Low-Energy π Mesons in the Cosmic Radiation*†

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The intensity of π mesons in the atmosphere is investigated in the energy region $E_{\text{kin}} \lesssim 50$ Mev at sea level and at mountain altitudes. Positive π mesons coming to rest in an absorber-scintillator are identified by the characteristic π-μ decay. They are detected electronically and recorded photographically.

The value 1.45 ± 0.09 is adopted for the negative-to-positive ratio at small energies.

The omnidirectional intensities J_{π}^{+} of slow positive π mesons at sea level (91m), Echo Lake, Colorado (3260 m), and Mt. Evans, Colorado (4310 m) are found to be 0.0094 ± 0.0024, 0.098 ± 0.005, and 0.240 ± 0.011 $g^{-1}day^{-1}$, respectively. The altitude dependence of $J_{\pi}^{\pm}$, $J_{\mu}^{\pm}$ and $J_{\pi}^{\pm}/J_{\mu}^{\pm}$ is given and the attenuation length of slow π mesons in the atmosphere found to be $L_a^{\pi} \approx 120$–130 g/cm² in this altitude interval. A discussion covering most of the available results along the same line is presented.

I. INTRODUCTION

THE purpose of the present work was to investigate the low-energy π mesons in the cosmic radiation and their intensity variation with altitude. Measurements were performed during the summer of 1957 at sea level in Berkeley, California (91-m altitude, $\lambda = 44°$N geomagnetic latitude, $x = 1030$ g/cm² atmospheric depth) and at mountain altitudes at Echo Lake, Colorado (3260 m, $\lambda = 48°$N, $x = 705$ g/cm²) and on Mt. Evans, Colorado (4310 m, $\lambda = 48°$N, $x = 625$ g/cm²). Barometric and temperature fluctuations were considered as having negligible influence on these measurements.

II. EXPERIMENTAL PROCEDURE

The identification of π mesons stopping in an absorber-detector is based on the two pulses arising from the π-μ decay. These pulses trigger the selection circuit electronically and are recorded photographically from an oscilloscope screen. The latter feature ensures satisfactory results as far as both the identification of useful events and statistics are concerned; the usual electronic recording could yield faster and more abundant data at the expense, however, of reliable identification. Figure 1 shows the block diagram of the experimental setup.

Detecting and Recording

The absorber-detector was a plastic scintillator 10.5 cm in diameter and 7 cm high. The lower surface was mounted on an RCA5819 photomultiplier and the output channeled to the amplification and selection system, the main part of which consisted of a π-μ delay discriminator essentially based on a fast coincidence circuit.[1] The coincidence output then reached the external triggering of the oscilloscope and the motor of the camera facing the cathode ray tube screen.

Operation

The entire volume of the scintillator (603.0 cm³) is only partially efficient for π-μ detection. Since the decay range of the 4.2-Mev μ meson is 0.15 cm in the plastic

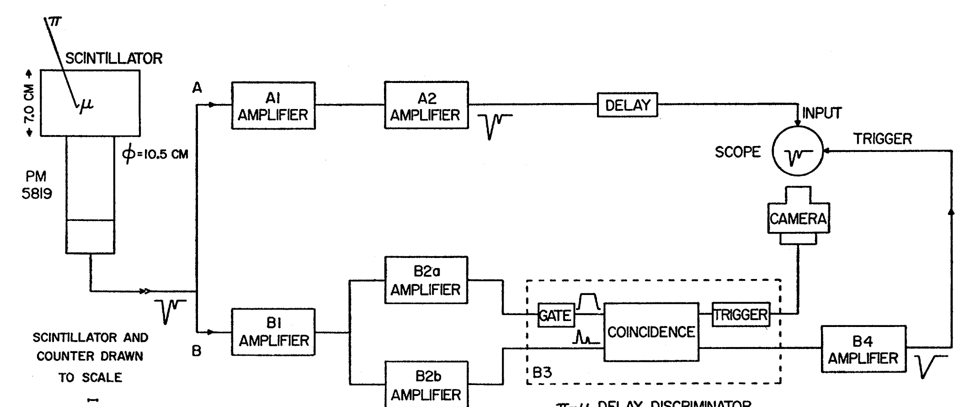

FIG. 1. Block diagram.

