Low-Energy Differential Range Spectrum of Cosmic-Ray μ Mesons*†

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The differential range spectrum of cosmic-ray μ mesons was investigated in the region from 0 to 410 g/cm^2 Pb for evidence of minima. Delayed coincidences in a tank of liquid scintillator were used to identify stopping mesons. The spectrum decreases monotonically with decreasing energy and shows no irregularity. Although only relative readings were taken, the method is adaptable to a precision determination of the *absolute* range spectrum. The delay data yield for the natural mixture of sea level cosmic-ray μ mesons a mean life in carbon of 2.13 ± 0.07 μsec.

I. INTRODUCTION

SEVERAL investigators have reported a minimum in the low-energy spectrum of cosmic-ray μ mesons. Rogozinski and Lesage[1] found a pronounced minimum under approximately 25 cm of lead (corresponding to a meson momentum of about 450 Mev/c). On the other hand, Kellermann and Westerman[2] found a marked minimum under 10 cm of lead. Since these investigators used anticoincidence methods, they attributed the anomalous rise at low momenta principally to cosmic-ray protons (and to a small residual electronic component arising from the inefficiency of their methods for eliminating electrons). Some experiments done in this laboratory[3] by means of a GM counter delayed-coincidence technique had indicated that there might be some irregularity in the meson spectrum itself in this energy region. Inasmuch as there was available an experimental arrangement which included a liquid scintillator tank of appreciable volume (3 liters), we were presented with the opportunity for a quick independent check of the spectrum of cosmic-ray μ mesons.

II. APPARATUS

The geometry of the experiment is shown in Fig. 1. The apparatus consists of two particle detectors, a GM counter tray "A" (30 cm×50 cm) and a 3-liter tank of liquid scintillator "B" (15 cm diameter×20 cm deep containing 5 g/liter terphenyl in toluene), with variable thickness of absorber between the two. Delayed coincidences $AB+B$ (delayed 0.5 to 8.0 μsec), i.e., events in which a coincidence AB is followed by a second pulse in the tank B with a delay of 0.5 μsec to 8.0 μsec, are used to identify μ mesons stopping in the tank. For each such event the delay between B and B (delayed) was recorded by a 4-channel delay discriminator.

III. METHOD

The following counting rates were recorded:

(a) B, the counting rate of the tank.

(b) AB, the twofold coincidence rate. This is essentially the integral cosmic-ray flux through the tank within the solid angle defined by the GM counters.

(c) $AB+B$ (delayed):

1. $AB+B$ (delayed 0.5 to 2.5 μsec),
2. $AB+B$ (delayed 2.5 to 4.4 μsec),
3. $AB+B$ (delayed 4.4 to 6.3 μsec),
4. $AB+B$ (delayed 6.3 to 8.0 μsec).

The B rate served as a continuous check on the operation of the tank and varied from ~7.7 to 6.7 counts/second depending on the absorber in the telescope.

The AB rate served as a monitor of the meson flux and to some extent as an indicator of the tank sensitivity. The AB rate varied from ~1250 to 800 counts/hr, depending on the absorber thickness. The calculated meson flux through the tank is approximately 1000/hr. For small thicknesses of absorber, a portion of the soft component will contribute to the AB rate and this accounts for the significant difference between the highest AB rate and the meson flux. The accidental rate, both as computed and as measured, is insignificant. Since the measurements required a period of several weeks, the AB data were used to normalize the stopped meson rate. This served to eliminate the effects of variations of cosmic-ray intensity and to some extent variations in detector efficiencies.[4]

IV. CORRECTIONS

There is a small correction for random or accidental AB events (about 20/hr) and for accidental $AB+B$ (delayed) events [of the order of 0.01 (counts/hour) per channel]. The correction applied is a computed one; however, the accuracy of this procedure has been checked by two methods:

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† A previous report has been given: A. Fafarman and M. H. Shamos, Phys. Rev. **95**, 648(A) (1954).

[1] A. Rogozinski and M. Lesage, *Cosmic Radiation* (Interscience Publishers, Inc., New York, 1949), p. 63

[2] E. W. Kellermann and K. Westerman, Proc. Phys. Soc. (London) **62**, 356 (1949).

[3] C. L. Eisen, Master of Science thesis, New York University, September, 1952 (unpublished).

[4] The AB data were used to normalize the stopped meson rate in two ways: (a) by comparison with the average AB rate for all runs under a given absorber thickness; (b) by comparison with the AB rate under a given absorber thickness as determined from a separate plot of the AB rate *vs* absorber thickness taken over a short period (i.e., within an 8-hour interval).

(a) Use of artificial pulses in the A or B channels,

(b) Use of a radium source to increase the counting rate in the B channel.

