The Intensity of Cosmic-Ray Electrons Relative to Mesotrons at Sea Level

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A cloud-chamber analysis of the electronic component of cosmic rays at sea level has been carried out with no distorting magnetic field. Electrons were identified by their behavior while passing through lead absorbers, and their energies were determined from the ranges, for low energies, and from the shower sizes, for high energies. The processes of mesotron collision and decay in air account for all of the observed electrons. The results are in agreement with the hypothesis that the mesotron decays into one electron and one neutrino.

INTRODUCTION

RECENT experiments and calculations have shown that all of the electrons observed at low altitudes can be accounted for in terms of mesotron collisions and decay processes.[1–3] Greisen's experimental results,[1] however, indicated a deficiency of electrons as far as the usual picture of mesotron decay is concerned, and he consequently suggested the possibility of a three-particle decay (two neutrinos and one electron).

Counter experiments involve so many important corrections and auxiliary experiments when it is desired to separate electron and mesotron initiated phenomena that there is considerable uncertainty in the results. Some of the corrections and, in some cases, the primary observations themselves are based on theoretical calculations that have never been adequately verified in the realm of cosmic-ray energies. For example, figures for the penetration of electron showers in lead are based on types of analysis that have never claimed accuracy of better than 20 percent insofar as approximations in the calculations themselves are concerned,[4] to say nothing of the lack of quantitative experimental verification of the radiation probabilities at high energies.

In view of the difficulties in the analysis of counter data, a preliminary experiment has been performed with a direct observation technique (Wilson Cloud chamber) that eliminates all of the aforementioned difficulties. Direct observations of the absorption of individual rays were made, and these observations, together with simultaneous confirmatory observations of scattering, ionization, change in ionization, and shower production, leave virtually no uncertainty in interpretation. The critical question of lower energy limits for the lower energy electrons involves collision loss, which has been well verified, and only a small amount of radiation loss. Since there was no magnetic field, the lower energy end of the spectrum was undistorted.

EXPERIMENTAL ARRANGEMENT

The cloud chamber was in the form of a cylinder of 30-cm diameter and 30-cm length. Six lead plates in the chamber, the upper three of 2-mm and the lower three of 7-mm thickness, acted as absorbers and aided in the identification of individual cosmic rays. The plates were faced with aluminum-foil reflectors so thin that their absorption was negligible. It was found that the thermally-dependent characteristics of cloud-chamber operation were very uniform throughout the chamber when the lead plates terminated an inch or two in front of the black velvet. The illumination was provided by argon flash tubes, as in previous work, but the high voltage of the power source (17 microfarads charged to 10,000 volts) necessitated the use of an "ignitron" switch in series with the flash tubes. The operation of the cloud chamber was initiated by three counter tubes placed above the chamber. The counters defined a volume that was in the observed region and that was completely intercepted by the lead plates. The counter cathodes were thin films of colloidal graphite painted directly on the glass walls. A hinged door in the

* Now at Universidad Nacional, Panama.
[1] K. Greisen, Phys. Rev. **63**, 323 (1943).
[2] H. E. Stanton, Phys. Rev. **66**, 48 (1944).
[3] D. B. Hall, Phys. Rev. **66**, 321 (1944).
[4] H. J. Bhabha and S. K. Chakrabarty, Proc. Roy. Soc. **A181**, 267 (1943).

