Scintillation Counter Study of Energy Spectra of Cosmic-Ray Photons and Electrons at 11 200 Feet*

C. N. Chou and Marcel Schein
Department of Physics, University of Chicago, Chicago, Illinois
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An apparatus designed to measure cascade showers initiated by photons and electrons of energies in the range of 1 Bev to 30 Bev was used to measure the energy spectra of cosmic-ray photons and electrons at Climax, Colorado (altitude 11 200 feet). The apparatus consisted of four anthracene-in-polystyrene plastic scintillators, interposed with 2.00 cm, 2.25 cm, and 2.25 cm of lead plates, respectively. Four trays of G-M counters and a set of anticoincidence G-M counters were used simultaneously with the scintillators.

More than 10 000 events were recorded and analyzed. The results show that in the energy range of 2 to 20 Bev, the integral energy distributions can be represented by a power law expression of the form $N(>E) = \text{const}\, E^{-s}$, with s equal to 1.6±0.2 for the photon component and s equal to 1.5±0.2 for the electron component.

SEVERAL experiments pertaining to the energy spectra of cosmic-ray photons and electrons have been reported.[1–12] These experiments were mostly carried out with G-M counter arrangements or with cloud chambers. The highest energy that has been measured with good precision was of the order of magnitude of several hundred Mev up to a few Bev. The previous results[13] reported here showed that large plastic scintillation counters could be used advantageously for the measurement of cascade showers initiated by photons or electrons up to energies of at least several Bev. Indeed it has been proved that large anthracene-in-polystyrene plastic scintillators are relatively simple to construct, convenient to handle, and the data obtained can be analyzed with the aid of cascade theory reasonably well.

I. EXPERIMENTAL ARRANGEMENT

The apparatus used was the same as the one used in a previous experiment concerning the study of penetrating showers produced by cosmic rays.[14] (Hereafter this paper will be referred to as I.) The arrangement was shown in Fig. 1 of I. It consisted of four anthracene-in-polystyrene plastic scintillators (one of size $18\times 9 \times 1.8$ cm^3, two of size $18\times 18\times 0.9$ cm^3, and one of size $18\times 18\times 1.8$ cm^3), interposed with lead plates of thicknesses of 2.00 cm, 2.25 cm, and 2.25 cm, respectively. Four trays of G-M counters and a set of anticoincidence counters were used simultaneously with the scintillators for the registration of high-energy photons and electrons at Climax (altitude 11 200 feet). Each individual event corresponding to the passage of an electron or photon triggered a synchroscope. The triggering arrangements used were those of $S_2{}^m$, $AB-S_2{}^S$, and $AB-S_2{}^m$ described in I. The lead block PB and the graphite block G (see Fig. 1 of I) were not used during this experiment. Electrons were selected by the triggering arrangements $AB-S_2{}^m$ and $S_2{}^m$. In the case of determining the energy spectrum of photons, only the triggering $S_2{}^m$ was used. Altogether more than 10 000 useful events were registered and analyzed, with roughly equal number for photons and electrons [see subsection III(b) below].

II. PROCEDURE AND ANALYSIS

Only events were analyzed in which none of the side counters E was triggered. This means that we selected predominantly single photons or electrons not accompanied by other ionizing particles. Singly charged penetrating particles were measured mainly for the purpose of calibration. The analysis was essentially the same as that described in subsection III(1) in I. These measurements are also used for the determination of the intensities of the μ mesons.

(a) Cascade Showers Initiated by Photons

In these events, none of the G-M counters in trays A or B was triggered, and no scintillation pulse or only very small scintillation pulse (with respect to minimum ionization particles) was registered in the top scintillator S_3. A cascade shower developed as the photon traversed the scintillators S_2, S_4, and S_1 and the interposed lead plates. The energy of the primary photon was then determined from cascade theory in exactly the same way as described previously, i.e., by fitting with graphs to curves representing the number of electrons expected from shower theory at the depth of the different scintillators for photons of different

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energies. As previously described, all pulse heights from the scintillators had been converted into equivalent number of minimum ionization particles. Due to the large thickness of lead above them, the G-M counters in tray *C* could be triggered only for showers of primary energy greater than about 10 Bev. G-M counters in tray *D* should not be triggered for photons of energies less than about 10^6 Bev. A correction was made for events which could be produced by neutron-initiated stars at the lead plate interposed between the scintillators S_3 and S_2 with the production of one or more π^0 mesons, which decayed into photons to initiate the showers. The frequency of these events was calculated from the actually observed known rate of nuclear interactions in the scintillator S_3.