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[1] J. Fischer and J. Marshall, Rev. Sci. Instr. 23, 417 (1952).

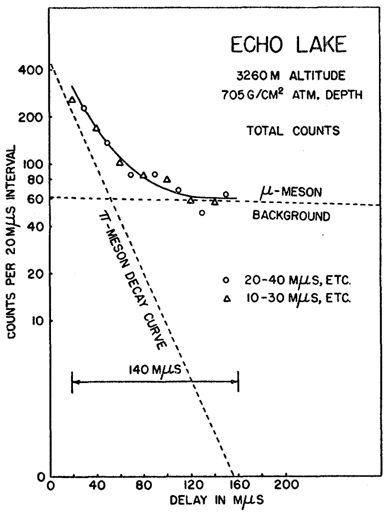

FIG. 2. Total delay distribution at Echo Lake, Colorado.

phosphor, we can assume that any π meson stopping at a distance larger than 0.15 cm from the walls will be detected. (The dimensions of the scintillator were such that the possible self-absorption of its own fluorescent radiation, less than 10% per 10 cm, was of the same order of magnitude as other possible fluctuations.) Furthermore a π meson stopping at the upper end will be detected if the μ meson is emitted downwards; similarly a π meson stopping at the lower end will be detected if the μ meson is emitted upwards. Using a similar argument for the vertical curved surface of the scintillator and assuming the μ mesons to be ejected isotropically from the stopping π mesons, the inefficient peripheral volume becomes 30.3 cm^3 and thus leads to a detection efficiency of 95%.

A pulse-height calibration was performed with cosmic-ray μ mesons which passed through the scintillator (energy loss 14–15 Mev) and with Pu^{239} and Co^{60} sources in order to calibrate the μ-meson decay pulse.

III. RESULTS AND DISCUSSION

The measurements performed during the present experiment yielded a total of some 2300 events. The conditions for the three runs are summarized in Table I.

In evaluating the numerical results we shall restrict the effective time interval between 20 and 160 mμsec after the first pulse. This choice is determined by the fact that, notwithstanding a resolution time of 8 mμsec for equal pulses, a large difference between two neighboring pulses results in decreased over-all separation power, and by the necessity of balancing two conflicting factors: on the one hand the short mean life of the π meson requires the detection of as large a decay fraction as possible in order to allow a reasonable extrapolation, and on the other hand the great abundance of μ mesons imposes as short an interval as possible in order to reduce the background and thereby distinguish more clearly between the two contributions.

TABLE I. Location of experimental stations.

Geographic location	Atmos depth (g/cm^2)	Altitude (m)	Geomagnetic latitude λ	Operation time (hrs)
(SL) Berkeley, California	1030	90	44°N	64.4±1.1
(EL) Echo Lake, Colorado	705	3260	48°N	222.5±3.7
(ME) Mt. Evans, Colorado	625	4310	48°N	90.5±1.5

Assuming the mean lives $\tau_\pi = 25$ mμsec and $\tau_\mu = 2200$ mμsec, the fractions of π and μ mesons decaying during the chosen time interval are $\eta_\pi = 0.448$ and $\eta_\mu = 0.061$, respectively. The distributions of counts, in each case, appear as sums of two exponential contributions, one corresponding to the π-meson decay and the other to the μ-meson contamination. (In view of the statistical fluctuations involved and of the somewhat limited amount of data available, the experimental curve follows quite satisfactorily the shape of a sum of two exponential curves.) An example of such a distribution is given in Fig. 2. If, furthermore, a selection is made for those double pulses in which the second pulse is smaller than the value decided upon by the calibration mentioned above, one obtains similar distributions in which, however, a certain μ-meson contamination is still present. This is not in the least surprising since on the one hand the selection criterion does not exclude possible low-energy electrons from μ-e decays giving pulses similar to those of the π-μ decays, and on the other hand the disproportion between the contributions from the two kinds of mesons is such as to ensure a substantial μ-meson contamination. A comparison between the π-meson decay curves in the delay distributions of selected and of nonselected pulses for the three sets of curves shows that they are very nearly the same.

TABLE II. Counting rate at the three experimental stations.