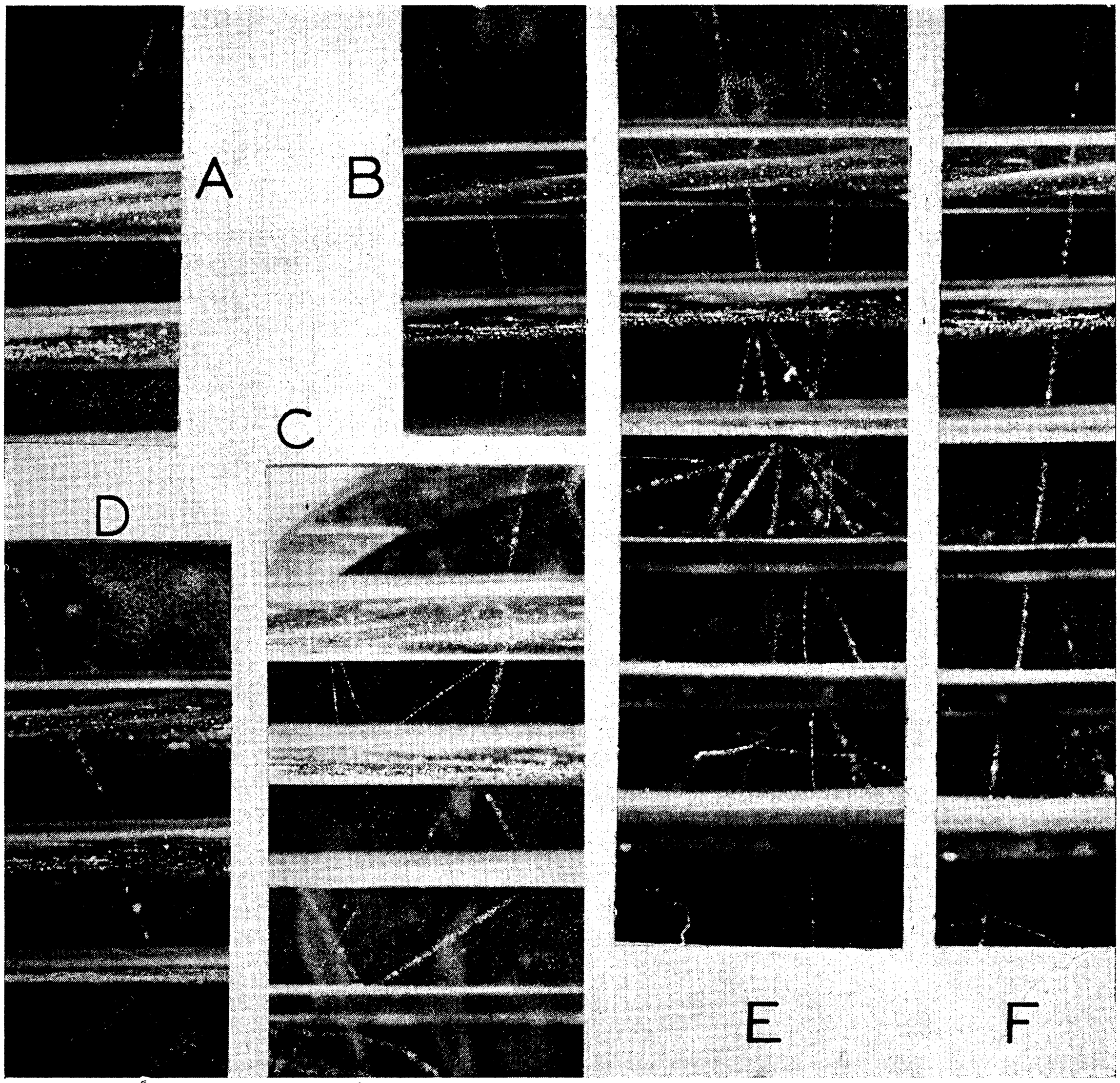


FIG. 1. Photographs illustrating various classifications of particles. (*A*) An electron with $6.6<E<10$ Mev. (*B*) An electron with $10<E<14.5$ Mev. (*C*) An electron with $21.5<E<83$ Mev. (*D*) An electron with $14.5<E<21.5$ Mev. (*E*) An electron with $250<E<500$ Mev. (*F*) A mesotron with $p>1.3\times10^8$ ev/c.

sheet-metal roof allowed the elimination, during favorable weather, of all absorber above the apparatus. Stereoscopic photographs were taken with 13.5-cm lenses and 35-mm film.

