the ranges and the (negative) differences of the intensity rates of corresponding counting periods yielding a correlation coefficient of $r_{i,H} = -0.56$ and a "magnetic storm coefficient," $m = -1.97$ percent of cosmic-ray intensity per percentage range of H. The cosmic-ray intensities used for this correlation had been corrected for pressure and temperature.

Considering the fact that in our analysis not individual magnetic storm effects but rather a general mean of this effect is obtained, it is of the expected order of magnitude (-2 percent). In individual magnetic storms this effect may be -15 percent, in others almost zero.[15]

[15] S. E. Forbush, Terr. Mag. Atmos. Elec. **43**, 203 (1938). Following a suggestion of Dr. J. A. Fleming our results on day to day variations of cosmic-ray intensities were compared by Dr. S. E. Forbush with results from the Compton model C meter placed at the Observatory at Cheltenham, Maryland. It was found that variations observed at both stations over the whole 11-month period were in good agreement.

Summing up our results on time variations it has been shown that it is possible to get cosmic-ray data with sufficient accuracy over a period of one year with a very simple double coincidence counter telescope. They allow conclusions on the variation of the temperature effect during the year, on the seasonal effect, on air mass effects connected with the passage of lows or of cold and warm fronts and on the magnetic storm effects.

The authors wish to thank Dr. W. F. G. Swann for placing the facilities of the Bartol Research Foundation at their disposal. They also express their indebtedness to Dr. J. A. Fleming, Director of the Department of Terrestrial Magnetism, to Dr. James H. Kimball (New York Meteorological Observatory) and to the Meteorological Staff of the Airports in Newark and La Guardia Field, Queens, N. Y., for supplying the necessary magnetic and meteorological data.

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The Genetic Relation Between the Electronic and Mesotronic Components of Cosmic Rays Near and Above Sea Level

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The hypothesis that the cosmic-ray electrons observed at sea level are mostly due to the disintegration of the mesotrons has been tested (a) by comparing the ratio *soft component/hard component*, found at sea level in free air, with the same ratio found at 2050 m under a dense absorbing layer; (b) by comparing the Rossi curves for small showers under the same conditions; (c) by an especially detailed study of the increase of the soft component with increasing altitude. The results indicate that the proper lifetime of the mesotron is at least four microseconds and that the soft radiation observed at sea level is not entirely due to secondary processes of the mesotron.

§1. INTRODUCTION

IT is now generally believed that the mesotrons, which form the penetrating component of cosmic rays, are unstable and have a mean life of a few microseconds. The evidence bearing on this very important hypothesis is twofold. First, the instability of the mesotron easily explains the long known and puzzling fact of the anomalous absorption of the hard component in air.[1] Second, there is the evidence concerned with the secondaries ("disintegration electrons") emitted when the mesotron disintegrates.[2]

The work described in this paper is chiefly concerned with this second aspect of the problem, which seems to us to be in a far more unsettled state than is generally thought. The

[1] H. Euler and W. Heisenberg, Ergeb. d. exakt. Naturwiss. **17**, 1 (1938); see also B. Rossi, Rev. Mod. Phys. **11**, 296 (1939).

[2] The mesotron is usually identified with Yukawa's hypothetical particle which disintegrates spontaneously into an electron and a neutrino. H. Yukawa, Proc. Phys. Math. Soc. Japan **17**, 48 (1935); further literature in the papers of reference 1.

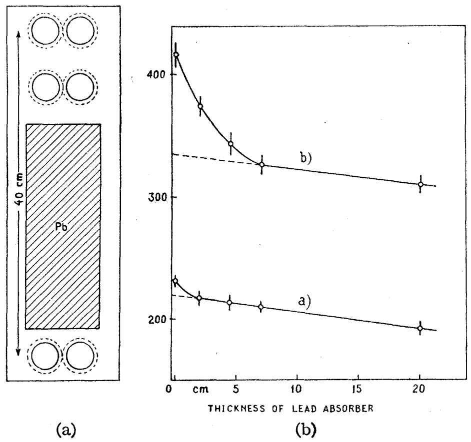

FIG. 1. (a) First arrangement of counter telescope. (b) Curve *a*, absorption curve of the vertical rays under a thick vault, equivalent to 4 or 5 m water; Curve *b*, absorption curve in open air; both curves at Rome.

striking confirmations which the instability hypothesis has received from experiments of the first kind have generated a strong confidence that the "disintegration electrons" can be found in some way. But—apart from *one* beautiful Wilson-chamber photograph obtained by Williams and Roberts[3] after the experiments here described were completed—a direct experimental confirmation of their existence is still wanting.

