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Further Measurements of the Mesotron Lifetime

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The average ranges before decay of two monoenergetic mesotron groups have been measured. Within the statistical errors, the ranges are found to be in the same ratio as the average effective momenta, as theoretically predicted. From the two above measurements, and with a mesotron mass $\mu=10^8$ ev/c^2, one obtains the values $\tau_0=(2.8\pm0.3)\times10^{-6}$ and $\tau_0=(2.9\pm0.7)\times10^{-6}$ second for the proper lifetime of mesotrons, in excellent agreement with previous measurements by Rossi and Hall.

INTRODUCTION

THE spontaneous disintegration of cosmic-ray mesotrons in the atmosphere has been the subject of many recent investigations.[1–10] The quantity which is experimentally determined is the so-called *average range before decay*. If this quantity is designated by L, dz/L represents the fractional number of mesotrons which disintegrate while traveling the distance dz. L is related to the lifetime of mesotrons at rest, τ_0, by the equation

$$L=p\tau_0/\mu, \tag{1}$$

where μ is the rest mass and p the momentum of the mesotrons. Equation (1) follows immediately from the relativistic transformation formula for time intervals.

The dependence of L on p expressed by Eq. (1) implies that the interpretation of the experimental results is most direct and unambiguous when mesotrons belonging to a narrow momentum interval are recorded. Experiments on monoenergetic groups of mesotrons have been performed by Rossi and Hall,[8] by Nielsen, Ryerson, Nordheim, and Morgan,[10] and by Bernardini, Cacciapuoti, Pancini, Piccioni, and Wick.[9] Under the assumption that the mesotron mass is $\mu=10^8$ ev/c^2, the experiments of Rossi and Hall give $\tau_0=3.0\pm0.4$ microseconds. Rossi and Hall have also compared the average range before decay of a fairly monoenergetic mesotron group with that of all mesotrons with momenta extending from the upper limit of this group to

[1] B. Rossi, N. Hilberry, and J. B. Hoag, Phys. Rev. **56**, 837 (1939); and **57**, 461 (1940).
[2] W. M. Nielsen, C. M. Ryerson, L. W. Nordheim, and K. Z. Morgan, Phys. Rev. **57**, 158 (1940).
[3] M. A. Pomerantz, Phys. Rev. **57**, 3 (1940).
[4] M. Ageno, G. Bernardini, N. B. Cacciapuoti, B. Ferretti, and G. C. Wick, Phys. Rev. **57**, 945 (1940).
[5] H. V. Neher and H. G. Stever, Phys. Rev. **58**, 766 (1940).
[6] N. N. Das Gupta and P. C. Bhattacharya, Proc. Nat. Inst. Sci. Ind. **6**, 713 (1940).
[7] A. Ehmert, Zeits. f. Physik **115**, 333 (1940).
[8] B. Rossi and D. B. Hall, Phys. Rev. **59**, 223 (1941).
[9] G. Bernardini, B. N. Cacciapuoti, E. Pancini, O. Piccioni, and G. C. Wick, Phys. Rev. **60**, 910 (1941).
[10] W. M. Nielsen, C. M. Ryerson, L. W. Nordheim, and K. Z. Morgan, Phys. Rev. **59**, 547 (1941).

infinity. In this way they were able to prove that L is an increasing function of p, in qualitative agreement with Eq. (1). The measurements by Nielsen, Ryerson, Nordheim, and Morgan were, in principle, similar to those of Rossi and Hall. They gave, however, a much smaller value for τ_0, namely, $\tau_0=1.2\pm0.3$ microseconds. Bernardini, Cacciapuoti, Pancini, Piccioni, and Wick found, in various measurements, values of τ_0 ranging from 1.65 ± 0.3 to 3.4 ± 0.3 microseconds. Recently Rasetti has investigated the disintegration of mesotrons by measuring the delay between the stopping of mesotrons in an absorber and the emission from the absorber of decay electrons.[11] He found $\tau_0=1.5\pm0.3$ microseconds.

