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Measurement of the Slow Meson Intensity at Several Altitudes

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The number of mesons stopped by a horizontal aluminum plate 2 inches thick was measured at several altitudes between sea level and 35,000 feet. The mesons were detected by recording the delayed emission from the absorber of the electrons produced by the decay of the absorbed mesons. An increase by a factor of about 37 between sea level and 35,000 feet was observed.

I. INTRODUCTION

VERY little information has been available on the number of low energy mesons in the atmosphere, because these particles are difficult to distinguish from other more abundant components of the cosmic radiation. Filtration through lead, as a method for separating mesons from electrons, obviously fails as soon as the range of the mesons becomes of the same order of magnitude as the range of the electrons (i.e., several radiation lengths). In principle one can still distinguish mesons from electrons by making use of the fact that the relative stopping power of substances of different atomic number is different for the two types of particles. Also, mesons can be recognized by their inability to produce showers. Both of these methods have been used,[1] but the interpretation of the results is always difficult, especially in the energy interval below 100 Mev. These methods, moreover, do not distinguish between low energy mesons and protons, which seem to be present in considerable number at high altitude. Low energy mesons can be distinguished from protons as well as from electrons by cloud chamber observations in a magnetic field. It is very difficult, however, to achieve by this method a sufficient statistical accuracy, especially since not all of the tracks obtained can be identified.

The methods for the detection of slow mesons mentioned above are based upon properties of mesons which depend on their mass. A much more selective criterion for the separation of slow mesons from other particles is provided by the instability of mesons; i.e., by the fact that mesons, when brought to rest, disintegrate with the emission of electrons and with a characteristic mean life of approximately 2 microseconds.

The present paper describes the results of some measurements on the slow meson intensity at several heights, which were carried out with a slow meson detector based upon the above criterion, i.e., with an instrument designed to detect the disintegration electrons arising from the decay of the mesons stopped in a comparatively thin absorber. It may be pointed out from the beginning that the method is better suited for measurements of relative intensities at two different heights than for the determination of the absolute intensity at any one height, because the detection probability of the decay electrons cannot be computed with great accuracy.

II. EXPERIMENTAL METHOD

The experimental arrangement is represented schematically in Fig. 1. *A*, *B*, *C*, and *D* are trays of four Geiger-Mueller tubes each. The tubes have an outside diameter of 1 inch, an effective length of 10 inches, and 0.04-inch brass walls. The four tubes of each tray are connected in parallel. The absorber *S* is an aluminum plate $2\frac{1}{16}$ inches thick. Consider a meson which traverses *A* and *B*, is stopped in *S*, and subsequently decays, giving rise to an electron which discharges *C* and *D*. Such an event is characterized by a coincidence (A, B) followed after a short time by a coincidence (C, D). These "delayed coincidences" are selected by the electronic circuit and analyzed into four groups corresponding to delays within four consecutive time intervals or "channels," each of 1.8-microsecond duration. The beginning of the first channel is

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* Now at Washington University St. Louis, Missouri.

[1] G. Bernardini and B. N. Cacciapuoti, Ric. Scient. 12, 981, (1941); K. I. Greisen, Phys. Rev. 63, 323 (1943); D. B. Hall, *ibid.* 66, 321 (1944); H. J. Bhabha, S. V. Chandrashekhar Aiya, H. E. Hoteko, and R. C. Saxena, *ibid.* 68, 147 (1945).

chosen to be 0.9 microsecond because of the spontaneous time lags of Geiger-Mueller tubes (see below). By counting delayed coincidences in four different channels it is possible to check, at least approximately, the exponential decay of mesons and the value of their characteristic lifetime, a test which enhances the confidence in the interpretation of the experimental results.

In addition to the delayed coincidences produced by the decay of mesons, delayed coincidences can also be produced (a) by spontaneous time lags in the Geiger-Mueller tubes, (b) by random events.