METHOD OF ANALYSIS

The minimum electron energies required for penetration of the various absorbers were calculated by numerical integrations of the curves for the rate of energy loss as a function of energy. The rate of energy loss due to electron collisions was obtained from Richtmyer and Kennard.[5] In the case of glass, an average value for A/Z and A was determined from the relative abundance of the constituents. This procedure is justified by the facts that A/Z is nearly $\frac{1}{2}$ for all the constituents, and Z enters only in a logarithm term.

[5] Richtmyer and Kennard, *Introduction to Modern Physics* (McGraw-Hill Book Company, Inc., New York, 1942), p. 682.

The rate of energy loss due to radiative collisions was obtained from curves interpolated between those of Heitler[6] for H_2O, Cu, and Pb. The equivalent radiation unit of length, which is used in the calculations of the asymptotic radiation probability for high energy and in the calculation of the energy loss from the radiation probabilities, was obtained by use of Eq. (1.29a) of Rossi and Greisen.[7]

The lowest energy rays that could be observed in the chamber were those that had penetrated 1.52 cm of glass. A numerical integration of the energy loss *versus* energy curve for glass indicates a minimum energy of 6.6 Mev for an electron to reach the interior of the cloud chamber. Some of the photographs were taken with an iron door of 1.0-mm thickness above the counters, and in this case the lower energy limit was 7.7 Mev. The remaining photographs were obtained with two sheets of iron and a layer of insulation board above the apparatus with a consequent raising of the lower energy limit to 9.6 Mev. In passing through the iron the energy loss of these low energy electrons is approximately one-third radiation loss. The resulting uncertainty in energy of individual rays arising from the large fluctuations in radiation loss involves only one-tenth of the total energy loss and therefore is not important. With the glass as the only absorber, radiation loss is negligible.

TABLE I. Observed numbers of electrons.

Absorber	E limit	No. of electrons	Electrons per mesotron
1.52 cm glass	6.6 Mev	52	38 percent
+2 mm Pb	10	38	28
+4 mm Pb	14.5	31	23
+6 mm Pb	21.5	27	20
+13 mm Pb	83	19	14
(showers)	100	10	7.3
	250	0	0
	500	0	0
Mesotrons		136	
1.52 cm glass and 1 mm Fe	8.1	71	31.5
+2 mm Pb	11.5	57	25
+4 mm Pb	16.5	44	19.5
+6 mm Pb	24	29	13
+13 mm Pb	90	19	8.5
(showers)	100	15	6.7
	250	6	2.7
	500	3	1.3
Mesotrons		225	
1.52 cm glass, 1.55 cm Celotex, and 1.4 mm Fe	9.6	70	31
+2 mm Pb	13.5	55	24.5
+4 mm Pb	18.5	43	19
+6 mm Pb	28	31	14
+13 mm Pb	93	22	10
(showers)	100	17	7.5
	250	3	1.3
	500	0	0
Mesotrons		225	
(showers)*	100	16	6.0
	250	9	3.4
	500	3	1.2
Mesotrons		267	

* The last four lines are from data of S. Nassar.

The second group of electrons, those that penetrated the first 2-mm lead plate but stopped in the second, would have larger fluctuations in energy loss since a larger fraction of the energy is dissipated in radiation, but the fluctuations would still be small. In the case of electrons that penetrated three or more lead plates, the radiation losses become comparable with collision losses, and the fluctuations in energy loss begin to limit the usefulness of data consisting of small samples in the determination of an energy spectrum at high energies. Electrons that penetrated any of the thicker lead plates nearly always gave rise to showers, and their energies could be estimated from the size of the shower.

Slow mesotrons that stopped in the chamber could be distinguished by the lack of multiplication, by the small scattering, and by the increased ionization in the last air space traversed. Actually there was only one such particle, and it was a post-expansion traversal. Illustrative photographs are shown in Fig. 1.

Only counter tripping particles were considered. These were identified from the track widths as far as time of occurrence was concerned and from the parallax in the stereoscopic photographs as far as position was concerned. These criteria were critical only in identifying the few cases where more than one particle passed through the counters simultaneously, particles that were separate before striking the apparatus. There

[6] W. Heitler, *Quantum Theory of Radiation* (The Clarendon Press, Oxford, 1936), p. 173.
[7] B. Rossi and K. Greisen, Rev. Mod. Phys. **13**, 240 (1941).

were only a few such cases, such as air showers and mesotrons accompanied by electron secondaries that had been produced in air. These few cases were not important when considering total numbers of particles.