In view of the disagreement between the above results, further experiments on the disintegration of mesotrons seemed desirable. In the present experiments, the average ranges before decay of two widely separated and fairly monoenergetic groups of mesotrons were measured. The purpose was to obtain a new determination of τ_0 as well as a more quantitative check of the relation between L and p expressed by Eq. (1).

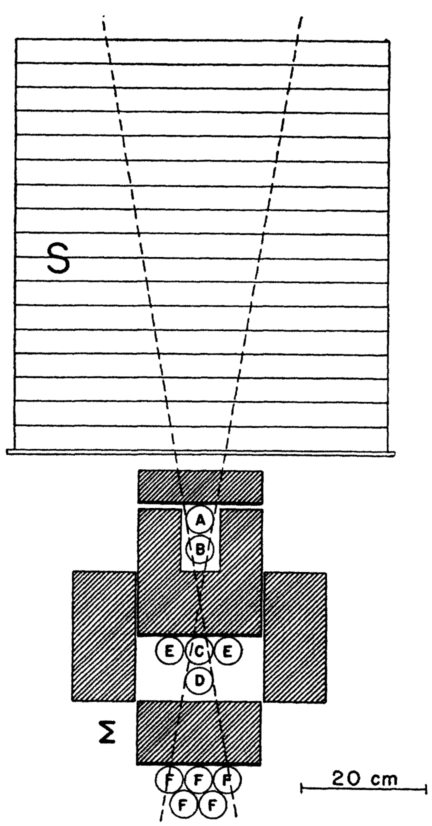

FIG. 1. Geometrical arrangement of counters and absorbers.

[11] F. Rasetti, Phys. Rev. **60**, 198 (1941).

EXPERIMENTAL METHOD

The experimental arrangement (see Fig. 1) was almost identical to the one used by Rossi and Hall.[8] The Geiger-Müller counters had an internal diameter of 4.24 cm. The length of the wire was 20 cm for counters A, B, C, D, and E, and 60 cm for counters F. The five counters F and the two counters E were all connected in parallel. The counter battery F covered completely the solid angle subtended by counters A, B, C, and D. Permanent lead absorbers were placed above counter A and between counter B and counter C. The total thickness of these permanent absorbers, including the material of the frame and the counter walls, was equivalent to 196 g/cm^2 of lead and was sufficient to stop the soft component of cosmic rays completely. Additional absorbers, S and Σ, could be placed above the apparatus and between counters D and F. The absorber S consisted of thick iron plates and was arranged so as to cover the whole solid angle subtended by counters A, B, C, and D. Its maximum thickness was 485 g/cm^2 and its total weight was about 5 tons. The absorber Σ consisted of 112 g/cm^2 of lead plus 2.4 g/cm^2 of steel and was thus equivalent to 115 g/cm^2 of lead.

By means of a coincidence-anticoincidence circuit, the two following phenomena were recorded: (1) simultaneous discharges of counters A, B, C, and D irrespective of discharges in counters E or F (coincidences [$ABCD$]), and (2) simultaneous discharges of counters A, B, C, and D not accompanied by a discharge either of counters E or of counters F (anticoincidences [$ABCD$–EF]). The anticoincidences [$ABCD$–EF] were caused by mesotrons stopped in the absorber Σ, apart from a small zero effect, which was determined by removing the absorber Σ. Thus the difference Δ between the number of anticoincidences per minute recorded with and without the absorber Σ was taken as a measure of the number of mesotrons capable of traversing 196 g/cm^2 of lead plus whatever iron absorber was present in S, and stopped by 115 additional g/cm^2 of lead.

TABLE I. Summary of the experimental results. [*ABCD*] and [*ABCD–EF*] are the number of fourfold coincidences and the number of anticoincidences per minute, respectively. Δ is the difference between the numbers of anticoincidences recorded with and without 115 g/cm² of lead in Σ.

