Electronic Component of Cosmic Rays in the Low Atmosphere. II. Experimental

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A comparison is made between the results of some cosmic ray counter experiments and the numerical values obtained in a preceding paper (Part I—Theoretical) for the number of secondary electrons in the low atmosphere. This comparison seems to give the following conclusions: (1) Even at 3000–4000 meters above sea level the electron component is not in equilibrium with the meson component, regardless of what may be the background of slow mesons. (2) At 3500 meters above sea level the electronic component contains some electrons of high energy which are not secondaries of mesons with 2.3×10^{-6} sec. lifetime. (3) The slow mesons are negligible at sea level and their intensity increases rapidly with height, roughly as the electron component.

I. ELECTRONIC COMPONENT

IN the preceding paper[1] we have deduced theoretically some simple formulae by means of which it is possible to evaluate the number of secondary cosmic ray electrons in the low atmosphere.

In the present paper we shall compare the numerical values obtained from these formulae with some results of counter experiments. For such a comparison we shall refer first of all to experiments in which an attempt has been made to separate distinctly the electron and meson components by means of the shower generating property of electrons. Experiments of this kind have been performed by Bernardini and Cacciapuoti,[2] Aiya and Saxena,[3] and by Hall,[4] but the experimental device used by Aiya and Saxena for the detection of showers was probably not sufficient for the purpose. Hall's apparatus is very similar to the one used by Bernardini and Cacciapuoti although the evaluation of the shower intensity is more indirect on account of the lower efficiency of the shower detecting counter system.

The apparatus used by Bernardini and Cacciapuoti is indicated in Fig. 1. Counters 1, 2, and 3 form a normal vertical telescope, while the counter sets (a,b) and (c,d) under the lead layer S (1.5 cm thick) work as detectors for the showers (or for mesons accompanied by secondaries) arising from S. Counters 1, 2, and 3 are connected to a threefold coincidence apparatus and each group (a,b) or (c,d) to a twofold coincidence device. We also counted the fivefold coincidences arising from twofold and threefold ones. According to a rough geometrical estimate, the probability for a group of at least two particles to be detected by the twofold coincidence set was rather high (about 75 percent), while a single particle crossing the telescope 1, 2, 3 could generate no twofold and, therefore, no fivefold coincidence. The measurements were performed with different lead absorbers, A. In this way, the threefold coincidences gave a normal absorption curve, while the fivefold coincidences detected the following events: (a) mesons crossing 1, 2, 3 and therefore A, but emerging from S accompanied by a secondary particle; (b) electrons crossing counter 1 and generating in S a shower at least one electron of which traverses A.

We must point out that the solid angle for mesons which cause the fivefold coincidences was possibly different from the solid angle for electrons. This cause of error is not peculiar to our device, e.g., it appears also in Hall's device, yet possibly with less consequence. The particles emerging from S with large deflection angles are, however, likely to be removed by A so that the difference between the two solid angles may be rather small when $A\neq 0$. In any case, in the following we shall deal essentially with direct comparisons between different values of the electron component only.

With the apparatus just described some

[1] G. Bernardini, B. N. Cacciapuoti, and R. Querzoli, Phys. Rev. **73**, 328 (1947).
[2] G. Bernardini and B. N. Cacciapuoti, Ricerca Scient. **10**, 981 (1941).
[3] S. V. C. Aiya and R. C. Saxena, Phys. Rev. **66**, 183 (1944).
[4] D. B. Hall, Phys. Rev. **66**, 321 (1944).

measurements have been performed at two different heights, at sea level, and at 3500 meters.

Unfortunately, our device was particularly sensitive to side showers. This cause of error is certainly the most important one and for this reason, generally, counter experiments may seem objectionable. In order to estimate the effect of side showers, we have counted the threefold and fivefold coincidences with counter 1 situated in the position 1′ of Fig. 1; a second run was made by shifting the whole upper set of counters to one side (those on the Al support).