RESULTS AND CONCLUSIONS

The results are summarized in Table I in terms of actual numbers of observed rays, and, in the last column, the observations are reduced to numbers of electrons relative to the numbers of mesotrons with $H\rho > 4.2\times 10^5$ gauss-cm or p (Rossi units) $> 1.3\times 10^8$ ev/c. The counter system defined a solid angle that restricted the rays essentially to the vertical. Rossi and Klapman[8] have calculated the number of electrons with $E > 10^7$ ev to be expected as a result of both the collisions and also the decay of mesotrons. Greisen[1] has made calculations for other lower energy limits that involve averaging over-all zenith angles. Since his average is not significantly different from the results of Rossi and Klapman for lower energy limit 10^7 ev, the results will be used as they stand for comparison with the experimental data. The theoretical values of Greisen for decay electrons have, however, been multiplied by 100/68 in order to reduce the figures to number of electrons per mesotron with $p > 1.3\times 10^8$ ev/c. The results are given for a mesotron mass of 180 and lifetime of 2.2 microseconds. Greisen's figures for collision electrons have likewise been multiplied by 64/68 to reduce the values to number of electrons per mesotron with $p > 1.3\times 10^8$ ev/c.

A comparison of the calculated and the measured values is made in the graph of Fig. 2. It is seen that the agreement is tolerable; i.e., it is probably within the uncertainties of the calculations and measurements. The scatter of the experimental points indicates the magnitude of the statistical uncertainties. As far as systematic errors in the data are concerned, it is believed that the points for the lowest three energies may be relatively too low since there existed some possibility of not detecting a ray that stopped in the first lead plate. As mentioned earlier, the points in the vicinity of energies 20–30 Mev and greater depend significantly on radiation theory which has not been carefully verified at these high energies. The points at energies greater than 70 Mev involve shower theory which also has not been quantitatively verified. But the estimates of energies are based on detailed observations of the showers and therefore are more reliable than counter observations which depend on a rather specific property in many cases.