Periodic checks were made of counting rates, waveforms, and critical voltages of the equipment. However, it is probable that there were some small changes in the sensitivity for $AB+B$ (delayed) events over the course of the experiment, since with the poor light collection of a single 5819 in the large tank of scintillator we were working with pulse heights where the efficiency for detecting some of the beta particles from μ-meson decay showed considerable variation with the bias. Unfortunately, the twofold coincidence AB rate shows considerably less dependence on this change of sensitivity (because of the much greater energy loss of a meson passing essentially vertically through the tank) and cannot be used to give an indication of these changes of sensitivity; also the independent variations of the AB rate caused by ordinary barometric fluctuations in cosmic-ray intensity make it difficult to apply this correction to the tank sensitivity. One might expect that the B counting rate (tank rate) could be used as an independent check on tank sensitivity. However, this would have required a knowledge of the relation between the beta sensitivity and the counting rate of the tank—a relation for which only a very rough approximation could be obtained. Hence no further correction beyond the normalization of the $AB+B$ (delayed) to the AB was applied. The essential constancy of the B rate, together with the substantial agreement within the statistical errors of the results obtained at various times for a particular absorber thickness, indicate the adequacy of this correction.

A serious source of error in this type of experiment exists in the possible contribution to the delayed counting rate by afterpulsing of the photomultiplier. It was found with several 5819 photomultipliers that a contribution to the delayed coincidence rate (particularly in the first channel of the delay discriminator) occurred in going to sufficiently small pulse heights. A convenient method for checking the presence of afterpulsing in our apparatus was to increase the accidental rate of $B+B$ (delayed) events by using a 1-mC radium source to cause a considerable increase in the counting rate (and hence the accidental rate) of the tank. The presence of afterpulsing was evidenced

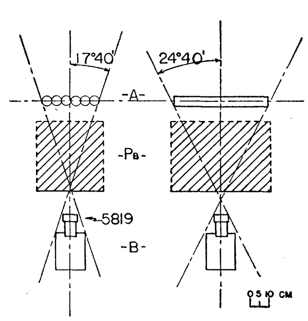

FIG. 1. Experimental arrangement for μ-meson range spectrum. A is a tray of GM counters 30 cm×50 cm, and B is a tank of liquid scintillator 15 cm in diameter and 20 cm deep.

TABLE I. Observed stopped-meson data and delay distribution.

Absorber	Hours	AB	$AB+B$(delayed) 1	2	3	4
0	86.6	10.98×10^4	89	30	19	8
55 g/cm² Fe	99.6	10.73×10^4	127	57	26	8
55 g/cm² Fe+115 g/cm² Pb	317.1	33.40×10^4	483	197	97	26
55 g/cm² Fe+230 g/cm² Pb	419.9	40.98×10^4	590	271	116	37
55 g/cm² Fe+345 g/cm² Pb	348.0	29.88×10^4	532	192	78	38

TABLE II. Calculated stopped-meson rates.

Range g/cm² (air equiv.)	Momentum Mev/c	$AB+B$ (delayed) rate minus random rate (counts/hr) (a) Observed	(b) Corrected by concurrent AB rate	(c) Corrected by short dur. AB rate	(d) Column (c) plus est. Scattering correction
11.1±8.7	112^{-42}_{+28}	1.64±0.14	1.63±0.14	1.78±0.16	1.78±0.16
48±9	212±20	2.14±0.15	2.12±0.15	2.28±0.17	2.28±0.17
127±9	368±17	2.48±0.09	2.48±0.09	2.37±0.10	2.39±0.10
204±9	525±17	2.37±0.07	2.37±0.07	2.36±0.09	2.41±0.09
277±9	670±17	2.36±0.08	2.37±0.08	2.53±0.10	2.65±0.10

by a significant departure from equality of the rates in the four channels of the delay discriminator, in particular a high count in the first channel.

For the 5819 with voltage and bias settings used in obtaining the results given in Sec. V, no evidence of afterpulsing was observed either visually on the oscilloscope or by the above mentioned method—nor was any observed at bias settings giving considerably higher B rates. However, even for this tube, it was possible, by increasing sufficiently the voltage across the tube to obtain a contribution from afterpulsing.[5]

An additional indication that there was no significant contribution from afterpulsing is the mean life obtained for the μ mesons (2.13±0.07 μsec) from the delay discriminator data.

The 4-channel delay discriminator was essentially the unit described by Morewitz and Shamos[6] and was calibrated by means of artificial pulses from a delay line-controlled double-pulse generator. The delay between the pulses was continuously variable by the insertion of a small variable delay line[7] between the fixed delay line steps.

V. RESULTS

The observed data for AB and $AB+B$ (delayed) events are collected and shown in Table I.