(b) Cascade Showers Initiated by Electrons

For events of this kind it was required that one G-M counter both in tray *A* and in tray *B* was triggered. Accordingly a scintillation pulse of a height of that of a minimum ionization particle was registered in the top scintillator S_3. A cascade shower developed in the scintillators S_2, S_4, and S_1 as the electron traversed the interposed lead plates. The energy of the primary electron was determined in a way very similar to that described in subsection (a) for the photon-initiated showers.

III. RESULTS

All the experimental data are plotted in Figs. 1, 2, and 3. In the energy range of less than 3 Bev, the

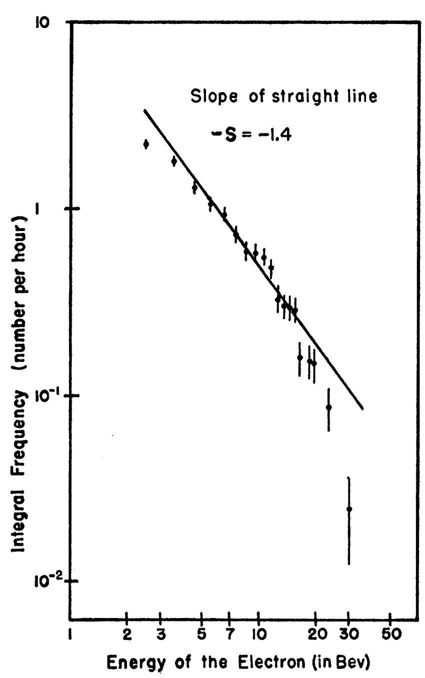

Fig. 1. Integral energy spectrum of cosmic-ray electrons at an altitude of 11 200 feet (with coincidence triggering).

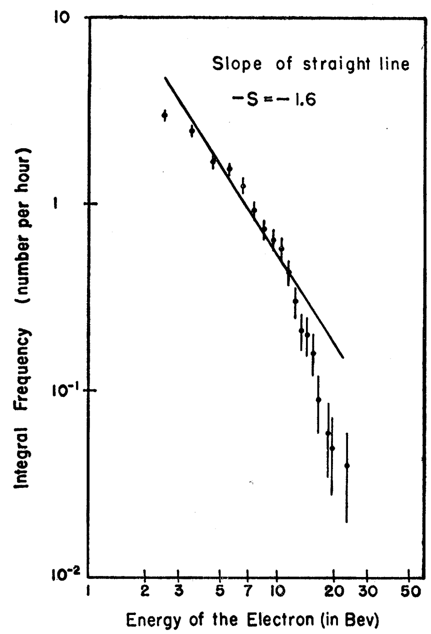

Fig. 2. Integral energy spectrum of cosmic-ray electrons at an altitude of 11 200 feet (without coincidence triggering).

sensitivity of identifying a cascade shower dropped off because in the analysis, allowance was made for the fluctuation in the shower theory. This range of allowance falls below the minimum pulse required in the present analysis when the energy is less than 3 Bev. On the other hand, for energies higher than 15 or 20 Bev, because of the greater probability of actuating one or more of the anticoincidence G-M counters *E* by the secondaries of the shower initiated by a high-energy primary, the effective solid angle of accepting the incoming flux of particles was estimated to be decreased by a factor of from 2 to 4 in going from 15 Bev to 30 Bev or higher. Hence a multiplying factor of this order of magnitude should be allowed for in interpreting the results.

(a) Energy Spectrum of Cosmic-Ray Electrons at 11 200 Feet

The results concerning the electron component obtained with the triggering arrangements $AB-S_2^m$ and the triggering S_2^m, respectively, are shown in Fig. 1 and Fig. 2. Straight lines best fitted with experimental points were drawn through the most reliable range of energies from 3 to 15 Bev. The integral frequency *vs* energy relation can be expressed by a power law of the form E^{-s}, with s equal to 1.4±0.2 in Fig. 1 and s equal to 1.6±0.2 in Fig. 2. Within experimental error these two exponents agree with each other.

