Absolute Intensity of Low-Energy Cosmic-Ray μ Mesons*†

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A cylindrical plastic scintillator weighing one kilogram has been used as both the absorber and the detector for the stopping of (omnidirectional) low-energy cosmic-ray μ mesons. Simultaneous delayed coincidences in each of two photomultipliers that view the scintillator serve to identify the decays of stopped mesons. A correction is made for mesons that decay outside the recorded delay intervals. A further correction is made for edge effects (decay beta particles which escape from the scintillator with insufficient energy loss to actuate the detector). The number of stopping mesons of average range 7 g/cm^2 (air equivalent) is $7.29\pm0.21\times10^{-6}$ sec^{-1} g^{-1}. Assuming a $\cos^3\theta$ distribution yields for the vertical intensity $4.64\pm0.13\times10^{-6}$ g^{-1} sec^{-1} sterad^{-1}.

INTRODUCTION

THE low-energy spectrum of cosmic-ray μ mesons has been examined thoroughly by several cloud-chamber investigators[1] in an attempt to separate the contributions of the mesons, electrons, and protons to the soft component. Cloud-chamber methods based on the simultaneous determination of the momentum and ionization of the particle are unsuitable at the lowest energies because of the magnetic field bias against low-energy particles. Moreover, even those methods in which the distinction between the particles is based on ionization and residual range become increasingly uncertain as the energy decreases. Thus the intensity of cosmic-ray μ mesons with residual ranges less than 50 g/cm^2 is indefinite by more than 20% because of the difficulty in identifying the electron component. Fortunately, an unambiguous measurement of the absolute intensity of low-energy μ mesons can be made by using a large scintillator as the meson absorber and identifying the stopped mesons by the method of delayed coincidences.[2]

METHOD

A large cylinder of plastic scintillator was used. The cylinder was 10.7 cm in diameter and 10.7 cm long, and weighed 992 grams. Its chemical formula[3] was essentially C_9H_{10} and its diametral range was, therefore, 12 g/cm^2 (air equivalent).

As is shown in Fig. 1, each of the two flat faces of the cylinder was viewed by a 5-inch type-6364 photomultiplier. The outputs were fed through distributed amplifiers to a coincidence amplifier that produced output pulses only if both photomultipliers furnished signals simultaneously. This minimized the effects of photomultiplier noise pulses, afterpulsing, and other spurious effects. The output of the coincidence amplifier, therefore, provided essentially a record only of the scintillations in the plastic. This output was then examined for delayed coincidences. The delayed coincidences were then sorted by time delay in a four-channel delay discriminator.[4]

Figure 2 is a schematic of the coincidence amplifier and gated coincidence portions of the circuit. The

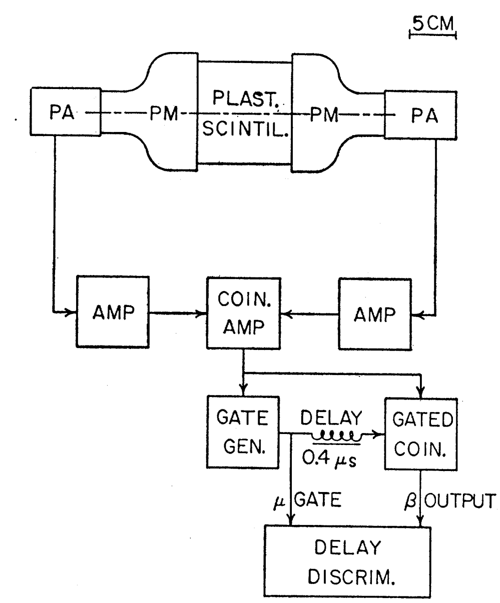

FIG. 1. Apparatus for measurement of μ-meson intensity. Two five-inch photomultipliers view a cylinder of plastic scintillator. The two channels are fed via preamplifiers and distributed amplifiers to a coincidence amplifier. A coincidence in the two channels generates the μ-gate pulse. A second coincidence in the two channels having a delay of 0.4 to about 10 μsec generates the β-output pulse. The events are sorted in a four-channel time-delay discriminator. Mu metal and light shields (not shown) are placed around photomultipliers and plastic.