The evidence brought forward so far is indirect in that it is based on detailed calculations of certain delicate effects with the cascade theory of showers. Let us call E and M, respectively, the electronic and mesotronic components of cosmic rays; further, call R that part of the electronic component which is just degraded shower radiation due to electronic primaries of very high energy, I the electronic secondaries produced by the interaction of the mesotrons with the matter they traverse, and D the disintegration electrons. Thus the "R" component is independent of the mesotrons, and $E=R+I+D$. The "interaction component" I is known to be small. It may account for 20 or 25 percent of E, as given by our apparatus (see §3). The evidence mentioned above tends to prove that R is negligible at sea level, so that the main part of the soft component must be due to the disintegration electrons D. The evidence rests on three arguments: (1) Heitler's calculations[4] show that the latitude effect of the R component at sea level cannot exceed 1 percent. Therefore, *if the latitude effect of the soft component is about as large as that of the hard one* (10 percent), only a small fraction of the soft rays can be due to R; (2) the "difference curves" of Bowen, Millikan and Neher[5] follow closely the theoretical multiplication curves at great altitudes; near sea level they indicate the presence of an excess radiation which must be due to D; (3) the R component at sea level must be due to high energy primaries which are also responsible for the extended air showers and, according to Euler, for the large Hoffman bursts; from the known frequency of the large bursts Euler evaluates R at sea level and finds that it is negligible.[6]

On arguments (1) and (2) one may remark that the difference curve used in (2) must refer, of course, to the soft component alone. Thus both (1) and (2) rest essentially *on the latitude effect of the soft component at sea level*, the experimental value of which *is still uncertain, and may be quite small.* Thus it is difficult to prove a contradiction even with the extreme—and probably untrue—assumption that $D=0$, since in this case the latitude effect to be expected (taking into account the I electrons) would be 3 or 4 percent, which is not quite incompatible with the experiments.[7]

As regards argument (3), we shall come back to it in the last section. In the experiments described in this paper we have tried to follow

[3] E. J. Williams and G. E. Roberts, Nature **145**, 102 (1940).

[4] W. Heitler, Proc. Roy. Soc. **161**, 261 (1937); also L. W. Nordheim, Phys. Rev. **53**, 694 (1938).

[5] J. S. Bowen, R. A. Millikan and H. V. Neher, Phys. Rev. **52**, 80 (1937); H. J. Bhabha and W. Heitler, Proc. Roy. Soc. **159**, 432 (1937); J. F. Carlson and J. R. Oppenheimer, Phys. Rev. **51**, 220 (1937); H. Snyder, Phys. Rev. **53**, 960 (1938); R. Serber, Phys. Rev. **54**, 317 (1938).

[6] H. Euler, Zeits. f. Physik **116**, 73 (1940); we are deeply indebted to Professor Heisenberg for telling us about these results before the publication.

[7] For a discussion of the results on the latitude effect until 1938 see: T. H. Johnson, Rev. Mod. Phys. **10**, 193 (1938). More recently P. Auger, R. Grégoire, R. Maze and B. Goldschmidt, Comptes rendus **209**, 794 (1939) have found that the small showers are, if at all, much less latitude sensitive than the vertical coincidences. This may indicate that the latitude effect of the soft component is smaller than 5 percent. The same authors have also measured the latitude effect of the vertical coincidences with and without a lead shield between the counters; they do not state, however, whether a value for the latitude effect of the soft component can be safely inferred from their results. See also G. Occhialini, Comptes rendus **208**, 101 (1939).

a more direct line of attack, based on the simple theoretical prediction that the number of disintegration electrons in equilibrium with the hard rays in a dense medium should be negligible (perhaps 2 percent of the hard rays). Hence if the intensities of the soft and hard components are measured first at sea level in free air and then at a certain height above sea level under a layer of dense material having, as closely as possible, the same atomic number as air and equivalent in stopping power to the air layer between the two altitudes, one should find: (a) many more electrons in the first experiment, if the electrons present at sea level are mostly disintegration electrons, (b) the same number of electrons in both experiments, if the electrons are *not* disintegration electrons.

Measurements under conditions approaching those of the first or the second case can be found in the literature, but it is hard to judge whether a comparison is allowed. This is, perhaps, the reason why certain results of Auger[8]—who found $E/M=0.30$ under a layer of ice 4 m thick at Jungfraujoch, and again, the same value at sea level in free air—have not been regarded as a serious objection to the disintegration hypothesis. In our experiment, described in §4, the two measurements were made, of course, with the same apparatus and the conditions were as similar as was feasible.

The experiment, however, has failed to give any certain sign of the existence of the disintegration electrons; this can be understood if the R component is not entirely negligible at sea level, so that the fraction due to the D electrons becomes smaller. From the quantitative discussion we draw the conclusion (§7) that the proper lifetime of the mesotron must be at least four microseconds.

This lower limit is in contradiction with some recent careful determinations by the "anomalous absorption" method;[9] it is compatible, however, with other equally recent results by the same method.[10]

The evidence from the experiment in §4 has been extended and substantiated by a study of the Rossi curves for small showers (§5) under the same conditions as in the previous section, and by an investigation of the increase of the soft component with altitude in the immediate vicinity of sea level (§6). Previous results of Cacciapuoti[11] had already shown that the increase of the soft component is somewhat more rapid than one would expect on the hypothesis that the electrons observed near sea level are the result of the disintegration of the mesotron.