In both cases we found that for $A=0$ and at 3500 meters the side showers gave over one-third of the pulses obtained with counters 1, 2, 3 on a vertical line. However, the measurements taken with counter 1 shifted to position 1′ show the same variation with height as the fivefold and threefold coincidences, within the experimental errors. Moreover, the intensity ratio of these showers (about 1 to 9) between sea level and 3500 meters agrees fairly well with the average ratio observed by many authors for not very wide showers in air. These two circumstances lead us to believe that a satisfactory correction for side showers may be obtained by subtraction of the

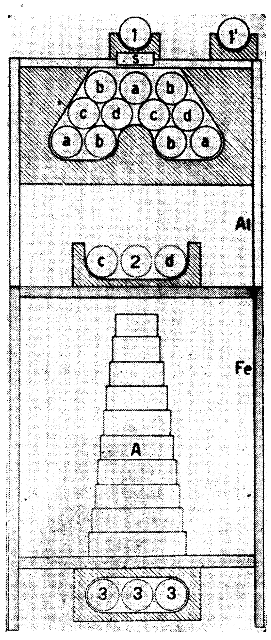

FIG. 1. Experimental arrangement of Bernardini and Cacciapuoti.

three and fivefold coincidences with counter 1 in position 1′, from the three and fivefold coincidences with counters 1, 2 3 in the normal position.

The results of the fivefold coincidence measurements, corrected as mentioned above, are depicted in Fig. 2. In the two curves we can distinguish clearly a background of collision electrons and a part due to atmospheric electrons.

The secondaries in lead have been calculated by means of formula (11) of the foregoing paper[1] and the full curves indicate the theoretical results for a cut-off, $\eta=4$ Mev, and a geometrical efficiency of 75 percent. We wish to point out that, on account of the large angle covered by the twofold counter system, the scattering is not so dangerous, as in other devices.

The curves are in very good agreement with the experimental points; yet the multiplication factor for the curve at 3500 meters, in order to make it agree with the experimental data, is a little higher than the corresponding factor at sea level (0.85 instead of 0.75). Therefore, we believe that our correction for side showers is too small at 3500 meters and that the whole curve at this height must be reduced by a factor about 1.15. In the following, we shall take account of this correction, although the comparison between Hazen's measurements and those of Nassar and Hazen shows an intensity variation for the secondaries arising from lead which agrees with ours and although the threefold coincidences seem to indicate that these ultimate corrections are excessive.

With this correction, if we subtract from the two curves the background due to collision secondaries (and this can now easily be done), we find that the two "difference" curves are similar and that the intensity ratio is 1:5.4.

Hall's experiment allows us to make a further determination of the increase with height of the electron component. Hall's measurements refer to only one level (4500 meters) but his results show that the electrons which can generate a shower arising from 1.5 cm Pb (as those considered in our experiment for $A=0$) have an intensity which is 18 percent of the meson intensity. According to the meson intensity increase with height, we find that the intensity increase of the electron component between sea

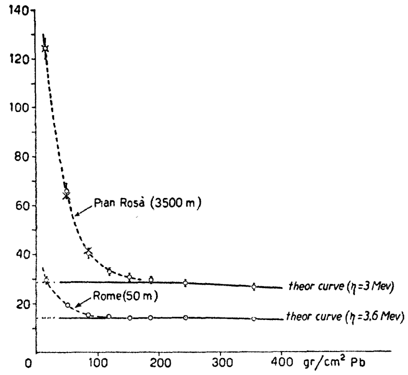

FIG. 2. Fivefold coincidences corrected for the side showers. The full lines give the evaluated knock-on electrons in Pb. The x points in Pian Rosà curve are obtained from the Rome curve by multiplying by a factor 6. The evaluated factor, if the electrons in atmosphere would be generated only by mesons of $2.3 \cdot 10^{-6}$ sec. lifetime, would be 3.5.