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[1] See, e.g., P. G. Lichtenstein, Phys. Rev. **93**, 858 (1954); C. M. York, Phys. Rev. **85**, 998 (1952); B. Rossi, Revs. Modern Phys. **20**, 537 (1948).

[2] A. Fafarman and M. H. Shamos, Phys. Rev. **96**, 1096 (1954).

[3] This scintillator was furnished through the courtesy of the National Radiac Company (their Sintilon brand); its composition was polyvinyl toluene plus small amounts of tetraphenyl butadiene and other additives.

[4] Since extreme accuracy in timing was not essential for this experiment, the secondary pulses (μ gate and β pulse—see Fig. 1) were used in the interests of simplicity, rather than a more involved gating scheme using the original distributed amplifier outputs.

6BN6 gated beam tube proved quite useful as the coincidence amplifier.[5] Each coincidence output of the 6BN6 tube was amplified (and inverted) and generated a μ gate. A second coincidence occurring with a delay of from 0.4 μsec to 10 μsec was able to pass through another 6BN6 (gated coincidence circuit) and generate the β-output pulse. The switch S_1 is used to remove the bias from one of the grids of the 6BN6 gated coincidence circuit when the β_{12} rate is to be monitored (during equipment checks).

EXPERIMENTAL RESULTS

The μ_{12} rate was monitored continuously; this twofold coincidence rate was about 194 per minute (for events greater than 2.0 Mev). Periodic checks of the counting rate in the delayed coincidence channel (β_{12} rate) were made; this twofold coincidence rate was about 680 per minute (for events greater than 750 kev).

TABLE I. Time distribution of delayed coincidences.

	Hours	Channel[a]	Delayed coincidences (corrected for accidentals) 1	2	3	4
	17.9		186	75	29	21
	20.7		225	81	37	14
	20.6		212	103	34	18
	23.2		256	91	39	20
Totals	82.4		879	349	139	73
		Average = (17.5 ± 0.5)/hr				

[a] Channel boundaries: (1) 0.49–2.21 μsec; (2) 2.22–3.95 μsec; (3) 3.97–5.83 μsec; (4) 5.84–7.74 μsec.

For the selected runs, the maximum observed variation of the μ_{12}-energy bias was 0.1 Mev, and that of the β_{12}-energy bias was 60 kev.

The following delayed coincidence rate data were noted: (a) sum of observed rates in Channels 1, 2, 3, and 4; (b) observed rates corrected for accidental rate; (c) observed total minus four times the rate in Channel 4. This result (c) is to be interpreted as the number of delayed coincidences in Channels 1, 2, and 3, minus three times the number of delayed coincidences in Channel 4, and includes no accidental events. This procedure corresponds to using Channel 4 as an experimental recorder of random accidentals.

Data from runs in which the β_{12} bias was less than 700 kev were not utilized, since below this bias it was possible for a delayed coincidence in only one of the photomultipliers to be registered.

The delayed coincidence results are:

(a) Total channels 1–4, (18.4 ± 0.3)/hr.

(b) Total minus computed accidentals, (17.5 ± 0.2)/hr.

(c) Total minus $4\times$(channel 4 rate), (13.8 ± 0.6)/hr.

[5] Another double delayed coincidence scheme utilizing crystal diodes was tested and proved unsatisfactory.

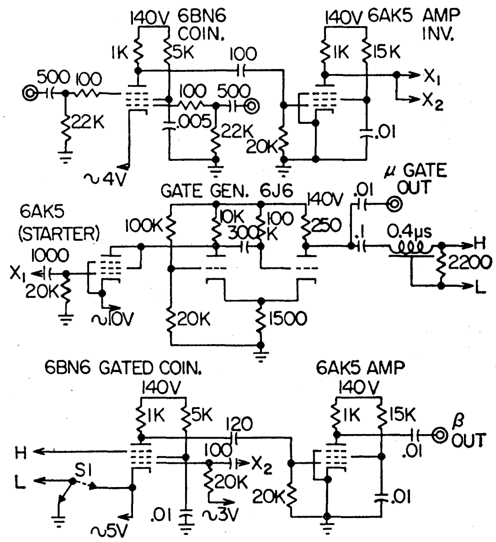

FIG. 2. Schematic diagram of coincidence amplifier and gating circuits. Simultaneous delayed coincidences in Channels 1 and 2 result in the generation of a μ-gate pulse and a delayed β-output pulse. Events are sorted by time delay between the leading edges of these pulses in a four-channel delay discriminator (not shown).