Location	Exp.	Absorber g/cm² S	Absorber g/cm² Σ	Time (minutes)	[*ABCD*]	[*ABCD–EF*]	Δ
Denver $z=1616$ m $h=857$ g/cm²	*a*	0	0	1332	5.31±0.064	0.031±0.0049	0.290±0.0089
		0	115	5921	5.40±0.030	0.322±0.0074	
	b	285	0	1452	4.32±0.054	0.032±0.0047	0.218±0.0071
		285	115	8600	4.39±0.023	0.250±0.0054	
Echo Lake $z=3240$ m $h=708$ g/cm²	*c*	0	0	1382	7.71±0.080	0.071±0.0072	0.567±0.014
		0	115	4340	7.64±0.042	0.638±0.012	
	d	200	0	1804	6.23±0.059	0.058±0.0057	0.413±0.011
		200	115	4884	6.27±0.036	0.471±0.0098	
	e	342	0	2273	5.35±0.050	0.047±0.0045	0.310±0.011
		342	115	4540	5.42±0.034	0.357±0.0090	
	f	485	0	3051	4.85±0.040	0.042±0.0037	0.258±0.0073
		485	115	7571	4.73±0.025	0.300±0.0063	

TABLE II. Comparison between the present results and those of Rossi and Hall (reference 8). The lead absorbers have the same thickness in both experiments (196 g/cm² above counter *D* and 115 g/cm² between the counters *D* and *F*).

	Rossi and Hall	Present exp.
Δ/[*ABCD*] at Denver with $S=0$	0.0535±0.0015	0.0538±0.0015
Δ/[*ABCD*] at Echo Lake with $S=0$	0.074 ±0.005	0.0742±0.0019
Δ/[*ABCD*] at Echo Lake with $S=200$ g/cm² Fe	0.0663±0.0020	0.0659±0.0016
(Δ at Echo Lake with $S=200$ g/cm² Fe) / (Δ at Denver with $S=0$)	1.43 ±0.06	1.42 ±0.06

We refer the reader to the paper by Rossi and Hall for a critical discussion of the experimental method, in particular of the various phenomena which may be responsible for the zero effect. We wish to point out that in the present experiments we succeeded in reducing the zero effect to a smaller fraction of the counting rate than in the previous experiments of Rossi and Hall, thus decreasing the influence of a possible source of error. As in the experiments by Rossi and Hall, the counters *E*, together with the lead walls on both sides of the apparatus, were used to eliminate anticoincidences produced by air showers.

EXPERIMENTAL RESULTS

Measurements were taken at Denver (1616 m above sea level) with 0 and with 285 g/cm² of iron in *S*, and at Echo Lake (3240 m above sea level) with 0, 200, 342, and 485 g/cm² of iron in *S*. In both locations the apparatus was housed under a tent and the axes of the counters were set in the east-west direction. The results are summarized in Table I.

A significant check of the experimental accuracy is supplied by a comparison between some of our present results and those obtained by Rossi and Hall one year earlier under similar experimental conditions. This comparison is presented in Table II. The excellent agreement between all comparable data lends support to the assumption that the accuracy of the measurements is limited only by the statistical fluctuations.

DISCUSSION OF THE EXPERIMENTAL RESULTS

It is safe to assume that mesotrons lose energy by collision processes only, at least as long as their energy is of the order of 10^9 ev or less.

Under this assumption, a well-defined relation exists between momentum and range of mesotrons, and the quantities listed under Δ in Table I may be taken as a measure of the numbers of mesotrons belonging to definite momentum intervals.

In the evaluation of these momentum intervals, we have used the momentum-range relation calculated by Rossi and Greisen.[12] Following Halpern and Hall, we have applied a correction of 3 percent to the ranges in lead and a correction of 2 percent to the ranges in iron, to account for the density effect in the energy loss by collision (see reference 8, footnote 9). The experimental results, translated to a momentum scale, are represented graphically in Fig. 2.