§2. Apparatus

All the measurements have been made with Geiger-Müller counters having a cylindrical brass cathode enclosed in glass and filled with an argon-alcohol mixture following the prescriptions of Trost[12] (10 percent alcohol, pressure 11 cm). The thickness of the counter walls (including the cathode) was equivalent to about 4–5 mm Al. The useful length of the counters was about 28 cm. All the counters had an

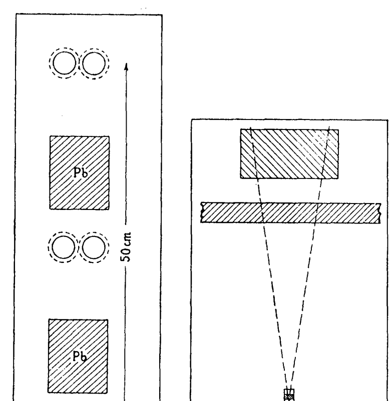

FIG. 2. (a) Second arrangement of counter telescope. (b) Position of the telescope relative to the roof and absorbing layer of earth (Cervinia 2050 m).

[8] P. Auger and L. Leprince Ringuet, *Les Rayons Cosmiques* (Actualités Scient. Hermann 340, Paris, 1936); P. Auger, L. Leprince Ringuet and P. Ehrenfest, J. de phys. et rad. **2**, 58 (1936).

[9] B. Rossi, H. van Norman Hilberry and J. Barton Hoag, Phys. Rev. **57**, 461 (1940); W. M. Nielsen, C. M. Ryerson, L. W. Nordheim and K. Z. Morgan, Phys. Rev. **57**, 158 (1940).

[10] M. Ageno, G. Bernardini, B. N. Cacciapuoti, B. Ferretti and G. C. Wick, Ricerca Scient. **10**, 1073 (1939); Phys. Rev. **57**, 945 (1940); M. A. Pomerantz, Phys. Rev. **57**, 3 (1940).

[11] B. N. Cacciapuoti, Ricerca Scient. **10**, 680 (1939).

[12] A. Trost, Zeits. f. Physik **105**, 399 (1937).

efficiency of 97 or 98 percent under working conditions.

The measurements of §3—which were already completed when the main work was planned—were made with the counter telescope shown in Fig. 1(a). Lead absorbers were inserted as shown in the figure. The pairs of neighboring counters were connected in parallel and were used as single counters.

For the later work (§§4 and 6) the geometry of the telescope was slightly improved, as shown in Fig. 2(a), but apart from this no essential change was introduced in the apparatus. In all these measurements with counter telescopes the triple coincidences between the three pairs were measured at the same time as the double coincidences between the two extreme pairs. The excess of the double over the triple coincidences was, of course, mostly due to chance coincidences, and gave a useful check on the regularity of operation of the apparatus. As a further check the number of single pulses from each counter was determined at intervals of an hour.

§3. The "Interaction" Electrons (Component *I*)

The intensity of the *I* component of the soft radiation can be determined by a measurement of the number of electrons in equilibrium with the mesotrons under a layer of dense material fulfilling the following conditions: The depth below sea level must be sufficient to make it quite certain that the degraded shower radiation is negligible; on the other hand, if the result has to be used as an indication of the *I* component in air, the depth should not be so large as to cause a great change in the spectrum of the hard component;[13] finally, the distance of the counter set from the dense layer should be large enough to prevent any effect due to the coherence of secondaries.[14]

Although such measurements have already been made several times, we thought it advisable to make a new determination. A counter telescope (Fig. 1(a)) was set vertically under the center of one of the great vaults of the Basilica di Massenzio (Rome). The minimum thickness of these vaults has been evaluated at about 4 or 5 m (water equivalent). The counters were about 30 m under the top of the vault; under these conditions we measured the absorption curve of the radiation in lead. Since the counters were mounted in a thin Al box on a rolling table, they could be removed every second hour from under the vault into free air, where the absorption curve was also taken for comparison. The results, which were reported in a preceding paper,[15] are summarized in Table I and in Fig. 1(b).

We evaluate the intensity of M by linear extrapolation from the 7 cm and 20 cm lead points to 0 cm; E is then obtained by difference from the zero lead point. In this way we get: $E/M=0.05$ under the vault; $E/M=0.25$ in free air, in accord with the results of Auger,[8] and—as regards the value in air—of many others.[16]

Under the vault, E should consist only of I electrons; the atomic number Z of the elements contained in the vault is somewhat larger than that of air. Since it is unlikely that I/M is a decreasing function of Z, we conclude that,

Table I. *Threefold coincidences per hour.*

Pb cm	0	2	4.5	7	20
Under the vault	230.8 ±4.3	218.8 ±5.8	214.0 ±6.2	211.6 ±4.3	191.6 ±5.3
In free air	413.1 ±9.6	375.7 ±9.7	343.7 ±9.9	327.3 ±8.5	316.2 ±8.4

Table II. *Threefold coincidences per hour.*

Pb cm	Cervinia (2050 m) Under 170 g/cm²	Under 7 g/cm²	Under 170 g/cm²	Under 7 g/cm²	Rome (50 m) In Free Air
0	283±6.8	405±7.9	295±7.5	383±13.8	225±4.2
5	240±4.8	286±7.5		279± 7.9	184±3.7
10	210±4.8	252±5.2	227±5.3	247± 8.9	174±3.3
20	206±5.6	240±5.8	210±5.4	244± 8.4	168±3.5

[13] W. M. Nielsen and K. Z. Morgan, Phys. Rev. **54**, 246 (1938); see also J. R. Oppenheimer, H. Snyder and R. Serber, Phys. Rev. **57**, 75 (1940).