The distribution of events in the delay channels is shown in Table I. The total rate (corrected for accidentals) is (17.5 ± 0.5)/hr[6]; the (integral) delay distribution is shown in Fig. 3 and is closest to a 2.07-μsec mean life.

CORRECTIONS

In order to determine the absolute rate of mesons stopping in the absorber, two additional corrections must be applied to the data.

(a) Mesons decaying outside the delay intervals accepted by Channels 1–4. By using the measured channel edges (Table I), and a mean life of 2.07 μsec, it is calculated that only 76% of the decays are recorded by the 4 channels.

(b) Correction for edge effects. This correction must be made for mesons which stop near the surface of the cylinder and the decay beta particles of which lose less than 750 kev in escaping from the scintillator. This is equivalent to reducing the effective volume of the scintillator.

In the spectrum of decay beta particles, only about one percent have energies below 10 Mev.[7] The most probable (collision) energy loss, $\Delta_{\text{p.c.}}$, for electrons included in this spectrum is given closely by the relation[8]

$$\Delta_{\text{p.c.}}(\text{Mev})=0.1537D(\sum Z/\sum A)\{19.43+\ln(D/\rho)\},$$

[6] The error limit here is the standard error based on the number of events, whereas that used in the paragraph above is the average deviation of the individual runs from the mean. The alternative calculation based on the use of Channel 4 as an experimental recorder of random accidentals yielded a value of (17.1 ± 0.7)/hr. This value is in agreement within the statistical error with the above value of (17.5 ± 0.2)/hr. The value (17.5 ± 0.5)/hr was used.

[7] H. Bramson and W. W. Havens, Phys. Rev. **83**, 861 (1951).

[8] Goldwasser, Mills, and Hansen, Phys. Rev. **88**, 1137 (1955).

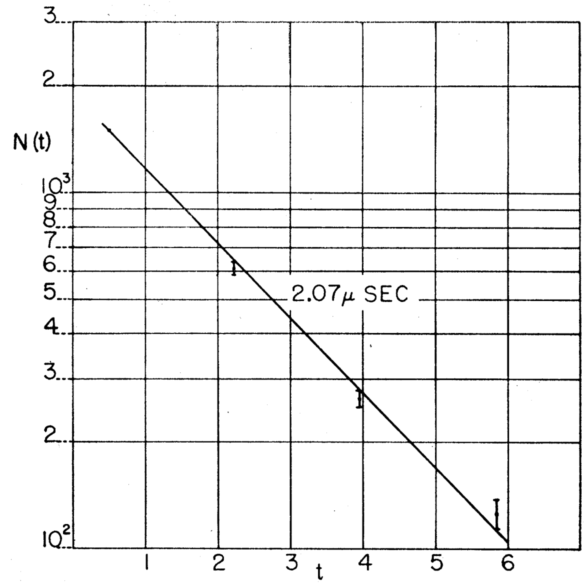

FIG. 3. Integral delay distribution of μ_{12}–β_{12}-time delays. The points are obtained from Table I and include a correction for mesons that decay beyond 7.74 μsec.

where the absorber thickness is D g/cm^2 and its density ρ g/cm^3. Solving for the D corresponding to $\Delta_{\text{p.c.}}=0.75$ Mev, gives $D=0.485$ g/cm^2 or 0.47 cm.