The flux was determined for single electrons defined as above. For energies greater than 3 Bev, the observed rates were 2.5 per hour for the triggering arrangement $AB-S_2^m$ and 3.0 per hour for the triggering arrange-

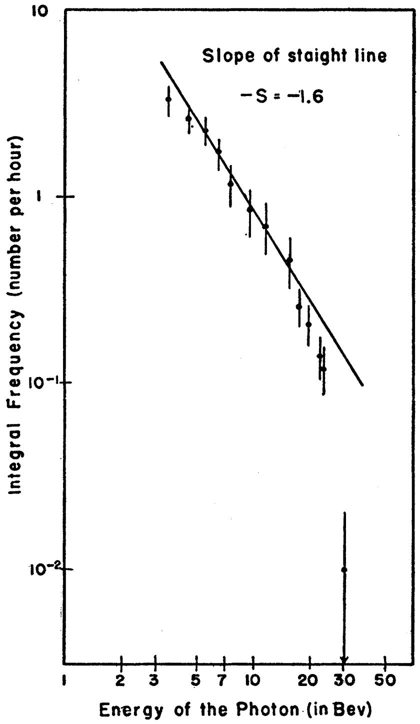

FIG. 3. Integral energy spectrum of cosmic-ray photons at an altitude of 11 200 feet.

ment S_2^m. This corresponds to an average rate of about 0.40 cm^{-2} $sterad^{-1}$ $hour^{-1}$.

(b) Energy Spectrum of Cosmic-Ray Photons at 12 000 Feet

The data referring to photons must be corrected for the contribution of neutron-initiated events in the lead plate between the scintillators S_3 and S_2. It is assumed that at the high-energy range dealt with in the present experiment, neutrons have approximately the same flux as protons. From the results in paper I we estimate the contributions of these neutron-initiated events and subtract them from the observed values. The corrected data thus obtained are plotted in Fig. 3. One sees that in the energy range from 3 to 15 Bev, a power-law spectrum holds for the integral frequency *vs* energy. The exponent of this distribution is equal to -1.6 ± 0.2. Within experimental error this value does not differ from the value for the electron spectrum.

At this high altitude (11 200 feet) most photons must be due to the decay of π^0 mesons from nuclear interactions of the incoming primaries. Based upon the observed spectrum of primary cosmic rays, the theoretical expected value of the exponent s is 1.7 or 1.8 for threshold energies of meson production of 1 or 2 Bev respectively.[15]

(c) Flux of Unaccompanied Single or Associated Penetrating Particles

From the results obtained with the triggering arrangement $AB-S_2^S$, we find that the rate of unaccompanied single or closely associated penetrating particles capable of traversing 12.5 cm of lead or more was about 13 cm^{-2} $sterad^{-1}$ $hour^{-1}$. They were probably mostly μ mesons. Now in the analysis of the hard component of the cosmic rays,[16] the vertical intensity of mesons with range greater than 167 g cm^{-2} of lead at the altitude of the present experiment was equal to about 58 cm^{-2} $sterad^{-1}$ $hour^{-1}$. If we take into account the fact that we detected and measured only unaccompanied single or closely associated penetrating particles, the two results are not inconsistent with each other.

IV. CONCLUDING REMARKS

The results of the present experiment show that at least in the energy range of 3–20 Bev, the integral energy distributions of the cosmic ray electrons and photons at an altitude of 11 200 feet can be represented by a power law of the form E^{-s}, with s equal to 1.6 ± 0.2 for the photon component and s equal to 1.5 ± 0.2 for the electron component. These values agree with the theoretical prediction for the energy spectra of electrons and photons assumed to be predominantly due to the decay of π^0 mesons from nuclear interactions initiated by the incoming cosmic-ray primaries.

The results of the present experiment indicate that large plastic scintillation counters of the type used here are quite adequate for the measurement of cascade showers initiated by photons or electrons of energies from 1 Bev up to tens of Bev.

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