X. CONCLUSION

In those mixtures where the photoelectric effect is the main process acting in the discharge build-up, the contribution to the pulse formation caused by the Townsend avalanche can be separated from the contribution caused by secondary processes. Consequently, it is possible to study the secondary process of electron production and measure its efficiency.

From our results the photoelectric process on the cathode is found to be responsible for the formation of the Geiger and corona zones in mixtures of argon plus carbon dioxide at concentrations less than 5×10^{-3} at any pressure used.

The same accuracy cannot be used in the study of mixtures where a process of electron production in the gas body will operate, as in the case of argon plus carbon dioxide, at percentage higher than 5×10^{-3}. However, these processes are very interesting due to their fast spreading.

Furthermore, the photons acting in the photoelectric effect on the cathode are found to be emitted by the first excited levels of argon. These photons are produced in collisions leading to destruction of these levels, and are not resonance photons. The values obtained for the lifetimes of these levels are roughly in accordance with the extrapolation of Molnar's values at the pressure used. More direct measurement of these lifetimes at pressures ranging from 10 to 1000 mm should be very interesting in order to investigate this effect further.

We wish to take this opportunity to thank Professor G. Bolla and Professor B. Ferretti for assistance received during this work, Dr. F. M. Penning for his interest and valuable discussions, Dr. Molnar and Dr. Hornbeck for notifying us of their results, and Dr. E. Gatti for helpful discussions. We finally wish to thank Professor L. Loeb for his interesting critique and for the useful suggestions offered to us.

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Range Distribution of Sea-Level Mesons at Low Geomagnetic Latitudes*

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Seven points of the meson differential spectrum at sea level have been obtained at a geomagnetic latitude of 29°N. The method used was that of delayed coincidences and anticoincidences, and the range interval covered has been from about 10 to 320 g/cm² of air equivalent. In this interval our spectrum curve is found to be nearly flat; that is, it does not show a clear maximum around 200 g/cm² air equivalent, as indicated by several authors working at geomagnetic latitudes around 45°N.

I. INTRODUCTION

THE range and the momentum distribution of sea-level ordinary mesons (μ-mesons) have been investigated in the past years by several authors[1] working at geomagnetic latitudes around 45°N. Various techniques have been employed for this purpose: coincidence, anticoincidence, delayed coincidence, and magnetic deflection methods.

Although it is quite well known that only a very small percentage of the charged particles at sea level are protons, as yet little information is available on the energy distribution of these protons. For this reason, and also in order to get rid of the electronic component, without uncertainty, even at very low energies the method of delayed coincidences (which yields the complete separation of the mesons at rest taking advantage of their instability) appears to be the most suitable to investigate the low energy end of the meson spectrum. This technique has also the advantage of being much simpler and less expensive than the one based on the use of a Wilson chamber in a magnetic field. It cannot be profitably used, however, for an accurate determination of the absolute number of the observed mesons, since it is in general difficult to evaluate the efficiency of the apparatus for the detection of the electrons resulting from the decay of the stopped mesons.

To overcome this point, delayed coincidences and anticoincidences have been recorded simultaneously in

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[1] M. H. Shamos and M. G. Levy, Phys. Rev. **73**, 1396 (1948); A. Rogozinski and M. Lesage, Compt. rend. **227**, 1027 (1948); B. G. Owen and J. G. Wilson, Proc. Phys. Soc. (London) **62**, 600 (1949); E. W. Kellerman and K. Westerman, Proc. Phys. Soc. (London) **A62**, 356 (1949); W. L. Kraushaar, Phys. Rev. **76**, 1045 (1949); M. Sands, Phys. Rev. **77**, 180 (1950); M. Conversi, Phys. Rev. **79**, 749 (1950); L. Germain, Phys. Rev. **80**, 616 (1950); Glaser, Hamermesh, and Safonov, Phys. Rev. **80**, 625 (1950); Caro, Parry, and Rathgeber, Nature **165**, 688 (1950); M. G. Mylroi and J. G. Wilson, Proc. Phys. Soc. (London) **A64**, 404 (1951); B. G. Owen and J. G. Wilson, Proc. Phys. Soc. (London) **A64**, 417 (1951); J. L. Zar, Phys. Rev. **83**, 761 (1951); C. M. York, Phys. Rev. **85**, 998 (1952). For work previous to 1948, see B. Rossi, Revs. Modern Phys. **20**, 537 (1948); articles by G. Puppi and N. Dallaporta and by George in *Progress in Cosmic Ray Physics* (North-Holland Publishing Company, Amsterdam, 1952). An investigation on the spectrum of high range mesons has been recently published by Brini, Rimondi, and Filosofo, Nuovo cimento **9**, 505 (1952).