Hence, within a layer extending 0.47 cm in from the surface of the cylinder, only $\frac{3}{4}$ of the decay beta particles will have path lengths greater than 0.47 cm (and lose more than 750 kev) in the scintillator.[9]

The effective volume is then decreased by δV corresponding to the fractional decrease in linear dimensions $(\delta a/a)$

$$-\delta V/V=(\tfrac{1}{4})3(\delta a/a)=0.066.$$

A similar, much smaller correction can be made for mesons that stop in the surface layer of the scintillator (losing less than 2 Mev), and gives $-\delta V/V=0.007$.

The above correction for the edge effect is based on energy calibrations which correspond to the peak of the pulse height distribution. It is estimated from the pulse-height resolution of the detectors that this correction should be increased by 60% (30% for each photomultiplier).

CORRECTED RESULT AND DISCUSSION

The application of these corrections to the observed rate of 17.5 per hour yields for the number of stopping

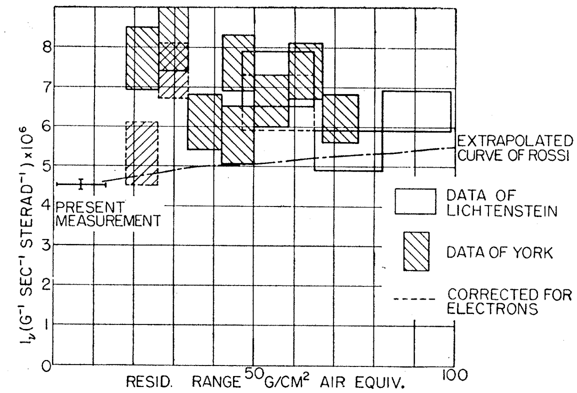

FIG. 4. Range spectrum of low-energy cosmic-ray μ mesons. The ordinate is the vertical intensity I_ν(g^{-1} sec^{-1} sterad^{-1}); the abscissa is the residual range in g/cm^2 (air equivalent). The graph shows the relation of the present measurement to the results of cloud-chamber investigations (reference 1). The clear blocks are measurements of Lichtenstein, the cross-hatched blocks are those of York, and the dashed lines are their results corrected for the electron component. The present measurement lies below the cloud-chamber results but appears to be in good agreement with the curve given by Rossi.

mesons of average range 7 g/cm^2 (air equivalent)[10]:

$$I=(7.29\pm0.21)\times10^{-6}\text{sec}^{-1}\,\text{g}^{-1}.$$

Assuming a $\cos^3\theta$ distribution[11] with zenith angle, one obtains for the vertical directional intensity corresponding to the above value:

$$I(0)=(2/\pi)I=(4.64\pm0.13)\times10^{-6}\text{g}^{-1}\,\text{sec}^{-1}\,\text{sterad}^{-1}.$$

This value appears to fall below the extrapolation of cloud-chamber measurements, even when a stringent elimination of electrons is made.[1] A comparable result for mesons stopping in a polystyrene absorber has been given.[12]

The major uncertainty in the present measurement is the correction for the edge effect.[13] The uncertainty in the correction is somewhat greater than the statistical standard error; however, the corrected result includes only the standard error.[6]

No estimate is made of other errors (e.g., use of $\cos^3\theta$ distribution and fluctuations of cosmic-ray intensity).

The relation of this measurement to the cloud-chamber measurements is shown in Fig. 4. As anticipated by Lichtenstein, cloud-chamber measurements of low-energy mesons seem to give a value at least 10% higher than that given on the basis of Rossi's extrapolated curve (which appears quite accurate from the

[9] The fraction of decay beta particles in this lamina which have path lengths less than D in the scintillator (and escape detection) is $\frac{1}{4}$. This is shown readily by using a cylindrical geometry. The fraction escaping is

$$\left(\frac{1}{D}\right)\left(\frac{1}{4\pi}\right)\int_0^D 2\pi(1-\cos\theta_m)dz;\ \cos\theta_m\equiv\frac{z}{D}.$$

[10] ~1 g/cm^2 (air equivalent) minimum absorber above scintillator (roof and light shield). Diametral thickness of scintillator was 12 g/cm^2 (air equivalent).

[11] J. Zar, Phys. Rev. **83**, 761 (1951).

[12] J. Steinberger, Phys. Rev. **75**, 1136 (1949). However, the values quoted are for mesons of average range 100 g/cm^2.