[14] L. Jánossy, Proc. Roy. Soc. **167**, 499 (1938).

[15] G. Bernardini, B. N. Cacciapuoti and B. Ferretti, Ricerca Scient. **10**, 731 (1939). Since this experiment plays an essential role in the final discussion (§7) we have asked Drs. Santangelo and Scrocco to repeat the experiment with a slightly different apparatus in a wide gallery, 6 m high, 5 m wide, under a limestone layer equivalent to about 10 m of water. They have found $E/M\approx 0.05$. (To appear shortly in the Ricerca Scient.)

[16] B. Rossi, Zeits. f. Physik **82**, 151 (1933); P. Auger, *Kernphysik* (Springer, Berlin, 1936); R. H. Woodward and J. C. Street, Phys. Rev. **49**, 198 (1936).

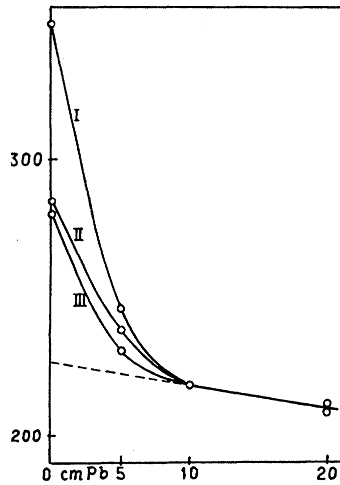

FIG. 3. Comparison between the absorption curves for vertical rays. Curve I, at Cervinia (2050 m) under a thin roof; Curve II, at Cervinia under an absorbing layer 170 g/cm² thick; Curve III, at Rome (50 m) in open air (under 0.5 mm Al). Curves I and II have been multiplied by suitable factors so as to make the points at 10 cm of lead coincide.

also in air, I/M cannot be larger than about 5 percent of M, or about 20 percent of the total electronic radiation measured by our apparatus in free air.

§4. THE DISINTEGRATION ELECTRONS (COMPONENT D)

We now come to the experiment whose principle was laid down in the introduction.[17] A counter telescope (Fig. 2(a)) was brought to Cervinia (2050 m) and placed vertically in a large room 4.2 m high. The concrete roof of the room was covered with a layer of earth 6×2 m broad, 1 m high weighing 1.3 tons/m². The underlying part of the roof had a weight of about 0.4 ton/m² so that the total mass above the counters was 170 g/cm². The general arrangement is shown in Fig. 2(b). The absorbing layer could be considered as roughly equivalent in absorbing power to the air layer between 0 and 2050 m altitude. It was, in fact, somewhat less than equivalent in g/cm², but account must be taken also of the slightly greater atomic number of the material ($Z=10$ or 12). The electronic component under that layer can, therefore, be compared with that present at sea level, in the sense that has been previously explained.

Under these conditions we measured the absorption curve of the vertical rays in lead, together with the absorption curve in lead under a thin wooden roof of about 7 g/cm² thickness, the two measurements being made in four alternative runs, the results of which are given in the columns 2 to 5 in Table II.

The data for the absorption curve in free air near sea level (Rome), with the same apparatus, are given in the sixth column; during this measurement the apparatus was enclosed in a thin aluminum box (0.5 mm thick).

These results are also represented in Fig. 3. The intensity of the hard component has been extrapolated linearly, as before, from the 10- and 20-cm lead points, and the soft component has been obtained by difference from the zero lead point as before. One finds:

(a) at Cervinia under a 170 g/cm² layer $E/M=0.27\pm0.03$
(b) at Cervinia under a 7 g/cm² layer $E/M=0.56\pm0.03$
(c) at Rome under practically 0 layer $E/M=0.27\pm0.03$

As stated previously, the intensity of the D electrons should be negligible under the thick layer; I is not greater than 0.05 M. Hence, we should expect the value (a) to be considerably smaller than (c). So the rather large number of electrons found in case (a) is puzzling; it must be largely due to electrons which are *not* secondaries of the mesotron, and which are able to make themselves felt through the thick layer. Hence, also, at sea level a considerable fraction of the soft component must be due to the degraded shower radiation R (discussion in §7).

§5. THE ROSSI CURVE

The results just described are in harmony with those of Auger and his collaborators,[8] but they are a little difficult to reconcile with the instability hypothesis. We have, therefore, sought an independent check in the study of the transition curve for small showers at Cervinia under a layer of concrete and bricks of about 175 g/cm²[18] and for comparison at Rome in free air in a thin aluminum box (0.5 mm thick) and within the Physical Institute of the University under 35 g/cm² of concrete. At great depths, where the soft rays are certainly in equilibrium with the hard component, the Rossi curve exhibits only a rapid increase unto saturation without any marked maximum; it was, therefore, of interest to see whether the Rossi curve under the thick

[17] Preliminary reports have been published—Ricerca Scient. **10**, 809 (1939) and **10**, 1010 (1939).