Place	Total counts	Rate (hr^{-1}) uncorrected	Intensity $J\pi^+$ corrected
SL	15.9±4.0	0.25±0.062	$(0.39\pm0.10)\times10^{-3}$ g^{-1} hr^{-1}
EL	571±23.9	2.57±0.12	$(4.10\pm0.19)\times10^{-3}$ g^{-1} hr^{-1}
ME	566±23.8	6.25±0.23	$(10.0\pm0.44)\times10^{-3}$ g^{-1} hr^{-1}

Correcting for the fraction $1-\eta_\pi$ decaying in the interval 0–20 mμsec and for edge effects, one obtains the values given in Table II.

Negative-to-Positive Ratio

It should be pointed out that the present investigation concerns essentially positive π mesons; in condensed material the negative π mesons give stars and thus are not distinguished on the oscilloscope trace. While there are about five times more negative than positive π mesons produced in condensed material in the low-energy region under consideration, the ratio π^-/π^+ for the mesons entering the detector from the atmosphere is not unambiguously agreed upon. In most

TABLE III. Previous experimental results on the negative-to-positive ratio of pions in the atmosphere.

Reference	Year	Altitude (m)	π^-/π^+ (uncorrected)	π^-/π^+ (corrected)[a]
Camerini *et al.*[2]	1948	3460	1.09 ± 0.40	1.49 ± 0.51
Occhialini and Powell[3]	1948	3050–5500	1.05 ± 0.25	1.44 ± 0.32
Bonetti[4]	1950	2800	$(89\ \sigma)/(45\ \pi-\mu)$	2.71 ± 0.47*
Fry[5]	1951	18 000	···	$3.2\ \pm0.7$*
Dallaporta *et al.*[6]	1952	4550	2.36 ± 0.80	3.24 ± 1.07*
Yagoda[7]	1952	27 000–32 000	$(542\ \sigma)/(520\ \pi-\mu)$	1.43 ± 0.08
Bonetti *et al.*[8]	1953	2000	···	1.75 ± 0.45
Babaian *et al.*[9]	1953	960–1950	···	2.25 ± 1.35*
Babaian *et al.*[9]	1953	3250	···	1.15 ± 0.25
Babaian *et al.*[9]	1953	3980	···	1.57 ± 0.75*
Calzolari *et al.*[10]	1954	4550	···	1.45 ± 0.19

[a] The values marked with an asterisk involve very large statistical errors and were discarded in determining the mean value of the π^-/π^+ ratio.

TABLE IV. Measured intensities of pions at the three experimental stations.

Altitude h (m)	$J\pi^+$ (10^{-3} g^{-1} hr^{-1})	$J\pi^\pm$ (10^{-3} g^{-1} hr^{-1})	$J\mu^\pm$ (10^{-3} g^{-1} hr^{-1})	$J\pi^h/J\pi^0$	$(J\pi/J\mu)_h$
90	0.39 ± 0.10	0.96 ± 0.18	14.4 ± 0.64	1.0	0.067 ± 0.013
3260	4.10 ± 0.19	$10.0\ \pm0.53$	45.5 ± 0.9	10.5 ± 2.0	0.223 ± 0.012
4310	$10.0\ \pm0.44$	$24.5\ \pm1.26$	62.4 ± 1.5	25.5 ± 4.9	0.396 ± 0.022

cases it was obtained from nuclear emulsions exposed at mountain altitudes and in the stratosphere by identifying the π mesons entering and stopping in the plates by the characteristic σ stars and π-μ decays. Table III gives the various results available[2–10]; the correction indicated for the π^-/π^+ ratio refers to the 27% of the negative π mesons known[11] to stop in emulsions without giving stars. Although in apparent contradiction with the positive charge of the primary radiation and the resulting positive excess of μ mesons at all energies, the pion negative excess is compatible with the much shorter mean life of the π meson and with the fact that, in this energy region, the neutrons and photons contribute a large fraction of locally produced π mesons. Theoretical calculations of pion photoproduction for a photon energy in the laboratory system between threshold and 240 Mev give[12] a negative-to-positive ratio of 1.85 or higher, whereas a value of about 1.4 is predicted by the perturbation theory. With the above considerations in mind and discarding the values marked with an asterisk involving very large statistical errors, we obtain a mean value of 1.45 ± 0.09 for the negative-to-positive ratio.