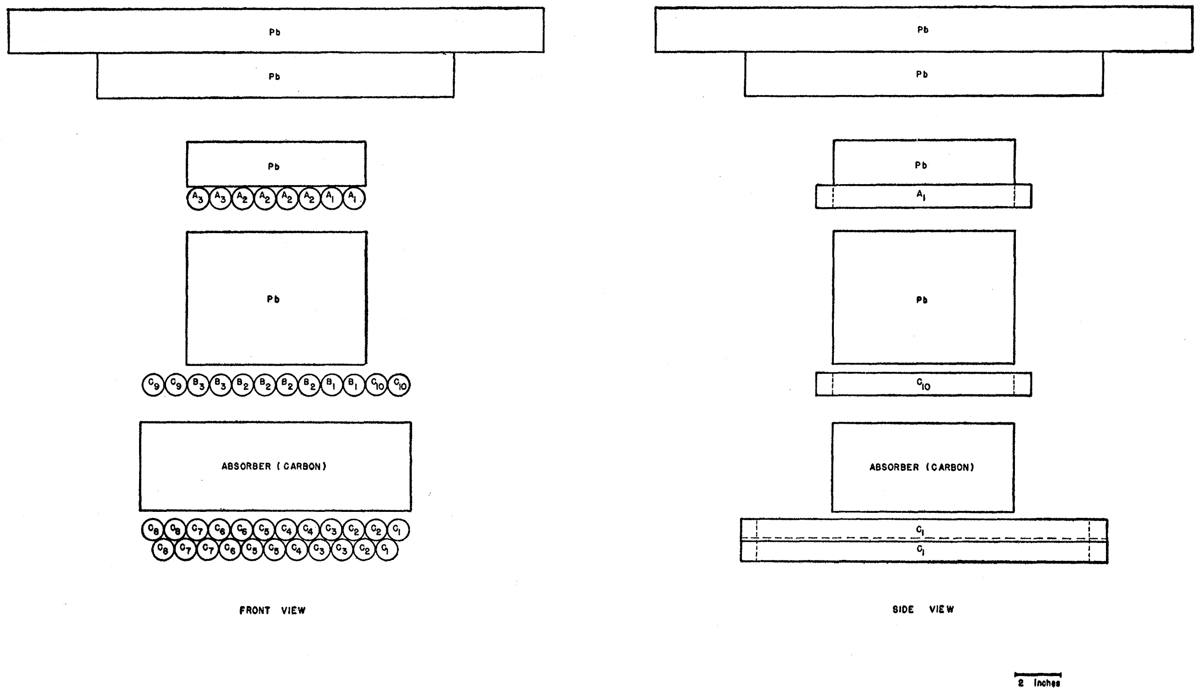

FIG. 1. Diagram of apparatus. The mesons actually recorded were those which, after crossing the counter telescope, were stopped in the graphite absorber and decayed between about 1.2 and 7 μsec into electrons discharging counters C.

recent experiments.[2] In this way the efficiency of the apparatus for the detection of the decay electrons can be directly derived from measurements taken under suitable conditions.

In the present experiment we have employed this method, though not much attention has been devoted to obtain a fully efficient anticoincidence system, since we were interested more in the spectrum shape than in the absolute numbers of mesons. Besides, apart from minor changes (see next section) we have employed the same apparatus designed and used by Conversi,[2] for which an accurate determination of the efficiency for the detection of the decay electrons was made in Chicago.

Actually the method used in the experiment reported in this paper yields the number of μ-mesons stopped in a given thickness of material (graphite) after crossing a certain variable amount of dense material, under the assumption that local production of π-mesons can be neglected. At the present stage of our knowledge, this assumption is certainly very reasonable at low altitudes, and, in particular, in the case of our experiment.