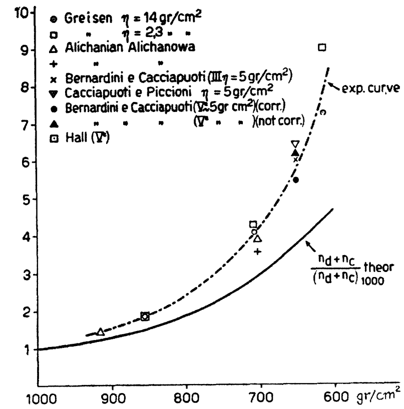

FIG. 3. Theoretical and experimental curves for the electron component.

level and 4500 meters is in the ratio of 1 to 9. This ratio may be overestimated on account of the different solid angles for the mesons and for the electrons, but in Hall's device the error is certainly small.

The full curve in Fig. 3 represents the electron component obtained from the tables in Section III of our foregoing paper[1] and from similar calculations for 4500 meters and 2000 meters for $\eta = 10$ Mev (the cut-off value does not affect the ratio much); the points are the experimental data obtained by Hall and other authors, including the rough values obtained from normal absorption curves (corrected for side showers).

If the correction for side showers does not affect the measurements with a great error (and the Wilson chamber experiments seem to indicate that it does not), we believe it is possible to conclude that, even at 3000–4000 meters *the electron component is certainly not in equilibrium with the meson component, regardless of what may be the background of slow mesons* ($E < 200$ Mev).

This statement can be checked, furthermore, by the following considerations. Bhabha,[5] in a recent paper, gives a very useful formula which establishes the maximum penetration t (given in radiation units) of a shower as a function of the ancestor electron energy. For $t \geqq 4$ Bhabha's formula seems to be correct to within 2 percent.

With reference to Fig. 2 and to the calculated behavior of the background due to the knock-on electrons in lead, it is possible to deduce the electron spectrum at 3500 meters above sea level. The results of these calculations are reported in Fig. 4. As abscissa, we have plotted the log of energy values (measured in 100 Mev) and as ordinate, the intensity of the electronic component (setting the intensity corresponding to 100 Mev equal to 100). The experimental points are deduced from the experiments performed by Hall and by us. The full line curve indicates the spectrum we should expect according to the calculations of Stanton if only electrons generated by $2.3 \cdot 10^{-6}$ sec. lifetime mesons were present. The electronic component, therefore, seems to consist of electrons of high energy in amount greater than what would be predicted on the base of Stanton's calculations. We have checked these calculations and we found that Stanton's results are substantially correct. We must then conclude that, at 3500 meters altitude, *the electronic component contains some electrons of high energy which are certainly not secondaries of mesons with* $2.3 \cdot 10^{-6}$ *sec. lifetime.* We may formulate several hypotheses in the origin of these electrons; the simplest one is to assume that the generation of $2.3 \cdot 10^{-6}$ lifetime mesons in the high atmosphere is accompanied by a generation of other mesons with a shorter lifetime. We will come back to this point in a later paper.

II. THE SLOW MESONS

We shall now discuss the problem of the slow mesons and establish at the same time a more

[5] H. J. Bhabha, Proc. Ind. Acad. Sci. **XIX**, 23 (1944).

careful comparison with the tabulated data in section 3 of our preceding paper,[1] and some other results on the electron component.

Let us consider, therefore, the absorption curve at sea level represented in Fig. 5; this curve is obtained with the consistent measurements of many authors and especially with the data of Cacciapuoti and Piccioni[6] and of Greisen.[7]

In order to separate the meson from the electron component in this curve, let us disregard momentarily the existence of slow mesons, generated locally. Then, since intensity variation of the meson component in the low atmosphere agrees very well with the disintegration hypothesis, for $\tau/\mu c^2 = 2.9 \cdot 10^{-8}$ sec./Mev[8] we can start from the meson absorption curve at 2000 meters[8] and calculate the low energy end of the integral spectrum of mesons at sea level. The dotted curve in Fig. 5 represents the result of such calculation. This curve has been adjusted so as to fit the experimental value corresponding to 170 g/cm² Pb.