[18] For certain reasons these measurements could not be made exactly at the same place as those of §4; the absorbing layer, however, was roughly equivalent.

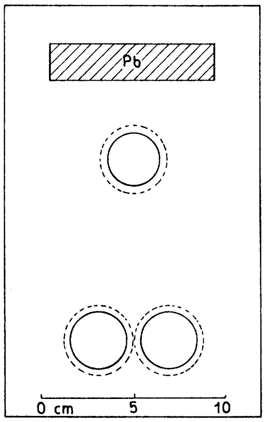

FIG. 4. Arrangement of coincidence set of three counters.

layer of Cervinia would exhibit the ordinary maximum or not.

The measurements were made with a coincidence set of three counters (Fig. 4) having a useful length of 27 cm and very similar to the counters used in the previous work. Lead plates were placed on the apparatus as shown in the figure. The arrangement is far from ideal: It has a strong bias for very small showers, and so the maximum of the Rossi curve is not so high as with other arrangements; the maximum occurs at a lead thickness somewhat smaller than the ordinary one, which is also understandable. The arrangement was chosen merely because of the high rate of counting, which was a great advantage, owing to the short time available at Cervinia. The results are given in Table III and Fig. 5(a).[19]

Thus even under the dense layer there is a pronounced maximum followed by a marked decrement which strongly indicates the existence of an electronic component which is not yet in equilibrium with the mesotrons, thus confirming our previous conclusions.

There is, nevertheless, a certain difference between the three curves of Fig. 5(a), which requires some comment. The maximum for the free air curve is considerably higher than in the two other curves. The interpretation of this fact is not unique; it may be due to the fact that the electrons observed under a layer of concrete are more degraded than the electrons in air (the mean atomic number of the medium is higher than that of air, and so the critical energy of shower theory is lower; the height of the maximum is quite sensitive to a change in the ratio *electron energy/critical energy* as is shown by the fact that the maximum is 10 times as large under lead as under aluminum). It might also be interpreted as an indication of the presence of disintegration electrons in air. In view of the results of §4, the first interpretation seems more likely.

At any rate it must be strongly emphasized, that the marked decrease after the maximum, observed at Cervinia under the thick layer, cannot be simply due to a transition effect from concrete to lead. In order to secure this point, the measurements have been extended recently to greater depths below sea level.[20] The measurements were made in the Physical Institute in Rome, under concrete layers of 35, 100 and 160 g/cm^2, respectively. The apparatus was always kept at a distance from the ceiling comparable to that in Cervinia. The result is given by the three curves of Fig. 5(b). Curve 3° shows clearly that, with our apparatus at least, no transition effect can explain the shape of the curve found in Cervinia. The comparison of the two curves, measured under comparable thicknesses of dense matter, namely curve 3° of Fig. 5(a) and curve 3° of Fig. 5(b) is very striking and lends strong support to our previous conclusions.

§6. INCREASE OF THE SOFT COMPONENT WITH HEIGHT

The curve of the logarithmic intensity of the vertical rays (electrons+mesotrons) as a function of depth below the top of the atmosphere shows a definite change of slope just above sea

TABLE III. *Frequency of showers* (*per hour*).

PB CM	CERVINIA (2050 M) UNDER 175 G/CM^2	ROME (50 M) UNDER 35 G/CM^2	ROME (50 M) IN FREE AIR
0	23.0±1.4	20.6±1.1	17.6±0.8
4		38.0±2.3	51.6±1.6
8	42.7±2.7	45.6±1.7	66.6±1.6
12	41.8±2	46.5±1.6	72.8±1.6
16	41.4±2.2	48.2±2.6	71.3±2.2
28	36.1±2		51.8±1.8
50	29.9±1.8	29.3±1.6	37.9±1.9
100	25.8±1.5	24.8±1.5	24.7±1.6

[19] See also G. Bernardini, B. N. Cacciapuoti, Ricerca Scient. 10, 933 (1939).

[20] We wish to thank Dr. G. Palmieri for her valuable collaboration in these measurements.

level (Pfotzer[21]). The same holds, of course, for the experiments with ionization chambers, but we prefer here to think of the vertical rays only. The change of slope indicates the increasing importance of the hard component.

For our problem it would be of interest to see whether *the curve for the soft component alone* exhibits a similar bend. It is certain that at 3500 m there is still some degraded shower radiation. If the electrons at sea level were entirely due to secondary processes of the mesotron, then the bend should occur between 3500 m and sea level and should be detectable by a sufficiently detailed study in this region.

Some preliminary results of Cacciapuoti have been extended[11] and the results are presented here. Previous measurements by others were chiefly concerned with higher altitudes; in experiments near sea level only two rather distant points (as, for instance, 0 and 3500 m) had been compared, as far as we know. We have aimed at a greater detail and accuracy, using also the intensity of the hard component as a check on the consistency of the results as will be presently shown. By means of the counter telescope (Fig. 2(a)) several absorption curves of the vertical rays in lead have been determined at Rome (50 m), Antey (1050 m), Cervinia (2050 m) and Pian Rosà (3460 m). The different thicknesses of lead were interchanged at intervals of an hour. At Rome the measurements were made in an aluminum box, with 1 mm thick walls; at Antey and Cervinia under a thin roof (about 3 g/cm² thick), at Pian Rosà within a wooden hut. The triple coincidences measured, together with the statistical standard errors are given in Table IV.