(a) The spontaneous delays of Geiger-Mueller tubes of the argon-alcohol type used in the present experiment, are known to be usually of the order of a few tenths of a microsecond.[2] However, it is possible that occasionally delays longer than 0.9 microsecond occur. Direct experiments were carried out to investigate this point and gave an *upper limit* of 1 in 5000 for the probability of time lags longer than 0.9 microsecond. Now, the number of "prompt coincidences," caused by cosmic-ray particles which traverse the absorber and the four trays of counters, is between 2500 and 3000 times the number of "delayed coincidences" caused by disintegration electrons from absorbed mesons. The possibility, therefore, that one in 5000 of the prompt coincidences is recorded as a delayed coincidence because of time lags in the counters represents a serious source of error. This source of error was eliminated by requiring that both the incoming meson and the decay electron discharge *two* counters and by using as timing signal the pulse of the counter which is discharged first. More specifically, the equipment operates as follows. The counter trays A, B, which detect the incoming mesons, are connected to a coincidence circuit C_1. When both A and B are discharged within 1 microsecond, this circuit gives a pulse delayed by 1 microsecond with respect to the discharge of A or B, *whichever occurs first.* The counter trays C, D, which detect the decay electrons, are connected to an identical coincidence circuit C_2. The output pulses of C_1 and C_2 are then fed into a four channel "delay discriminator," which records an event whenever a pulse from C_1 is followed by a pulse from C_2 after 0.9 but before 8.1 microseconds. Thus a spurious delay is recorded in place of a prompt coincidence only if *both* C and D give pulses with a time lag longer than 0.9 (and shorter than 8.1) microseconds. The probability for this event is less than 1 in $(5000)^2$ and is therefore completely negligible.[3]

(b) In order to compute the spurious delays caused by random events one has to consider that the circuits are so constructed that when a Geiger-Mueller tube is discharged, the whole tray to which the tube belongs remains insensitive for a period of about 20 microseconds. Therefore, the only type of random events which can give rise to spurious delays is a cosmic-ray particle traversing trays A, B *but failing to traverse either* C *or* D, followed after a short time by a particle which traverses C, D. (If the particle which has traversed A, B also discharges one or both of the trays C, D, the circuit C_2 is made insensitive for 20 microseconds, and cannot record a pulse within the time interval covered by the "delay discriminator.") The spurious counting rate in each channel of the delay discriminator is therefore given by

$$[(A, B)-(A, B, C+D)](C, D)\tau,$$

where τ is the width of the channel ($\tau = 1.8$ μsec.), (A, B), (C, D) are the counting rates for twofold coincidences between A and B and between C and D respectively, and $(A, B, C+D)$ is the counting rate for threefold coincidences between A, B and C *or* D. The twofold coincidence rate

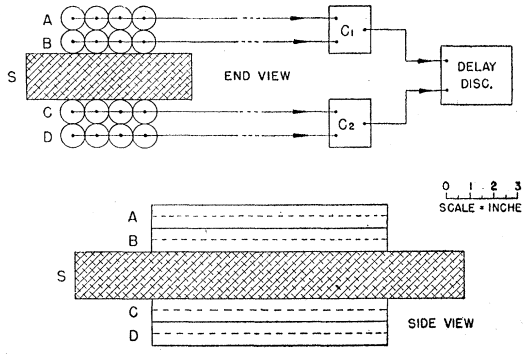

FIG. 1. Experimental arrangement.

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[2] See Bruno Rossi and Norris Nereson, Phys. Rev. 62, 417 (1942).

[3] A detailed description of the electronic circuit will be published elsewhere by one of us (M.S.).

(A, B) minus the threefold coincidence rate, $(A, B, C+D)$, gives the number of particles which traverse A, B but traverse neither C nor D. At sea level, spurious delays from random events are a small fraction of the true delays and can be corrected for accurately. The coincidence rate between counter trays, however, increases very rapidly with altitude, while the number of slow mesons turned out to increase with altitude somewhat more slowly than one might have expected. As a consequence the relative value of the correction for random events becomes very large at the highest altitude reached during the present set of experiments.

III. EXPERIMENTAL RESULTS

Measurements were taken at the following elevations above sea level: 0, 14,000, 25,000, 35,000 feet. The measurements at sea level were carried out at Cambridge in a wooden building, under a thin roof consisting of $\frac{3}{4}$-inch planking covered with tar paper. For the measurements at high altitude the equipment was installed in the rear cabin of a B-29 aircraft. The cabin was pressurized. Its walls were made of thin aluminum sheet. The flights took place at constant magnetic latitude of about 53°N. Three flights were made at 14,000 feet, two at 25,000 feet, one at 35,000 feet above sea level. The internal consistency of the data obtained in different flights at the same altitude was quite satisfactory. A summary of the experimental results is presented in Table I. At 0, 14,000 and 25,000 feet, the rate of spurious delays due to random events was computed as indicated in the preceding section from the threefold coincidence rate $(A, B, C+D)$ and the twofold coincidence rates (A, B) and (C, D). Because of the very large number of coincidence counts recorded, the statistical error of the correction is negligible. At 35,000 feet, unfortunately, the counting rate for the threefold coincidences $(A, B, C+D)$ was not recorded. Thus the number of spurious delays could not be computed directly, but was obtained by the following method of successive approximations. It was assumed first that the delays recorded in the last channel (6.3 to 8.1 microseconds) were all spurious and the total number of true delays in the other three channels (0.9 to 6.3 microseconds) was computed accordingly. From this number and under the assumption of a mean-life time of 2.15 microseconds for the mesons, the number of true delays in the last channel was computed and subtracted from the number observed to obtain the number of spurious delays in a second approximation. The process was repeated, and thus a rapidly converging set of values for the number of spurious delays was obtained. Of course, the statistical error in the evaluation of the correction is large because of the small number of counts in the last channel. For this reason, and because only data from one flight are available at 35,000 feet, the results at this altitude are considerably less certain than those at the lower levels.

