, s)}{dp}=\frac{\mu c^2}{\tau}\frac{p_0}{c\delta}\frac{\Pi(p, W, \theta, s)}{pW\cos\theta}.$$

We may calculate the energy W of the meson at the point where the pressure is p in terms of its energy W_0 at the point where it is created by assuming that it loses a quantity α of energy for each unit of mass/cm² crossed.

$$W=W_0-a(p/\cos\theta-s),$$

$$=\frac{(W_0+as)\cos\theta-\alpha p}{\cos\theta},$$

$$=\frac{E\cos\theta-\alpha p}{\cos\theta},$$

where $E=W_0+as$ is the virtual energy of the meson at the top of the atmosphere (the values listed in column 11 of Table I). Substituting and integrating we get

$$\log\Pi(p, E, \theta, s)$$

$$=A\frac{\mu c^2}{\tau}\frac{1}{E\cos\theta}\log\left(\frac{\alpha p-E\cos\theta}{\alpha p}\right)+\text{const.}$$

where $A=p_0/c\delta$. Assuming $\Pi=1$ for $p=s$ gives

$$\Pi(p, E, \theta, s)=\left[\frac{(E\cos\theta-\alpha p)s}{(E-\alpha s)p}\right]^{\frac{\mu c^2}{\tau}\frac{A}{E\cos\theta}}.$$

In calculating Π we assume $p_0=1033$ g/cm², $\delta=1.40\times10^{-3}$ g/cm²,* $c=3\times10^{10}$ cm/sec. From Wick's charts it is reasonable to assume that, for $E=5\times10^9$ ev, $\alpha=2.2\times10^6$ ev cm²/g.

We have calculated in this way the value of Π (1020, E, θ, s) for the various values of θ in Table I as a function of $\tau/\mu c^2$ and for three values of s ($s=50$, 100, 200 g/cm²). For each value of s we have obtained two curves which give as a function of $\tau/\mu c^2$ the values of the ratios

$$R_1=\frac{\Pi(1020;\,4.98\times10^9;\,45°52';\,s)}{\Pi(1020;\,4.98\times10^9;\,20°00';\,s)}$$

and

$$R_2=\frac{\Pi(1020;\,5\times10^9;\,60°32';\,s)}{\Pi(1020;\,5\times10^9;\,54°16';\,s)}.$$

* Mean temperature of air 20°C. It is to be noted that generally authors have assumed an isothermal atmosphere at 0°C. All the values of mean lifetime calculated on this basis are about 8 percent too low.

The six curves are shown in Fig. 2 together with the three experimental values and their statistical errors. An examination of the curves shows that the different values of s do not seriously affect the theoretical values of R_1 and R_2. Since s almost certainly lies between 50 and 200 g/cm², it seems reasonable to conclude that the assumption $s=100$ g/cm² will not cause an error in $\tau/\mu c^2$ greater than 10 percent. Since we are here primarily interested in relative values this uncertainty will not appear.

With $s=100$ g/cm² we get for the first series of measurements

$$\tau/\mu c^2=(2.8\pm 0.5)\times 10^{-14}\text{ sec./ev.}$$

For the second series the two values

$$\tau/\mu c^2=(2.6\pm 0.4)\times 10^{-14}$$

and

$$(2.3\pm 0.4)\times 10^{-14}\text{ sec./ev.}$$

We therefore conclude that the value of $\tau/\mu c^2$ does not increase when the path traversed is increased from 23 to 43 km. (If anything there is a slight decrease.) We believe, therefore, that these measurements confirm what we have already stated[4] that $\tau/\mu c^2$ is independent of path traversed, at least within the experimental errors of the measurements to date.

The three measurements together give a mean value for $\tau/\mu c^2$ of $(2.6\pm 0.3)\times 10^{-14}$ sec./ev. This value agrees within experimental errors with that given by Bernardini[6] from an extensive analysis of all measurements to date. It also agrees with the recent careful direct measurements of M. Conversi and O. Piccioni[7] which gave $\tau=(2.30\pm 7\text{ percent})\times 10^{-6}$ sec.

[6] G. Bernardini, Zeits. f. Physik **120**, 413 (1943).
[7] M. Conversi and O. Piccioni, Nuovo Cimento **11**, 71 (1944).

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On the Mean Life of Slow Mesons

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A new investigation on the spontaneous decay of mesons is performed by counting delayed coincidences between the impinging low energy mesons and the decay electrons. Four points of the decay curve of mesons are obtained for relative delay times ranging between −0.91 and 2.43 μsec. The results give an exponential curve which is evidence of the decay process. For the mean life we find $\tau=2.33$ μsec. ±6.5 percent. The effect disappears completely by inverting the sign of the delay.

1. INTRODUCTION

ACCORDING to current ideas, the particles which make up the hard component of cosmic rays have properties very similar to those of the particles first postulated by Yukawa[1] to explain the nuclear forces. This particle (meson, positive, or negative) having a mass of about 200 electron masses, undergoes spontaneous disintegration producing—according to the scheme generally accepted—one electron and one neutrino. The instability of mesons was assumed in order to explain the anomalous absorption of the hard component, upon which are based all the measurements performed up to now of the ratio $\tau/\mu c^2$ of the mean life τ to the rest energy μc^2 of mesons.[2–14]

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