The four rectangles (*c*), (*d*), (*e*), and (*f*) in Fig. 2 correspond to the four mesotron groups recorded at Echo Lake (measurements *c*, *d*, *e*, and *f* in Table I). The area of each rectangle is proportional to the number of mesotrons (Δ) in the corresponding group, while the base of the rectangle represents the momentum interval. The shaded areas above and below the top of each rectangle indicate the statistical errors of the measurements. Curve *s* represents what seems the most plausible differential momentum spectrum of mesotrons at Echo Lake. In other words, *s* is drawn so that the areas of the rectangles (*c*), (*d*), (*e*), and (*f*) are equal to the areas under the corresponding portions of the curve.

The rectangles (*a*) and (*b*) correspond to the mesotron groups observed at Denver. In plotting these data, the momentum losses between Echo Lake and Denver have been added to the momenta of the observed mesotrons. Thus all the abscissae in Fig. 2 refer to the momenta of mesotrons *at the altitude of Echo Lake.*

For each of the mesotron groups (*a*) and (*b*), the area of the rectangle gives the number of mesotrons at Denver, n_2, while the area under the corresponding portion of the curve *s* gives the number of mesotrons at Echo Lake, n_1. The two numbers should be equal if the mesotrons were stable. The fact that $n_2 < n_1$ is accounted for by the disintegration of mesotrons in the air layer between Echo Lake and Denver.‡ The ratio n_2/n_1 represents the *probability of survival* at the lower station for the mesotrons present at the upper one. This quantity is related to the average range before decay by the equation

$$\log (n_1/n_2) = (z_1 - z_2)/L, \quad (2)$$

where z_1 and z_2 are the elevations of Echo Lake and Denver, respectively. From the experimental data one calculates the following values of L for the two mesotron groups:

$$L_a = (4.26 \pm 0.46) \times 10^5 \text{ cm},$$
$$L_b = (8.5 \pm 1.9) \times 10^5 \text{ cm}.$$

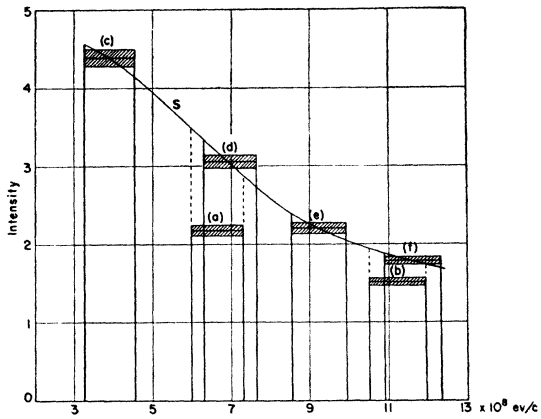

FIG. 2. Graphical representation of the experimental results. Abscissae are the momenta of the mesotrons at the altitude of Echo Lake. Rectangles (a) and (b) refer to measurements at Denver; rectangles (c), (d), (e), and (f) refer to measurements at Echo Lake. The area of each rectangle represents the number of mesotrons recorded in the corresponding momentum interval. Curve *s* represents the differential momentum spectrum of mesotrons at Echo Lake.

[12] B. Rossi and K. Greisen, Rev. Mod. Phys. **13**, 240 (1941).

‡ *Note added in the proof:* In this discussion, we have disregarded the possibility of an appreciable influence of mesotron production on our experimental results. It was thought that, even if mesotrons are produced in appreciable number in the air layer between Echo Lake and Denver, the effect on the lifetime measurements would be negligible because an approximately equal number of mesotrons should be produced in the compensating iron absorber. In the light of recent measurements by Regener (Bull. Am. Phys. Soc. **17**, No. 2, abstract No. 17) which show a comparatively large mesotron production at moderate altitudes and a strong dependence of mesotron production on atomic number, the above conclusion may be not completely justified. If more mesotrons are produced in one g/cm² of air than in one g/cm² of iron, as Regener's experiments indicate, the production of mesotrons partly cancels the effect of decay and the value of the lifetime deduced from our measurements is too large. How great the error may be cannot be estimated until more quantitative data about the mesotron production are available.