We thought that it might be of some interest to measure accurately a few points of the low range end of the meson spectrum at Río Piedras, Puerto Rico, in view of (a) the fact that the agreement among the results so far obtained by the various workers is not always very satisfactory, and (b) the possibility of comparing the shape of the meson spectrum at the relatively low geomagnetic latitude of our station (29°N) with that obtained in Chicago using essentially the same apparatus.

The range interval covered in our measurements was from about 10 to 320 g/cm^2 of air equivalent. The corresponding intervals in energy and momentum, as deduced from the conventional relationships[3] presumably valid for μ-mesons (rest energy = 110 Mev), are from 45 to 620 Mev and from 110 to 720 Mev/c, respectively.

II. EXPERIMENTAL PROCEDURE

As stated above, the apparatus used in the present experiment was essentially the same one employed in the experiments reported in reference 2. There is only a slight difference in the geometry, because we have preferred to use mostly 1-inch-diameter counters, as shown in the cross-sectional views of the disposition of the counters and absorbers reported to scale in Fig. 1.

All counters were of the all-metal type, had a 0.08-cm thick wall, and were filled with the usual argon-alcohol mixture. Counters with the same symbol and subscript were connected directly in parallel. The counters of group C were connected to a mixer circuit in order to mix their pulses and have each of them uncoupled with respect to all the others.

The following double coincidences were formed and then mixed together: (A_1, B_1+B_2), (A_2, B_2), and (A_3, B_2+B_3). Thus, apart from random events, each

[2] M. Conversi, Phys. Rev. **79**, 749 (1950).

[3] G. C. Wick, Nuovo cimento **1**, 302 (1943); D. J. X. Montgomery, *Cosmic Ray Physics* (Princeton University Press, Princeton, 1949).

of these double coincidences was caused by a particle whose direction crossed in general counters C (see Fig. 1). This was done, as it will be seen later, in order to reduce to a small fraction the number of random delayed coincidences. In what follows, all of the above double coincidences will be indicated as (AB). The coincidence circuit employed to obtain any of the coincidences (AB) had a resolving time of approximately 2μsec.

Counters C were at the same time in delayed coincidence and in anticoincidence with respect to any of the coincidences (AB). An event was actually recorded as an anticoincidence $(AB-C)$ if no counter C fired within about 1 μsec before, to 8 μsec after, the time of occurrence of a double coincidence (AB). If, instead, one of the counters C fired within about 1.2 to 7 μsec after the time of occurrence of a double coincidence (AB), the event was recorded as a "delayed coincidence" in one of the four channels of the electronic equipment.

More precisely, each of these channels had a "time width" θ of about 2.8 μsec, while the "time distance" between each of them and the next one was 0.96 μsec. In this manner, four points of the decay curve, corresponding to the mesons stopped in the graphite absorber after crossing the material placed above counters B, could be obtained simultaneously.

The pulse forming circuit triggered by counters C had a recovery time of 12 μsec. Consequently, random delayed coincidences could occur only when a single discharge of one of the counters C followed after a short time the instant of arrival of a particle producing a coincidence (AB) *but failing to discharge counters C.* If the counting rate of the latter events is indicated by $n_{(AB-C)}$ and n_C is the counting rate of counters C, the number of spurious delayed coincidences recorded per unit time in each channel is given by

$$N_r = n_{(AB-C)} n_C \theta. \tag{1}$$

This is found to be very small under the conditions of our measurements (see below). For further details about the pulse recording circuits and for the final calculation of the numbers of mesons stopped in the absorber the reader should consult Conversi's paper.[2]

To obtain the various points of the range distribution of the meson component, measurements have been taken with seven different thicknesses of material in, or above, the apparatus. Part of the measurements have been performed in a shelter on the roof of our building, with only about $\frac{1}{2}$ inch of wood and $\frac{1}{4}$ inch of roofing board over the apparatus, corresponding approximately to 3 g/cm² of air equivalent. Alternately 0-, 2-, and 4-inch thick absorbers of lead were placed between counters A and B in order to obtain three points of the meson spectrum.