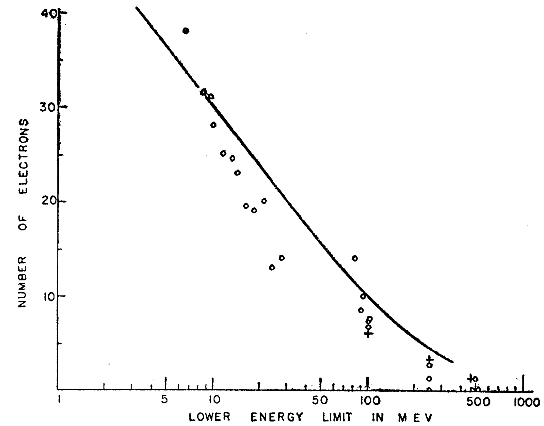


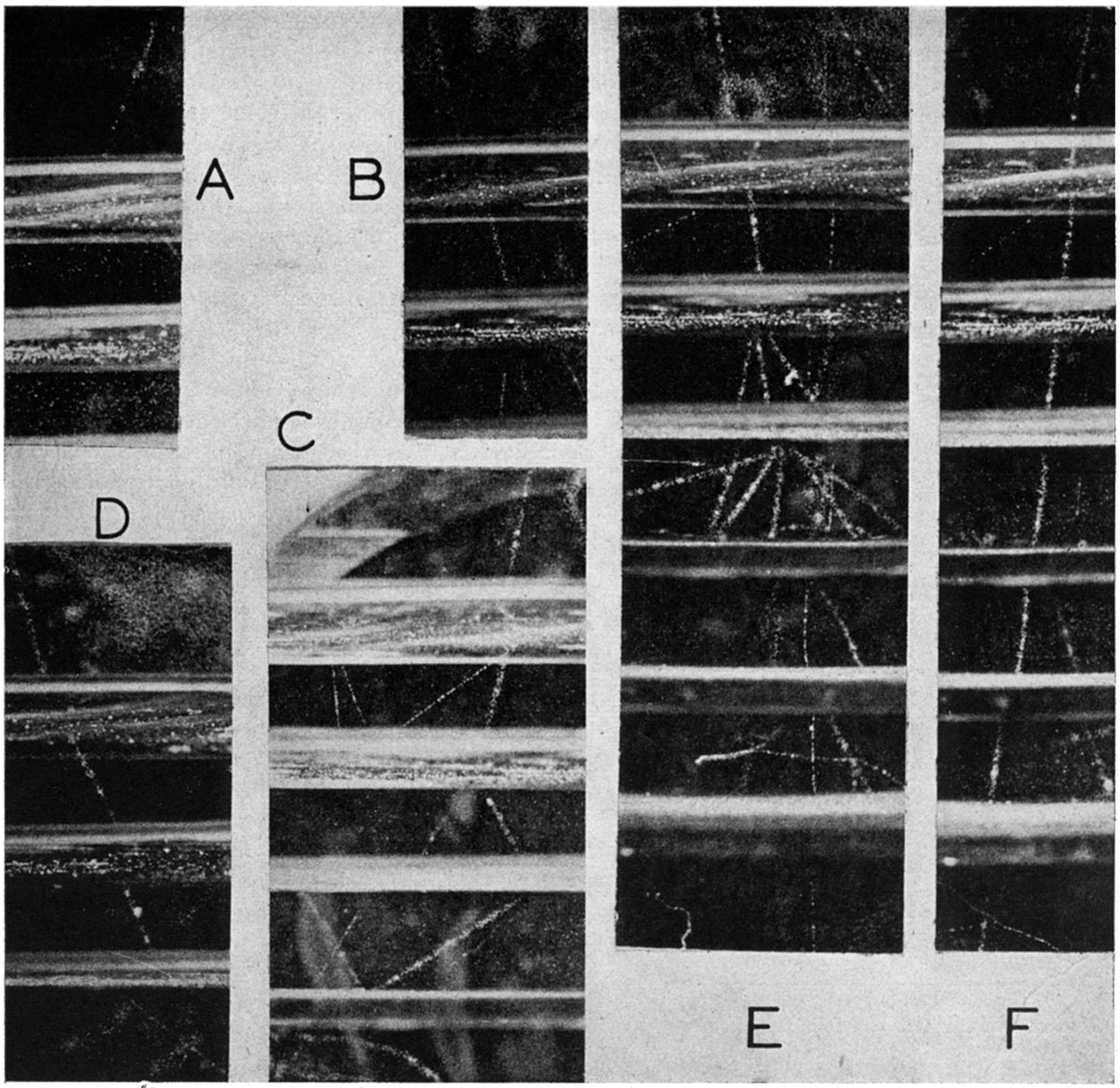
FIG. 2. Integral spectrum for electrons at sea level. The curve is from calculations of Greisen. (See reference 1.) The number of electrons is relative to the number of mesotrons with $p > 1.3\times 10^8$ ev/c and is expressed in percent. The points indicated by + are from data obtained by S. Nassar in connection with another experiment.

Scattering in the absorbers and the variation in the traversed thickness of counter walls, both of which increase the energy loss, have been neglected. The latter increases the average energy loss only a few percent. The former is most important in lead and, if taken into account, would shift the points between 10 and 50 Mev to the right in Fig. 2.

In all of the above, it has been assumed that the mesotron decay products are one electron and one neutrino. Thus we can conclude that there is no need for the hypothesis of decay into one electron and two neutrinos unless evidence for another source of cosmic-ray electrons is uncovered.

We are much indebted to Mr. Robert Brown who assembled the original apparatus and obtained some preliminary photographs and to Miss Salwa Nassar who furnished data on the frequency of occurrence of electron showers.

[8] B. Rossi and S. J. Klapman, Phys. Rev. 61, 414 (1942).



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