TABLE I. Experimental results.

Altitude, feet	0	14,000	25,000	35,000
Pressure, g/cm^2	1030	610	390	250
Twofold coincidences (A, B), per min.	214	884	3220	7057
Twofold coincidences (C, D), per min.	197	756	2770	5865
Threefold coincidences $(A, B, C+D)$, per min.	92.3	319	971	
Fourfold coincidences (A, B, C, D) per min.	67.7	222	664	1282
Delayed coincidences per hour				
0.9–2.7 μsec.	0.85	5.61	24.0	72.5
2.7–4.5 μsec.	0.38	2.05	18.6	64.0
4.5–6.3 μsec.	0.20	1.51	13.2	55.5
6.3–8.1 μsec.	0.13	1.10	12.8	50.0
Spurious delays in each channel per hour	0.038	0.79	11.5	47.5
True delays per hour, 0.9–8.1 μsec.	1.42 ± 0.06	7.15 ± 0.84	22.8 ± 2.6	52 ± 17
Duration of observation (hours)	369	14.6	15.4	3.66

IV. DISCUSSION OF THE EXPERIMENTAL DATA

Figure 2 shows a semi-logarithmic plot for each altitude of the corrected counting rates in the four channels against the delay of the channel. The statistical errors are unfortunately too large for an accurate determination of the lifetime at the four elevations. One can state, however, that there is no indication for a variation of the average lifetime of mesons with height, i.e., that there is no indication for the existence of more than one kind of mesons with comparable lifetime. Our data are consistent with a value of the meson lifetime in the neighborhood of 2.15 μsec, as measured by Nereson and Rossi.[4]

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[4] N. Nereson and B. Rossi, Phys. Rev. **64**, 199 (1943).

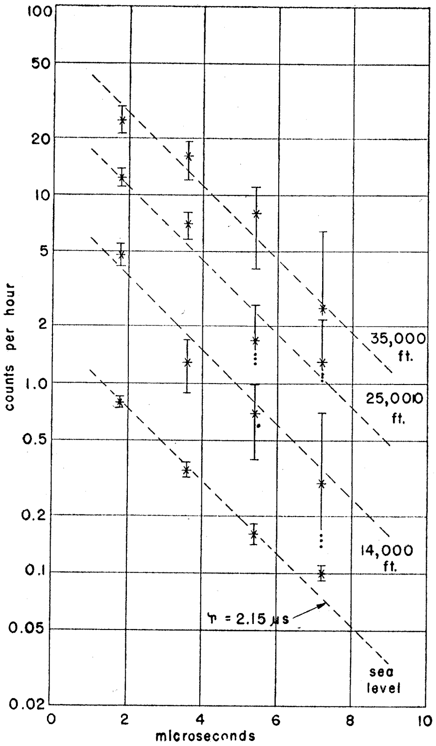

FIG. 2. Differential decay curves of mesons at different heights. The abscissae represent the midpoints of the channels. The ordinates represent, on a logarithmic scale, the *corrected* counting rates in each channel. The vertical lines indicate the standard statistical deviations. The broken lines represent exponential decay curves corresponding to a lifetime of 2.15 microseconds.

If the shape of the meson decay curve does not change with height, the sum of the corrected counting rates in the four delayed channels as given in the last line of Table I may be taken as a relative measure for the number of slow mesons present at the different heights. By "slow mesons" we understand here those mesons which are stopped by the aluminum absorber. The mass of the material in the vertical direction above the absorber is 2.2 gm/cm^2 so that only mesons with momenta between 0.6×10^8 ev/c and 1.2×10^8 ev/c are detected. The corresponding limits to the energy are 17×10^6 ev and 56×10^6 ev.

It is not easy to deduce from the experimental data an absolute value for the number of slow mesons because of the uncertainty in the detection probability of the decay electrons. An approximate computation can be carried out under the following simplifying assumptions: (a) the thickness of the absorber is very small compared with the *effective* lateral dimensions of the absorber, i.e., of the area covered by the Geiger-Mueller tubes; (b) the decay electrons have a definite range; (c) the mesons are uniformly distributed in range; (d) all decay electrons coming out from underneath the effective area of the absorber are detected.