For the other four points, corresponding to the higher energy region of the distribution curve, the apparatus was placed on the top floor of the building, quite close to the ceiling. A large box holding sand was prepared over the roof, directly over the apparatus. The box measured 9 feet by 9 feet and had a depth of 1 meter of sand. The apparatus underneath was covered with a 6-inch thickness of lead, placed between the ceiling and the top of the frame. With this arrangement the total solid angle of the counters was completely covered by the sand and by the lead.

The total amount of material (1 m of sand plus 6 inches of lead), which, during this part of the experiment, was kept over the apparatus, was equivalent to about 200 g/cm² of air. The additional four points of the meson spectrum were obtained in these conditions by putting alternately 0-, 2-, 4-, and 6-inch thicknesses of Pb absorbers between counters A and B.

The thicknesses of air equivalent, corresponding to the seven points of the distribution curve investigated in the present experiment, have been obtained using Wick's calculations.[3] One must also add 8 g/cm² of air equivalent (corresponding to the half-thickness of the graphite absorber) in order to obtain the average amount of air equivalent crossed by an incoming vertical meson before stopping and being observed. Thus, the thicknesses for such mesons are found to be 11, 44, 110, 215, 250, 285, and 320 g/cm² of air equivalent. These figures are not given with a greater accuracy because our results show that the intensity of the observed mesons is nearly constant in the range interval investigated (see Fig. 2).

As stated in Sec. I above, we were more interested in the shape of the meson distribution curve than in the knowledge of the absolute numbers of mesons. For this reason the anticoincidence counters employed in the present experiment did not include the D counters used in the measurements taken with the same apparatus in Chicago.[4] The lack of a full efficiency of the anticoincidence system does not allow us to properly utilize the $(AB-C)$ counting rates, in order to get the absolute numbers of mesons through a sufficiently accurate determination of the efficiency of the apparatus for the recording of the decay electrons. The anticoincidence counting rate $n_{(AB-C)}$ has been measured during the experiment merely to introduce the correction for the

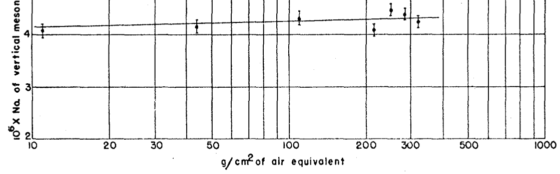

FIG. 2. The differential range spectrum of sea-level mesons at Rio Piedras, Puerto Rico—geomagnetic latitude 29°N. The absolute number of mesons per sec sterad g is represented as a function of their range expressed in g/cm² of air equivalent.

[4] See reference 2, Fig. 1.

spurious events, N_r, which becomes appreciable when no lead, or a small amount of lead, is placed between counters A and B.

III. RESULTS AND DISCUSSION

The seven points of the differential range spectrum of the sea-level mesons have been obtained through 1685 hours of effective observation. Each of these points was actually found by adding the results of a few (three or four) series of measurements performed in identical conditions, each partial series corresponding to a period of around 70 hours.

The results of the partial series were compared among themselves and their internal consistency was always found to be satisfactory. The recording of the delayed coincidences in four distinct channels allowed us to make, for each series of measurements, an evaluation of the meson lifetime τ. The values thus obtained for τ were found always to be in agreement with the best determination of this constant.[5]

It must be mentioned, however, that in part of our experiment only the delayed coincidences recorded in the last three channels have been considered, since unfortunately during these measurements the first channel of the electronic equipment did not work properly. In some of the partial series of measurements, therefore, not a very high accuracy was obtained in the determination of the number of stopped mesons and of their lifetime.

During the entire period of the performance of the experiment, checks were frequently made of the counting rate of the various groups of counters. In particular, the counting rate of the C group, which was necessary for the determination of the number N_r of random delayed coincidences, was recorded at the end of each individual measurement, namely, about four times per day. Frequent checks were also made of the pulse shape of the coincidence pulses and of other important points of the registering set, by means of a syncroscope.