In Table II are listed the computed stopped-meson

[5] It should be noted that the noise pulses from the tube are considerably fewer when the tank is at the potential of the photocathode of the 5819. We have observed this effect in almost all photomultipliers. It seems reasonable that these additional noise pulses arise from positive ion bombardment of the photocathode. Whenever light collection is a problem and pulse measurements must be carried down into the noise region, it is advisable to use a shield at the potential of the photocathode. Despite the presence of a metallic coating at cathode potential inside the glass envelope of the 5819, the shield effect was present in our tank.

[6] H. A. Morewitz and M. H. Shamos, Phys. Rev. 92, 135 (1953).

[7] Advance Electronics Company, Model 302.

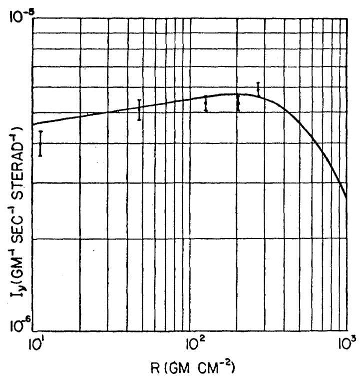

FIG. 2. Differential range spectrum of cosmic-ray μ mesons at sea level. The abscissa is the range in g cm^{-2} (air equivalent). The experimental points have been normalized to the spectrum given by Rossi (see reference 13) (smooth curve).

rates. The conversion from absorber thickness (of Table I) to equivalent range in air[8] was made with the aid of the following information:

(a) 2.4 g/cm^2 (air equivalent) minimum absorbing material (roof, framework, etc. above tank).

(b) Because of scattering, the range in Pb is 11 percent greater than the thickness traversed.[9]

(c) The thickness of the liquid scintillator was 17.4 g/cm^2 air equivalent.

The conversion from range to meson momenta was made by using the Gross range-momentum curves[10] for air with momenta increased by 5 percent to correct for the meson mass ($210m_e$ instead of $200m_e$).

The remaining columns of Table II give the stopped-meson rate, corrected for a small random rate of 0.05/hr, and further corrected as follows:[4]

(*a*) Observed $AB+B$ (delayed) rate events/hr,

(*b*) $AB+B$ (delayed) rate corrected by the concurrent AB rates,

(*c*) $AB+B$ (delayed) rate corrected by using an AB rate curve taken over a comparatively short time interval ~8 hr. The standard error has been increased to take account of the statistics of the short duration AB curve,

(*d*) Results in Column (*c*) plus an estimated scattering correction.

Inasmuch as the scattering correction for this arrangement is small, the correction was estimated from the "second correction" of Germain,[11] multiplied by a factor $(2\pi)^{\frac{1}{2}}$ as suggested by York.[12] As a rough check on Germain's calculations, an approximate calculation was made to determine an upper limit of the scattering loss for our apparatus. The result was 8 percent for the maximum absorber thickness as compared to 5 percent from Germain's calculation; the latter were used in obtaining the last column (*d*) of the $AB+B$ (delayed) rates.

It is seen that the difference is insignificant between columns (*a*) and (*b*) and substantially within the error limits for columns (*a*) and (*b*), (*c*), or (*d*). The insignificant difference between columns (*a*) and (*b*) indicates that the ratio $AB+B$ (delayed)$/AB$ was a constant for a given absorber thickness. Since, as indicated in the foregoing, the tank detects essentially all μ mesons, whereas only a fraction of the decay betas are detected, the constancy of this ratio is at least a first order check of the tank stability. In addition, this constancy points to the absence of afterpulsing.

The differential range spectrum obtained from the column (*d*) $AB+B$ (delayed) rates of Table II has been fitted to the curve given by Rossi[13] and is plotted in Fig. 2. The values used for Fig. 2 have also been used to obtain a plot of the differential momentum spectrum.[14] The corresponding ordinates are plotted in Fig. 3, together with the momentum spectrum given by Rossi. The agreement in Fig. 2 is fairly good with the possible exception of the lowest point. Because of the excessive ratio of the thickness of the tank to the mean range (i.e., range corresponding to the center of the tank) for this lowest point, one might expect some disagreement. Furthermore it must be noted that the normalization procedure compares ordinates at the higher values of absorber where the spectrum is flat with values at little or no absorber where the spectrum is decreasing rapidly. Despite these considerations, a graphical analysis shows that the lowest point (11.1 g/cm^2) is plotted correctly, provided that the range spectrum is linear throughout the region 11.1±8.7 g/cm^2: a reasonable estimate of the nonlinearity correction for the mean range of the lowest point is

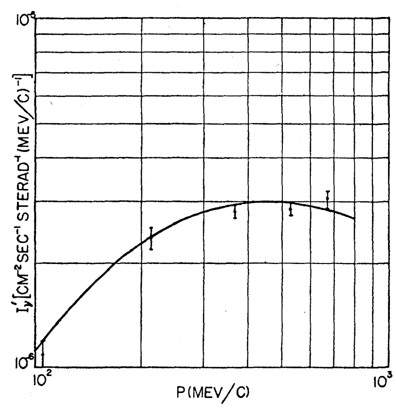

FIG. 3. Differential momentum spectrum of cosmic-ray μ mesons at sea level. The experimental points plotted in Fig. 2 have been transformed with the range-momentum relations and are shown together with the spectrum given by Rossi (see reference 14) (smooth curve).