[13] This correction would appear to be relatively less important if the experiment had been performed with a larger scintillator. However, in that case one has the increased difficulty of adequate light collection in the larger scintillator.

results of the present experiment). Combining this result with the relative measurements published previously[2] seems to indicate that the cloud-chamber results are higher than the delayed coincidence measurements. More exact determination of the reason for this difference is difficult because of the uncertainty in zenith angle distribution (as well as the variation in scattering among the different experiments). Moreover, the cloud-chamber results may still contain some small contributions from other particles such as electrons and π^- mesons, whereas the present experiment records only the $\mu^\pm$ and π^+ mesons which stop in the absorber.

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Comparison of Spin-Flip Dispersion Relations with Pion-Nucleon Scattering Data*

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The dispersion relations for the spin-flip, forward-scattering amplitude have been tested against pion-nucleon scattering data for energies up to 300 Mev. The Fermi set of phase shifts satisfy these relations while the Yang set do not. An approximate value for the renormalized coupling constant, $f^2=(g\mu/2M)^2$, of 0.1 is obtained from the P-wave phase shifts.

1. INTRODUCTION

THERE are four noninterfering scattering amplitudes for pion-nucleon scattering, corresponding to the independent possibilities of flipping the spin or isotopic spin of the nucleon. The squared magnitude of each gives its contribution to the differential cross section. Independent dispersion relations have been derived[1] for each of these amplitudes, which relate their real part to integrals over energy of their imaginary part.

We will consider here only the amplitude for spin flip, and examine the phase shift interpolations made by Anderson and Metropolis[2] in the light of these dispersion relations. We are thus imposing some new constraints on the phase shift determination problem. Since we are discussing the spin-flip amplitudes, we are in effect performing a theoretical polarization experiment and will in fact be able to differentiate between the Fermi and Yang phase shifts.

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[1] This work has been done by several people. See, for example, M. L. Goldberger, *Sixth Annual Rochester Conference on High-Energy Physics, 1956* (Interscience Publishers, Inc., New York, to be published); M. L. Goldberger, Midwest Conference on Theoretical Physics, State University of Iowa, Iowa City, Iowa, 1956 (unpublished); R. Oehme, Phys. Rev. **100**, 1503 (1955); **102**, 1174 (1956); A. Salam, Nuovo cimento **3**, 424 (1956).

[2] H. L. Anderson, *Sixth Annual Rochester Conference on High-Energy Physics, 1956* (Interscience Publishers, Inc., New York, to be published).

2. THE DISPERSION RELATIONS

Though the spin-flip amplitude vanishes in the forward direction, we can determine its derivative with respect to $\sin\theta$, where θ is the angle of scattering in the center-of-mass system, evaluated at $\theta=0$. This derivative (in the center-of-mass system) can be written as $(1/\mu)\bar{\eta}^2 a$, where $\bar{\eta}$ is the center-of-mass momentum in units of μc and a is a dimensionless quantity which in general approaches a finite nonzero limit as $\bar{\eta}\to 0$. We will work with four a's, $a^{1,2}$ corresponding to isotopic spin nonflip and flip, and $a_{3,1}$ corresponding to total isotopic spin of 3/2 and 1/2. These are related by

$$\begin{aligned} a^1&=\tfrac{1}{3}(2a_3+a_1),\\ a^2&=\tfrac{1}{3}(a_1-a_3). \end{aligned} \tag{2.1}$$

The quantities a_3 and a_1 can be expressed in terms of the corresponding phase shifts by

$$a_{3,1}=\sum_{l=1}^{\infty}\frac{l(l+1)}{2i}\frac{1}{\bar{\eta}^3}(e^{2i\delta_{l+}}-e^{2i\delta_{l-}})_{3,1}, \tag{2.2}$$

where $\delta_{l\pm}$ is the phase shift for the state of orbital angular momentum l, total angular momentum $l\pm 1/2$, and total isotopic spin 3/2 or 1/2 as indicated outside the parenthesis.

To terms of order $(\mu/\varphi)^2$, the dispersion relations