The relevant results are summarized in Table IV. In order to make a comparison with the total π-meson intensity $J_\pi\pm$, the total μ-meson intensity $J_\mu\pm$ has also been given as a by-product of the present investigation; its increase with altitude agrees very satisfactorily with the values given earlier by Rossi.[13]

Figure 3 shows the altitude dependence of J_μ, J_π, and J_π/J_μ.

We are thus led to the following conclusions: (*i*) the ratio of π to μ intensities increases smoothly with alti-

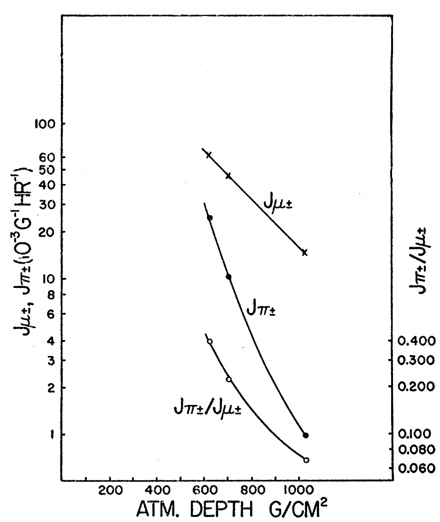

FIG. 3. Altitude dependence of J_μ, J_π, and J_π/J_μ.

[2] Camerini, Muirhead, Powell, and Ritson, Nature **162**, 433 (1948).
[3] G. P. S. Occhialini and C. F. Powell, Nature **162**, 168 (1948).
[4] A. Bonetti (private communication, 1950), quoted in reference 5.
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[9] Babaian, Zinger, and Marutian, Doklady Akad. Nauk S.S.S.R. **92**, 263 (1953).
[10] Calzolari, Dascola, Gainotti, and Mora, Nuovo cimento **11**, 565 (1954).
[11] F. L. Adelman and S. B. Jones, Phys. Rev. **75**, 1468 (1949).
[12] Beneventano, Bernardini, Carlson-Lee, Stoppini, and Tau, Nuovo cimento **4**, 323 (1956).
[13] B. Rossi, Revs. Modern Phys. **20**, 537 (1948).

TABLE V. Comparison of the results of the present experiment with previous experimental work.

Reference	Altitude (m)	Method	π^- (g^{-1} day^{-1})	π^+ (g^{-1} day^{-1})	π^- corrected
Camerini *et al.*[2]	3460	Ilford *C*2	0.19 ±0.03	0.17 ±0.06	No
Dallaporta *et al.*[6]	4550	Ilford *G*5	0.17 ±0.03	0.072 ±0.02	No
Bonetti *et al.*[8]	2000	Ilford *G*5	0.072±0.013	0.040 ±0.008	Yes
Calzolari *et al.*[10]	4550	Ilford *G*5	0.36 ±0.03	0.248 ±0.023	Yes
Present work	90	Scintillator	···	0.0094±0.0024	···
Present work	3260	Scintillator	···	0.098 ±0.005	···
Present work	4310	Scintillator	···	0.240 ±0.011	···

tude with an attenuation length intermediate between the attenuation mean free paths of π mesons and μ mesons; (*ii*) the increase in total intensities with altitude is faster for π mesons than for μ mesons; in the range 625–1030 g/cm^2 the average value of the attenuation length of slow π mesons is smaller than that for slow μ mesons by a factor of about 2; (*iii*) the attenuation length of slow π mesons in the atmosphere, $L_a^\pi \approx 120 - 130$ g/cm^2, is very nearly the same as that of bursts and penetrating showers.

All presently available data for π mesons (positive or negative) are given in Table V. Taking into account the differences in altitude involved, it appears that a very good agreement exists only between the value more recently given by Calzolari *et al.*[10] and the corresponding present value. As for the low result of Dallaporta *et al.*,[6] the difference by a factor of 3 or so is too big to be justified solely by statistical fluctuations; furthermore the ratio π^-/π^+ computed from their data, in spite of the large statistical error, is substantially higher than that adopted in the present investigation.

It should be pointed out finally that in all present measurements the counter was placed with minimum shielding as far as possible both from big masses of condensed material and above the ground in order to avoid the influence of π mesons produced in these materials and not in the atmosphere. It was also tacitly implied that there is no significant contribution to our present data from other short-lived unstable particles or from possible $\pi^+ - e^+$ decays.

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