We shall assume that these coincidences represent single particles going through the counter telescope; actually two corrections should be made, one for air showers and one for a slight change of efficiency of the apparatus at the greater altitudes, due to the greater number of single pulses in each counter; it was found[22] that the two corrections were both small and nearly canceled each other.

By means of Table IV we can compare the

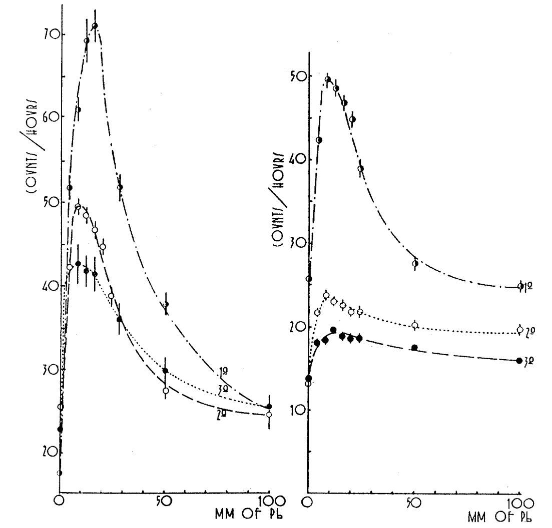

FIG. 5. (a) Rossi curves for small showers at Cervinia (2050 m) and Rome (50 m). 1°—Rossi curve at Rome, open air (under 0.5 mm Al); 2°—Rossi curve at Rome under a layer of concrete 35 g/cm² thick; 3°—Rossi curve at Cervinia under a layer 175 g/cm² thick. (b) Rossi curves at Rome (50 m) under various absorbing layers. 1°—Concrete layer 35 g/cm² thick (same curve as 2° of (*a*)); 2°—Concrete layer 100 g/cm² thick; 3°—Concrete layer 160 g/cm² thick.

intensity *versus* altitude curves of the soft and hard components. In order to get an idea of the effect on the final result of the somewhat arbitrary assumptions which must be made in the separation of the total intensity into the contributions due to the two components, we have examined several assumptions (Fig. 6).

As regards the hard component M, we have drawn two intensity *vs.* altitude curves (the two upper curves in the figure), assuming that M is proportional to the radiation, M', filtered by 10 cm of lead, or alternatively to the radiation M'' filtered by 20 cm of lead. The two curves are sufficiently smooth—an indication of the constancy of the apparatus during the measurements—and consistent with each other.[23] They are also in accord with the well-known absorption anomaly in air; this is shown by the full dots, which are the points of the curve for M'', shifted to lower altitudes corresponding to a change in pressure by 70 g/cm², the mass of air

[21] G. Pfotzer, Zeits. f. Physik **102**, 41 (1936).

[22] For the method used in evaluating the corrections see our paper of reference 10.

[23] The two points at 3460 m are not very satisfactory, however; the quite large absorption between 10 and 20 cm of lead is puzzling; we hope to investigate this point in greater detail.

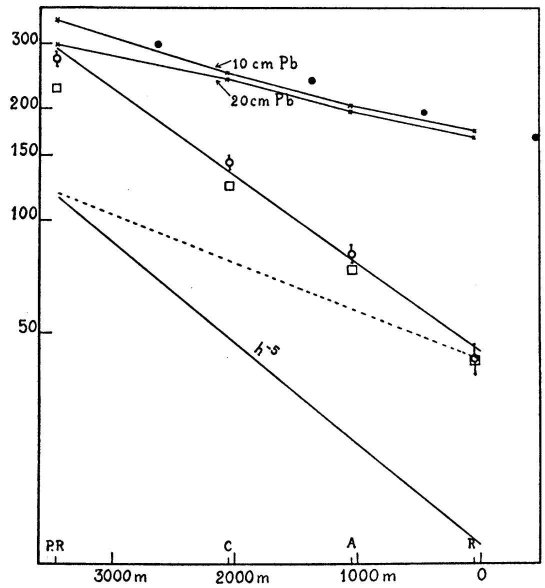

FIG. 6. Law of increase with height of the various components of cosmic rays (vertical intensity). The abscissae give the height above sea level. The points marked *P.R.*, *C*, *A* and *R* correspond to Pian Rosà, Cervinia, Antey and Rome, respectively. The intensities (log scale) are coincidences per hour. The two upper curves give the intensity of the hard component, filtered by 10 and 20 cm of lead, respectively. The anomalous absorption of the hard component in air is exhibited by the black dots as explained in the text. The open circles and the square dots give the intensity of the soft component evaluated in two different ways. The dotted line gives the number of electronic secondaries due to the disintegration of the mesotron, to be expected if the proper lifetime of the mesotron is 2 microseconds. The straight line marked h^{-5} represents for comparison the law of increase of small showers found by Regener and Ehmert[27] between 350 and 760 mm Hg.

which should be equivalent in stopping power to $20-10=10$ cm of lead, if there were no anomaly.[10] The full dots lie consistently higher than the curve for M', as one should expect if the absorption in air is anomalously large.