Since the mesotron momentum changes as the mesotrons travel in the atmosphere, the momentum p in Eq. (1) must be understood as a kind of average between the values of the momentum at the two elevations z_1 and z_2, where the measurements are made. This average is called the *effective momentum* and is defined by Eq. (5) in the paper by Rossi and Hall (see reference 8). According to this equation, the effective momenta in the mesotron groups (a) and (b) range from 4.52×10^8 to 5.86×10^8 ev/c and from 9.03×10^8 to 10.44×10^8 ev/c, respectively. As average effective momenta for the two groups we may take

$$p_a=5.15\times10^8 \text{ ev/c}, \quad \text{and} \quad p_b=9.72\times10^8 \text{ ev/c}.[13]$$

Comparison of the values of p with the values of L_a and L_b shows that, within the statistical errors, the *average ranges before decay are proportional to the effective momenta*, in agreement with Eq. (1). This equation then yields:

from the measurements on group (a),

$$\tau_0/\mu=(8.3\pm0.9)\times10^{-4} \text{ cm c/ev}$$

from the measurements on group (b),

$$\tau_0/\mu=(8.8\pm2.0)\times10^{-4} \text{ cm c/ev}.$$

If one takes $\mu=10^8$ ev/c^2, the corresponding values of τ_0 are, respectively,

(a) $\tau_0=(8.3\pm0.9)\times10^4$ cm/c, or $\tau_0=(2.8\pm0.3)\times10^{-6}$ sec.

(b) $\tau_0=(8.8\pm2.0)\times10^4$ cm/c, or $\tau_0=(2.9\pm0.7)\times10^{-6}$ sec.

The above results are in excellent agreement with those of Rossi and Hall (reference 8). As a matter of fact, the agreement is even better than it appears, because the difference between the value obtained by Rossi and Hall ($\tau_0=3.0\times10^{-6}$ sec.) and our present value for group (a) ($\tau_0=2.8\times10^{-6}$ sec.) arises entirely from the more accurate method of calculation which we have used.

It is possible to obtain from our measurements a third independent evaluation of the lifetime. The difference between the number of coincidences per minute recorded at Echo Lake with 200 and with 485 g/cm^2 of iron in S gives the number of mesotrons with momenta between 6.30×10^8 and 10.89×10^8 ev/c at z_1. Since 200 g/cm^2 of iron are approximately equivalent to the air layer between Echo Lake and Denver, the difference between the number of coincidences recorded at Denver with 0 and with 285 g/cm^2 of iron gives the number of mesotrons in the same group at z_2. From the ratio between the two differences, one obtains $L=(4.2\pm0.46)\times10^5$ cm. The average effective momentum of the group under consideration may be taken as equal to 6.3×10^8 ev/c. Accordingly, one obtains for the lifetime the value

$$\tau_0=(2.2\pm0.24)\times10^{-6} \text{ sec.}$$

The difference between this value of τ_0 and the values obtained by the anticoincidence method may be accounted for by statistical fluctuations. It is possible, however, that the third determination is subject to errors other than purely statistical. In fact, the data used in the third determination are small differences between large counting rates measured independently. Any fluctuation in the cosmic-ray intensity is bound to affect these data to a much larger extent than the data obtained by the anticoincidence method, in which the significant differences are recorded directly.

For this reason we believe that only the results obtained with the anticoincidence method should be considered in evaluating the most probable value of the lifetime τ_0. By combining our data with those of Rossi and Hall, re-evaluated by our present method, one then obtains

$$\tau_0=(2.8\pm0.2)\times10^{-6} \text{ sec.} \qquad (\text{with } \mu=10^8 \text{ ev/c}^2).$$

[13] Since the observed effects are proportional to $1/p$, as average momentum we have taken the reciprocal of $(1/p)_{Av}$.