The results of our measurements are summarized in Table I. In the first column of this table is reported the amount of material placed above the apparatus, plus that located between counters A and B, plus the half-thickness of the absorber, the total amount of material being expressed in g/cm^2 of air equivalent. As stated above, this represents the average range of the observed mesons (see Sec. II). The second column of the table contains the total time interval during which the corresponding data were obtained. The total number of spurious delayed coincidences occurring, within the time width of the channels, in the time interval specified in the second column, is reported in the third column.

For the sake of simplicity we are not reporting the numbers of counts recorded in each channel, but only the numbers of "extrapolated delayed coincidences,"

[5] N. Nereson and B. Rossi, Phys. Rev. **64**, 199 (1943). Also, see reference 2, and W. E. Bell and E. P. Hincks, Phys. Rev. **84**, 1243 (1951).

TABLE I. Results of measurements on the differential range distribution of sea-level mesons at a geomagnetic latitude of 29°N.

g/cm^2 of air equiv	Hours	Spurious counts N_r	Coinc./hr from mesons decaying within 0–2.8 μsec (N_0)	$10^6\times$number of mesons per sec, g sterad
11	212	27	5.1±0.16	4.07±0.13
44	210	9	5.2±0.16	4.15±0.13
110	210	8	5.4±0.16	4.31±0.13
215	263	11	5.1±0.14	4.08±0.11
250	264	8	5.6±0.14	4.48±0.11
285	263	9	5.5±0.14	4.40±0.11
320	263	7	5.3±0.14	4.25±0.11

corrected for the spurious counts N_r. These numbers, which we have indicated as N_0 and reported in counts per hour, appear in the fourth column of the table. They have been obtained by fitting through the points corresponding to the counting rates recorded in the channels, the "most probable" decay curves of 2.2 μsec lifetime. They represent, therefore, the most probable numbers of mesons stopped in the absorber and decaying between 0 and θ ($\theta=2.8$ μsec) into electrons which discharge at least one of counters C.

The statistical accuracy of the numbers N_0 indicated in the table is based on the standard deviations of the numbers of counts recorded in the four channels. The errors relative to the N_0's do not include the error in the determination of the minimum delay for which a delayed coincidence can occur. This minimum delay, as stated in Sec. II, was found to be nearly 1.2 μsec and its error is supposed to be smaller than the statistical errors of the N_0's. Similarly, the statistical uncertainty of the random delayed coincidences, N_r, has not been taken into consideration because it is very small and cannot appreciably affect the precision of our results. In the evaluation of the N_0 errors, allowance has been made, of course, for the fact that the channels are partially overlapping.

Also, in the determination of the extrapolated delayed coincidences and of their errors, we have closely followed the method described in reference 2, where the reader can find further information.

If p represents the average value of the probability that the decay electron of a meson stopped in the absorber discharges one of the C counters, then the total number of mesons stopped per unit time in the graphite absorber is given by

$$M=N/p[1-\exp(-\theta/\tau)]. \tag{2}$$

If, according to the determination of the constant p made in Chicago,[2] we assume $p=0.28$, we find that $M\approx 5N_0$. At 110 g/cm^2 of air equivalent this yields, according to the results of Table I, about 27.5 mesons per hour stopped in the 10-cm thick graphite absorber. In the same conditions 37 mesons per hour had been found in Chicago.[2] This corresponds to a ratio of about 1.35 between the intensities of mesons having ranges in the neighborhood of 100 g/cm^2 at the latitudes of

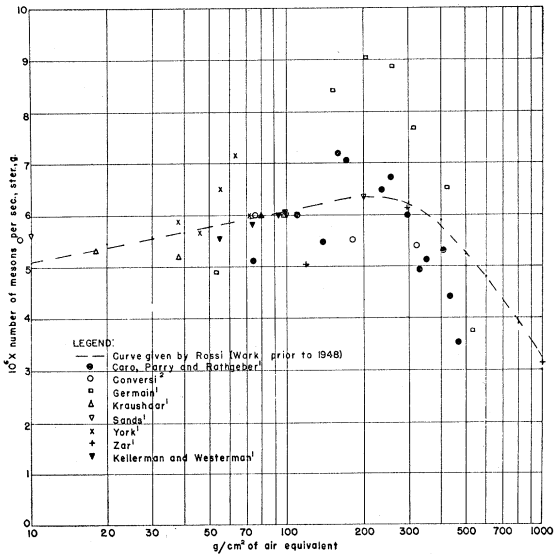

FIG. 3. A plot of most of the results obtained after 1948 on the differential meson spectrum. The dashed line represents the spectrum given by Rossi (see reference 6).