Let $N(\theta)$ represent the directional *intensity* per unit range interval of mesons at the zenith angle θ (i.e., their number per cm^2 per second and unit solid angle). Let S be the effective area of the absorber, z its thickness, $V=Sz$ its effective volume, and ρ the density of the absorber material. Mesons arriving at an angle θ are stopped in the absorber, if they have a range less than $\rho z/\cos\theta$ g/cm^2. The number of such mesons striking the absorber per unit time within the solid angle $d\omega$ is

$$\left[N(\theta)\frac{\rho z}{\cos\theta}d\omega\right]S\cos\theta=\rho zSN(\theta)d\omega.$$

Hence the total number of mesons stopped in the absorber per unit time is given by

$$\rho V\int N(\theta)d\omega,$$

where the integration is extended over the whole upper hemisphere. Of the mesons which are absorbed in aluminum, presumably only the positive ones, or approximately half of the total, decay. The probability for a decay electron produced at a distance x from the lower face of the absorber to come out through this face and be detected by the counters underneath is given by $\frac{1}{2}(1-\rho x/R_e)$, where R_e is the range of the electron in g/cm^2. The probability for detecting the decay electron is the average value of this expression or, if the mesons which decay are distributed uniformly in range and if $\rho z<R_e$, $\frac{1}{2}(1-\rho z/2R_e)$. The decay electrons are supposed to have an energy of about 50 Mev; the corresponding average range in aluminum, calculated by neglecting fluctuations in the radiation losses, is 19 g/cm^2. Since the thickness ρz of the absorber and the walls of the adjacent Geiger-Mueller tubes is 14.9 g/cm^2, the detection probability is 0.3. Of the decay electrons striking the

counters, only a fraction are counted, namely, those emitted between 0.9 and 8.1 microseconds from the time of arrival of the mesons. Under the assumption of a mean lifetime equal to 2.15 microseconds, this fraction is 0.63. Therefore the sum of the counting rates in the four delayed channels is related to the *integrated intensity* $\int N(\theta)d\omega$ of mesons per g/cm^2 range by the equation:

$$\textit{Counting rate} \Big/ \rho V \int N(\theta)d\omega = 0.5\times 0.3\times 0.63 = 0.1.$$

By introducing the counting rates as given in Table I and by substituting for ρ and V the density 2.7 g/cm^3 and the effective volume (1520 cm^3) of the aluminum absorber, one obtains the integrated intensities listed in the second line of Table II. Line 3 in Table II gives, for the purpose of comparison, the integrated intensities of "fast" mesons, i.e., of mesons with range larger than 167 g/cm^2 of lead measured by Greisen near sea level (Ithaca, New York) and at 14,300 feet (Mt. Evans, Colorado).[5] Line 4 gives the ionization produced by the electrons arising from the decay of mesons which are stopped in air, computed under the assumption that in air both positive and negative mesons disintegrate.[6] Line 5 gives the total ionization of cosmic rays as measured by Millikan and his collaborators.[7]

TABLE II. Summary of cosmic ray effects at various altitudes.

Depth below the top of the atmosphere (g/cm^2)	1030	610	390	250
Integrated intensity of slow mesons in each g/cm^2 range interval (per cm^2 per sec.)	0.94×10^{-6}	4.8×10^{-6}	15.4×10^{-6}	35×10^{-6}
Integrated intensity of mesons with range above 167 g/cm^2 of lead (per cm^2 per sec.)	1.5×10^{-2}	3.6×10^{-2}	—	—
Ionization produced by the decay electrons from mesons stopped in air (ion pairs per cm^3 per sec.)	1.7×10^{-3}	8.6×10^{-3}	28×10^{-3}	63×10^{-3}
Total cosmic ray ionization (ion pairs per cm^3 sec.)	1.75	15	54	120

From an examination of Table II, one recognizes that even though slow mesons increase with height more rapidly than fast mesons, at no altitude do electrons arising from the decay of mesons at rest contribute appreciably to the total intensity of the cosmic radiation. This is true even if the absolute intensities of slow mesons are underestimated by as much as a factor of 10.