As regards the soft component E, we have first assumed E to be proportional to the difference between the total intensity and the intensity of the radiation filtered by 5 cm of lead, as given by the second and third columns, respectively, (Table IV). The result is represented by the square dots in Fig. 6. Strictly speaking, the quantity which must be subtracted from the total intensity is the intensity M_0 of the hard component extrapolated to zero lead thickness. Assuming a constant absorption coefficient $\mu=0.005$ cm^{-1} for the hard component in lead, we may evaluate M_0 from the data of the fourth or alternatively the fifth column of Table IV ($M_0=1.05\ M'$ or alternatively$=1.10\ M''$). Taking the arithmetical mean of the two values thus obtained and subtracting from the total intensity we get the E values corresponding to the open circles in Fig. 6. (The errors indicated are purely *statistical* and do not include, therefore, the (probably larger) uncertainties involved in the procedure of extrapolation.)

Now, looking at Fig. 6, we do not see any evidence of a bend in the curve for the soft radiation. Unfortunately the accuracy of the E values is rather poor and a small bend could well escape our notice. Nevertheless it is nearly certain—especially in view of the similar result previously obtained by Cacciapuoti[11]—that the slope of the E curve *at sea level* is definitely larger than the slope of the M curve, and also larger than the slope to be expected for the D electrons. These are given in the figure by the dotted line.

Thus the results of this section also lend some support to the conclusion that *the soft radiation observed at sea level is not entirely due to secondary processes of the mesotron.*

§7. DISCUSSION

Euler and Heisenberg[1] have given a widely used formula for the number D of disintegration electrons in equilibrium with the mesotronic component M

$$D/M=\frac{9}{8}\frac{X_0 mc}{E_0\tau_0}, \qquad (1)$$

neglecting a small term, unimportant in air. Here m is the mass of the mesotron, E_0 and X_0 are, respectively, the critical energy and the unit length of shower theory (in the Bhabha-Heitler form). In this theory the energy loss per cm path due to ionization is: $a=\ln 2\cdot E_0/X_0$

TABLE IV. *Threefold coincidences per hour, for various absorber thicknesses.*

ALTITUDE	0 CM PB	5 CM PB	10 CM PB	20 CM PB
3460 m	620 ±13	391.5±7.7	348±6	300 ±6
2050 m	407 ± 6.7	283 ±5.4	251±4.4	241.5±4.8
1050 m	297 ± 6	224 ±5	205±4.5	196 ±4.2
50 m	224.5± 4.2	184 ±3.7	174±3.2	168 ±3.5

so that the above formula becomes

$$D/M = 0.78\frac{mc}{a\tau_0}. \tag{1a}$$

Using a simple idea of Williams,[24] we may show that these formulae probably give a somewhat exaggerated value for the ratio D/M. As is well known, the probability of disintegration dw of a mesotron of momentum p in the path dx is $dw = (m/p\tau_0)dx$. The disintegration electron gets, on the average, half the mesotron energy, that is $\frac{1}{2}cp$ (assuming $p \gg mc$). As Williams points out, the total electron path in the shower initiated by the disintegration electron can be evaluated without a detailed knowledge of the multiplication mechanism, since the whole energy must be finally dissipated by ionization, assuming a constant energy loss per cm path: a, the total electron path in the shower must be given by $cp/2a$. From this it easily follows that the ratio D/M is:

$$D/M = \tfrac{1}{2}mc/a\tau_0, \tag{2}$$

which is about 0.64 times the value given by (1) and (1(a)).

Williams' assumption of a constant ionization loss is admittedly rough, but in the detailed shower theory even cruder assumptions have to be made. Actually formula (2) should, rather, give an upper limit, since it includes the total electronic path, while a counter telescope only counts electrons from a certain energy upwards. This correction is probably quite large; on the other hand, in deriving (2), we have neglected the fact that the D electrons belong to showers started at a greater altitude, let us say 3 or 4 units X_0 (that is roughly the distance after which a shower reaches its maximum size) above the place where D and M are measured. This means that the evaluation has to be raised by 10 or 20 percent. Taking the two corrections together, we still think that (2) should represent an upper limit.

Because of the fact that the energy loss a is proportional to pressure, the ratio (2) must slowly increase with increasing altitude, as already remarked by Euler and Heisenberg. Thus the dotted line of Fig. 6 has a slightly greater slope than the curve for the hard component.

Let us now consider the results of §§3 and 4 more closely. The experiment of §3 is important in that it shows that the large number of electrons found at Cervinia under the dense layer cannot be simply due to a large increase of the I component in clay as compared to air (due to the difference in atomic number). We shall assume that I is always of the order of 5 percent of M. As already stated, we take the data at Cervinia under the dense layer (§4) as a measure of the number $I+R$ of "interaction"+"degraded shower radiation" electrons which one should find at sea level in open air. Then we find (referring all intensities to $M=100$):

$$I+R = 27\pm 3$$
$$I+R+D = 27\pm 3,$$

so that:

$$D = 0\pm 4.2 \quad \text{or:} \quad D<10 \tag{3}$$

as a statistically safe upper limit.