Now, if we subtract the fivefold from the threefold coincidences obtained in the measurements of Bernardini and Cacciapuoti, we have directly the points indicated with a cross. When corrected for geometrical efficiency, these points lie practically on the calculated meson curve.

Notwithstanding the possible criticism mentioned above, we believe that this agreement is not purely accidental and that, *at sea level, the local generation of slow mesons must be considered as negligible when compared with the total meson intensity.**

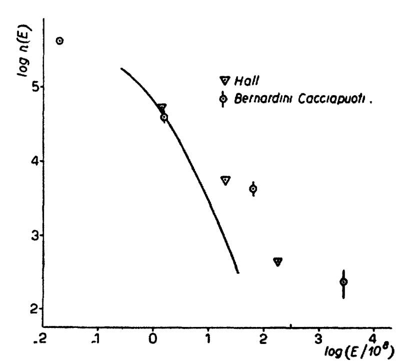

FIG. 4. Electron spectrum at 3500 meters.

We can then establish a quantitative comparison between the calculated values in our preceding paper[1] and the difference of the two curves in Fig. 5; we attribute this difference mainly to the presence of electrons. For this, we must find an energy-range relation. It can be given directly by some measurements of Bernardini and Franchetti[9] and by the data kindly supplied to us by Professor E. Amaldi, on the penetration in Al and Pb of Compton electrons generated by gamma-rays of 17 Mev from D+Li. With this energy-range relation we obtained, for the soft part of the electron spectrum at sea level, the curve indicated in Fig. 6, where the experimental points can also be seen. The agreement is very good and we conclude that, at sea level, the electronic component is mainly composed of the secondary electrons of the $2.3 \cdot 10^{-6}$ lifetime mesons.

Considering that the above mentioned energy-range relation is referred only to the maximum penetration (in counterwall and screens) of low energy electrons, we have tried to correct the theoretical curve of Fig. 5. Using a rough approximation for the behavior of our experimental absorption curves of mono-energetic electrons, we found that the theoretical curve in Fig. 5 must be modified as is indicated by the dotted line in Fig. 7. The full line gives the experimental curve. It can be seen that the two curves are quite similar and the electrons surely do not seem to be less than the calculated ones.

A similar analysis can be done on the absorp-

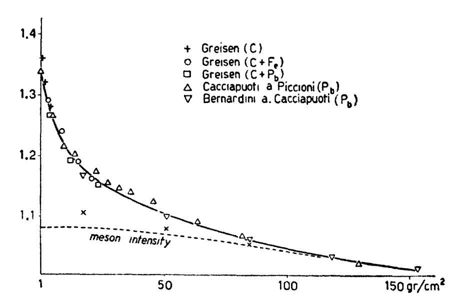

FIG. 5. Absorption curve at sea level.

[6] B. N. Cacciapuoti and O. Piccioni, Nuovo Cimento **I**, 3 (1943).
[7] K. I. Greisen, Phys. Rev. **61**, 212 (1942).
[8] See, for example, G. Bernardini, Zeits. f. Physik **120**, 413 (1943).

* This conclusion is checked by the results of J. G. Wilson, Nature **158**, 414 (1946).
[9] G. Bernardini and S. Franchetti, Ricerca Scient. **8**, 406 (1937).

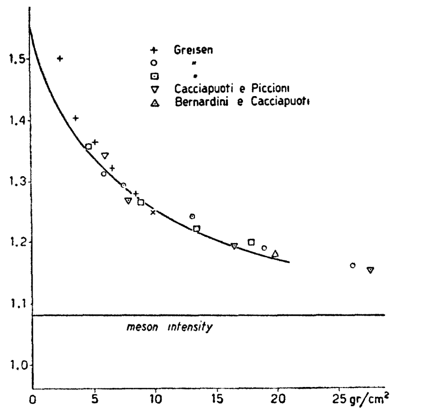

FIG. 6. Soft part of electron spectrum at sea level.