From lines 2 and 3 of Table II one obtains a value of 0.6×10^{-4} for the ratio at sea level of the number of "slow" mesons which stop in 1 g/cm^2 to the number of mesons with ranges greater than 167 g/cm^2 of lead. Absorption measurements of "fast" mesons at sea level[8] give the result that for each meson which passes through 144 g/cm^2 of lead, about 5×10^{-4} are stopped by an additional gram per square centimeter of a light element. The numbers of mesons per unit range interval, found in the two experiments, are different by a factor of eight. The decay of mesons in flight should deplete the low energy end of the spectrum to some extent, and it is also possible that the spectrum averaged over all directions differs appreciably from that in the vertical direction. It does not seem, however, that either of these effects can be sufficient to explain the discrepancy. On the other hand, even though the *absolute* values for the integrated intensities of slow mesons obtained in our experiment are much more uncertain than the *relative* values at different heights, it does not seem likely that the estimate of the absolute intensities could be in error by a factor of eight unless the energy of the decay electron is less than 50 Mev. Further experiments are necessary to determine whether or not the apparent depletion of the low energy end of the meson spectrum represents a real effect.

The knowledge of the dependence of the number of slow mesons on height provides an experimental test for any hypothesis on the

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[5] K. I. Greisen, Phys. Rev. **61**, 212 (1942).

[6] This quantity is calculated in the following way. The number of mesons per unit time which stop in 1 g/cm^2 of air is $\int N(\theta)d\omega$. By the disintegration of each meson of mass m an electron of energy $mc^2/2=50$ Mev is produced. This energy is dissipated in ionization, the average energy per ion pair being about 35 ev. The density of air at standard temperature and pressure is 1.29×10^{-3} g/cm^3. Thus the total number of ion pairs per cm^3 per unit time is given by $(50\times 10^6\times 1.29\times 10^{-3}/35)\int N(\theta)d\omega = 1.8\times 10^3 \int N(\theta)d\omega$.

[7] R. A. Millikan, H. V. Neher, and W. H. Pickering, Phys. Rev. **61**, 397 (1942).

[8] See, for instance, B. Rossi, N. Hilberry, and J. B. Hoag, Phys. Rev. **57**, 461 (1940).

variation of the rate of production of mesons with altitude and on the energy spectrum of the produced mesons. To determine how sensitive this method is as a test for the energy spectrum, we have calculated the ratio between the numbers of vertical mesons at the end of their range at the atmospheric depths of 300 g/cm^2 and 1000 g/cm^2 respectively, under the following assumptions: (a) The meson producing radiation undergoes exponential absorption in the atmosphere with a mean free path L. (b) Mesons are produced with a differential energy spectrum which obeys a power law dE/E^3 down to an energy E_0, and is constant from E_0 to zero. (c) Mesons have a mass of 10^8 ev/c^2 and a lifetime of 2.15 microseconds. The calculation was carried out for $L=100$ g/cm^2 and for different values of E_0. The results were as given in Table III.

The only conclusion one can draw from a comparison between the results listed in Table III and our experimental data is that the comparatively slow increase with height of the slow meson intensity found experimentally indicates that the production spectrum of mesons is not very rich in low energy mesons.

TABLE III. Computed variation of slow meson intensity.

E_0 (ev)	2.1×10^8	3.9×10^8	7.7×10^8
Meson range corresponding to E_0 (g/cm^2)	100	200	400
Increase of slow meson intensity from 1000 to 300 g/cm^2	137	34	5.5

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On the Meson Theory of Nuclear Forces

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The failure of the Møller-Rosenfeld-Schwinger mixture to yield quantitative agreement with the observed properties of the proton-neutron system suggests the possibility that this agreement might be obtained with other such mixtures in which tensor force singularities are cancelled. Several such possibilities exist involving vector, pseudovector, and pseudoscalar mesons, certain of which possess the characteristic that they yield a finite tensor and central interaction in the limit where the meson masses approach equality and the square of the coupling constant increases indefinitely inversely as the difference in masses. The resultant interaction is of an especially simple form so that it was felt warranted to carry out calculations on the proton-neutron and proton-proton systems in spite of admitted conceptual difficulties concerning the result. These calculations indicated that satisfactory agreement with experimental results cannot be obtained with these limiting forms of the interaction, if one employs in the theory the mass of observed cosmic ray mesons. Substantially better agreement can be obtained with a meson mass of the order of 300 electron masses.

1. INTRODUCTION

IN spite of the qualitative correctness of the range and spin dependence of internucleonic forces derived from current weak coupling meson theories, it is well known that serious difficulties are encountered when one attempts to obtain quantitative agreement with the available experimental data. A part of these difficulties is connected with the overly singular radial dependence of the non-central or tensor part of the interaction, which, if accepted literally, precludes the existence of a complete set of eigenfunctions for the Schrödinger equation. One solution of this

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[*] National Research Fellow (Predoctoral).