[8] The conversion was made by using the Gross range-energy tables for Pb and air. [E. P. Gross, *Range, Energy, Ionization Curves* (Princeton University Press, Princeton, New Jersey, 1947)].
[9] H. P. Koenig, Phys. Rev. **69**, 590 (1946).
[10] See E. P. Gross, reference 8.
[11] L. Germain, Phys. Rev. **80**, 618 (1950).
[12] C. M. York, Phys. Rev. **85**, 1002 (1952).
[13] See Fig. 6, B. Rossi, Revs. Modern Phys. **20**, 543 (1948).
[14] See reference 13, Fig. 24 and Fig. 4.

-3 percent. Hence, it does not appear possible to bring this point into good agreement with the curve.

The possibility that there might be a distortion of the counting rates because of afterpulsing or because of high random background is rendered unlikely by the fact that the delay rates in channels 2 to 4 show the same variation.

The lifetime data for the cosmic-ray μ mesons are shown in Fig. 4, in which are plotted the counting rates in each channel (corrected for random counts) as a function of the delay of the channel. One of these curves represents the delay distribution of a separate run of $B+B$ (delayed) events; the other is compiled from the delay distribution of $AB+B$ (delayed) events obtained in the range spectrum runs. The lifetimes, computed by the method of Peierls[15] are 2.13±0.07 μsec and 2.18±0.07 μsec. The errors are standard errors and do not include an estimate of systematic errors. Somewhat more reliance is placed on the first (lower) value since GM counters were not used in this measurement. The former value is also in good agreement with that of Bell and Hincks[16] 2.12±0.02 and with the value 2.10±0.02 obtained by Harrison, Cowan, and Reines[17] in a 12-hour run with their 300-liter scintillation tank.

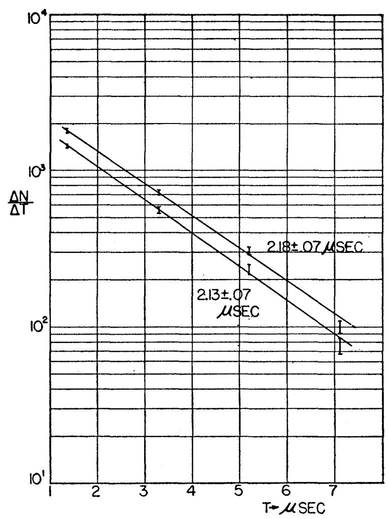

FIG. 4. Delay distribution of $B+B$ (delayed) events (lower curve) and $AB+B$ (delayed) events (upper curve) in the 4-channel delay discriminator.

VI. DISCUSSION

The results of this experiment are essentially similar to those of Sands,[18] who used a delayed coincidence technique. In general it appears that all the differential range methods in which fairly good identification of mesons is possible give results somewhat higher than those obtained by magnetic measurements in cloud chambers.

The earlier delayed-coincidence technique suffered from the disadvantage that only relative results were obtainable. However, the present method should permit a determination of the absolute intensity of mesons, particularly in the region below 300 Mev/c where the scattering correction can be kept quite small. It should be noted that this conclusion has been arrived at independently by at least one cloud-chamber investigator,[19] who has studied this portion of the cosmic-ray spectrum. Aside from its phenomenological importance, the *absolute* low-energy meson spectrum is significant in analyzing cloud chamber and differential absorption data for protons in the cosmic radiation. Although in this experiment only relative readings were taken, the method is readily adaptable to a precision determination of the absolute differential range spectrum of low-energy mesons, a region of the spectrum where some uncertainty[12,19] exists. In performing such an experiment, one can use a large plastic or liquid scintillator with (or without) a direction-defining telescope.[20]

VII. ACKNOWLEDGMENT

We wish to thank Dr. H. A. Morewitz for his assistance in the initial stages of the experiment.

[15] R. Peierls, Proc. Roy. Soc. (London) **A149**, 473 (1935).
[16] W. E. Bell and E. P. Hincks, Phys. Rev. **88**, 1424 (1952).
[17] Harrison, Cowan, and Reines, Nucleonics **12**, 44 (1954).
[18] M. Sands, unpublished data cited by Rossi.
[19] P. G. Lichtenstein, Phys. Rev. **93**, 858 (1954).
[20] Shortly before submission of this paper, a report of essentially this experiment has come to our attention. N. T. Seaton Bull. Am. Phys. Soc. **29**, No. 6, 18 (1954).