Chicago (46°N) and of Río Piedras (29°N). This ratio is smaller, but only slightly, than the ratio found for the same mesons and between the same latitudes at 30,000 feet above sea level.[6] Nevertheless, no great significance may be given to this comparison, on account of the relatively large statistical errors and also because the geometry of the apparatus was not exactly the same at the two stations where the observation have been made.

Again, following Conversi's paper, the absolute numbers of mesons (per sec steradian g) have been obtained by multiplying the results contained in the fourth column of Table I by 5 and then by the factor $16.\times 10^{-7}$. These absolute numbers are reported in the fifth column of the table. They have been used in the graphical representation of our results, which have been plotted in Fig. 2. This figure gives, in a semilogarithmic plot, the differential range spectrum of the mesons observed at Río Piedras.

For the purpose of comparison we have reported in Fig. 3 the results obtained by a number of authors in works performed after 1948, at geomagnetic latitudes around 45°. Where necessary, conversion has been made from momentum into range of air equivalent by means of the nomograms reported in appendix E of Montgomery's book.[3] All the results have been normalized so as to give approximately the same number of mesons around a range of 100 g/cm² of air. This number has been chosen as equal to 6×10^{-6} meson per sec steradian gram, a figure which is supported by the results of various experiments.[7] The results previous to 1948 have not been included in the figure because they were already analyzed by Rossi,[7] who gave the spectrum which we have also represented, by a dotted line, in the same figure. In the plot we have not shown the results obtained by Owen and Wilson and by others, because they refer to momentum higher than 1 Bev/c and are out of the range interval in which we are interested in relation with the present experiment.

Figure 3 shows that most of the recent results seem to be in agreement, within their statistical errors (not shown in the figure) with the general shape of the spectrum given by Rossi. This is actually true with the exception of Germain's work whose final data, however, were obtained by introducing very large corrections, which for greater ranges increased considerably the intensity of the recorded events. The results reported in Fig. 3 indicate the presence of a broad maximum around 200 g/cm² of air equivalent, and show that the spectrum decreases, but slowly, for lower ranges.

The spectrum obtained by us, instead, does not show any maximum in the range interval explored. The number of mesons seems, in fact, to be constant, within the statistical errors which are rather small, between about 10 and 320 g/cm² of air (Fig. 2).

A possible shift of the maximum of the spectrum towards greater ranges may be qualitatively accounted for in terms of a latitude effect. In fact, the average energy of the meson spectrum should increase with decreasing latitudes since the magnetic field of the earth is more effective for the primaries of lower energies. However, this fact should also cause a depletion in the low energy end of the spectrum at low latitudes, whereas it seems from the comparison of Figs. 2 and 3 that the differential spectrum obtained at 29°N geomagnetic latitude is even flatter than that deduced by measurements performed at high latitudes.

Further data should be collected, nevertheless, before drawing any definite conclusion from this slight difference. As a matter of fact, there is enough agreement between our results and those obtained at high latitudes with similar techniques (Kraushaar, Sands, and Conversi) to make us think that the cause of this apparent difference lies rather in the diversity of the methods employed than in an actual change of the meson spectrum with latitude.

We are indebted to Professor M. Conversi for suggesting and directing the research in its beginning during his short sojourn in Puerto Rico. We wish also to express our sincere appreciation to Professor S. K. Allison, Director of the Institute for Nuclear Studies of the University of Chicago, who made possible the loan of the main apparatus previously used by Dr. Conversi in Chicago.

[6] See Fig. 2 of reference 2. Professor Conversi has pointed out to us that the errors represented in this figure include also the error relative to the determination of the constant p. By this data the latitude ratio at 30,000 feet between 28.5°N and 40°N geomagnetic latitude is found to be 1.45 ± 0.1.

[7] B. Rossi, reference 1.