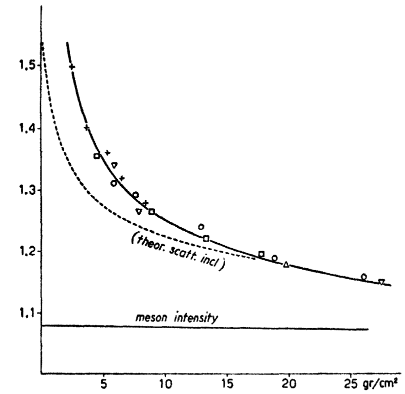

FIG. 7. Correction to the theoretical curve of Fig. 5.

tion curve at 3500 meters. For this we took the results of Bernardini and Cacciapuoti[2] and those of the experiment performed by Cacciapuoti and Piccioni[5] in which a very accurate absorption curve for the first 200 g/cm^2 has been obtained for Pb and Al. The two curves have then been treated in the manner followed by Auger[10] in his discussion on the nature of the soft component.

Our analysis leads to the conclusion that some slow mesons probably exist at 3500 meters, but their number is not higher than 10 percent of the total meson component, and they certainly do not constitute the whole part of the soft component in excess of the electron component generated by mesons with an energy beyond 200 Mev; this is in disagreement with what seems to be the opinion of Alichanow and Alichanian.[11] Hall has found, however, at 4500 meters, a number of slow mesons that is twice as large, and Schein, Wollan and Groetzinger[12] report that they have detected 30 percent of the meson component, at 6700 meters, in the energy band between 2.9 and 5.2×10^8 ev. We must then conclude that the number of slow mesons increases very rapidly with height; i.e., about at the same rate as the soft component. Therefore, we should argue once more that an intimate bond exists between this band of slow mesons and the electron-photon component. We believe, however, that the excess in the electron component must not be considered as a product of the disintegration of these slow mesons, in disagreement with the opinion of several authors.[13] A simple calculation shows indeed that the disintegration products of such mesons are quite insufficient, in number and in energy, in order to account for so large a contribution to the electron component. On the contrary, it can be thought that the slow mesons may be partially due to the electron-photon component (pairs, etc.).

[10] P. V. Auger, Phys. Rev. **61**, 684 (1942).

[11] A. Alichanow and A. Alichanian, J. of Phys. USSR **9**, 73 (1945).

[12] M. Schein, E. C. Wollan and G. Groetzinger, Phys. Rev. **58**, 1027 (1940).

III. CONCLUSIONS

As a conclusion of this discussion we may argue:

(1) At sea level no objection can be raised against the hypothesis that the penetrating part (beyond 10 cm. Pb) of cosmic radiation consists mainly of mesons with a $\tau/\mu c^2 = 10^{-8}$ sec./Mev, which disintegrate into an electron and a neutrino, because the electron component accompanying these mesons does not seem to be in default, but rather in excess of what should be expected for the equilibrium condition between the two components.

(2) The electronic component at 3000 to 4000 meters above sea level is, in large part, composed of electrons which do not arise from the disinregration of the above mentioned mesons.

(3) The slow mesons are negligible, at sea level and their intensity increases rapidly with height, roughly, as the electron component.

(4) It is likely that the slow mesons are secondaries of the electron-photon component because the electron-photon component is composed also of high energy electrons.

[13] See, for instance, M. Schein, W. P. Jesse, and E. O. Wollan, Phys. Rev. **57**, 847 (1940).

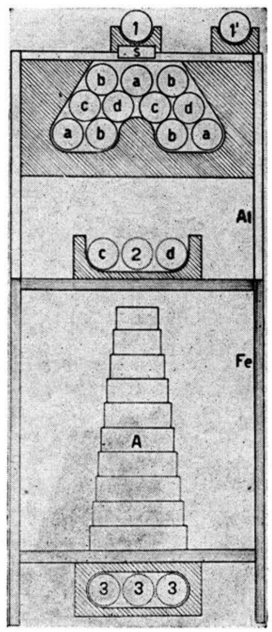

FIG. 1. Experimental arrangement of Bernardini and Cacciapuoti.