If we accept the upper limit (3), then a lower limit to the proper lifetime of the mesotron ensues (Eq. (2)):

$$mc/a\tau_0 < 1/5.$$

If we take $a = 3000$ ev/cm, $mc^2 = 80$ Mev we finally get:

$$\tau_0 > 4.4\times 10^{-6}\ \text{sec}. \tag{4}$$

In Eqs. (3) and (4) we have so far considered the statistical errors only. The most dangerous source of errors, however, may lie in coherence and other geometrical effects. Auger and Grivet have found,[25] for instance, that the apparent intensity of the soft component (that is the absorption by the first 5 or 10 cm of lead) is much increased if one of the counters is protected by lateral screens.

It is not entirely clear whether one is justified in taking the values obtained in this way as a true measure of the soft component; at any rate, the experiment shows how strongly results can be affected by such factors. We incline to the view, however, that the use of lateral screens in

[24] E. J. Williams, Proc. Roy. Soc. **172**, 194 (1939); an evaluation on very similar lines of the *ionization* due to the disintegration secondaries has been recently published by B. Rossi, Phys. Rev. **57**, 469 (1940).

[25] P. Auger and T. Grivet, Rev. Mod. Phys. **11**, 232 (1939).

such experiments can introduce disturbing secondary effects (like the creation of showers in the shield by rays which pass through the two upper counters and miss the lower one).

Until such problems are clarified by further experiments, we shall accept the lower limit (4) with great caution, especially in view of the low values for τ_0 obtained by some authors.[9] On the other hand, the recent discovery by Fermi[26] of an effect of density on ionization losses should mean that the older evaluation of τ_0 by Euler and Heisenberg[1] must be increased well above three microseconds.

Let us now examine to what extent conclusion (3) is compatible with Euler's argument (see §1). Euler shows that the spectrum of the primary rays probably follows a power law with an exponent $y=1.8\pm0.17$; then, assuming $y=1.8$, he shows that the intensity of R at sea level is only $\frac{1}{5}$ of the electronic radiation observed. Now from (3) we see that only 37 percent of the electrons, at most, can be due to D, and only about 60 percent can be secondaries of the mesotron at all $(I+D)$. So R is at least 40 percent of the observed radiation. The discrepancy from Euler is only a factor 2, which is compatible with the uncertainty of the exponent y as given by Euler.

As Professor Heisenberg has kindly pointed out to us, however, the value of y not only determines the value of R at sea level, but also—and perhaps more accurately—the slope of the intensity *vs.* altitude curve. From Serber's table[5] we find

$$\begin{array}{cccc} & y=1.6 & 1.7 & 1.8 \\ -\dfrac{1}{R}\dfrac{dR}{dh}= & 0.397 & 0.435 & 0.470, \end{array}$$

where h, the depth below the top of the atmosphere, is measured in units of shower theory ($h=25$ corresponds to sea level). According to our measurements (Fig. 6) the soft component in the vicinity of sea level may well increase according to the law $E\sim h^{-5}$ found by Regener and Ehmert[27] for the small showers. Component I must increase like the hard component M and component D like M/h, according to (2). Thus we find, at sea level,

$$-\frac{h}{I}\frac{dI}{dh}=1.3, \quad -\frac{h}{D}\frac{dD}{dh}=2.3, \quad -\frac{h}{E}\frac{dE}{dh}=5.$$

Assuming the percentage of I as known (20 percent) the percentages of D and R are then determined. One finds that R/E takes the values 0.38, 0.34, 0.31 according as $y=1.6$, 1.7 or 1.8. This evaluation is admittedly rough because of the low accuracy of the slope for the E curve, but it shows at least that there is *no very serious discrepancy* between our conclusions and Euler's work. The slope for the E curve might be smaller than $5/h$ and then R would become negligible. On the other hand it is hardly likely that the slope is *larger* than $5/h$. Hence the above evaluation might be used to show that the percentage of the electronic radiation due to the R electrons cannot exceed 40 percent.

We wish, finally, to mention an evaluation of τ_0 by Pomerantz,[10] on lines somewhat similar to ours. He evaluates $I/M=0.05$ in air, in accord with our value. He then finds that the ratio E/M is 0.19 and concludes, neglecting the degraded shower radiation altogether, that D/M is 0.14. From this ratio, and by means of Eq. (1), he then deduces the value $\tau_0=6$ microseconds. Although this value of τ_0 is in agreement with our conclusions, some differences must be pointed out. If, instead of (1), we use formula (2) we get, from $D/M=0.14$, a value $\tau_0=3.2$ microseconds (which, by the way, is in better accord with the other values found by Pomerantz by a different method). Moreover, the rather low number of soft rays found by Pomerantz illustrates once more how sensitive such measurements are on the apparatus. If we had treated our value $E/M=0.27$ in the same manner as Pomerantz, that is, neglecting the shower radiation altogether, we would have found 2 microseconds.

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[26] E. Fermi, Phys. Rev. **57**, 485 (1940).
[27] E. Regener and A. Ehmert, Zeits. f. Physik **111**, 501 (1939).