Energy Spectra of Cosmic-Ray Photons and Electrons from Plastic Scintillation Counter Measurements*

C. N. CHOU
Department of Physics, University of Chicago, Chicago, Illinois

(Received January 26, 1953)

A new method of measuring high energy photons and electrons is reported. Using an experimental arrangement consisting of G-M counters and scintillation counters with large plastic scintillators, the number *vs* size distribution of cosmic-ray showers produced by photons and electrons in a lead block of one inch thickness was measured. From the results of shower theory the energy spectra of cosmic-ray photons and electrons at Chicago (600 ft above sea level and 51° N geomag. lat) were deduced. The results of the present investigation show that in the energy range of 0.3–2.0 Bev, the differential energy distributions can be represented by a power law of the form E^{-s}, with $s=2.71\pm0.13$ and $s=2.81\pm0.13$ for the photon and electron components, respectively. The exponent s decreases considerably at energies below 0.2 Bev. An essential part of this investigation is to provide a suitable means of measuring the energies of energetic γ-rays or electrons, or the energy distribution of energetic γ-rays or electrons. The results show that scintillation counter arrangements consisting of large plastic scintillators are suitable instruments for these purposes. This method could also be applied to energy measurements of photons and electrons from high energy accelerators.

SOME information about the energy distributions of the electron component[1–4] and the photon component[5,6] of cosmic rays has been reported previously. In many cases, the accuracy of the results has been limited by the experimental instrumentation available. Recently we have been able to make large plastic scintillators with little internal absorption,[7] and with linear response to energy loss up to at least several times minimum ionization.[8] These properties make it possible to use this kind of scintillators in suitable arrangements to measure the energy of electron showers more accurately.

I. EXPERIMENTAL ARRANGEMENT

A schematic sketch of the experimental arrangement used is shown in Fig. 1. PS_1 and PS_2 are two anthracene-in-polystyrene plastic scintillators,[7] each of dimensions 1.90 cm×7.35 cm×17.0 cm. The lead block Pb of dimensions 2.54 cm×6.35 cm×17.0 cm placed between these plastic scintillators was used as the shower generator. All the G-M counters A, B, C, E, D_1, $\cdots$, D_6, were made of brass of a wall thickness of 1/32 inch. The side counters E were connected in parallel, and events in which any one of the counters E was fired are excluded from the data reported here. With the lead shielding S (of about 4.5 radiation lengths) in position, at least one of the side counters would be actuated by photons entering from the sides.

The pulses from the two 5819 photomultiplier tubes which viewed the two plastic scintillators were shaped to a width of 1.5 μsec by the use of delay-line units (see Fig. 2). The pulse from the upper scintillator PS_1 was delayed 4 μsec and the pulses from the G-M counters A, B, C, E, D_1, D_2, D_3, D_4, D_5, and D_6 were

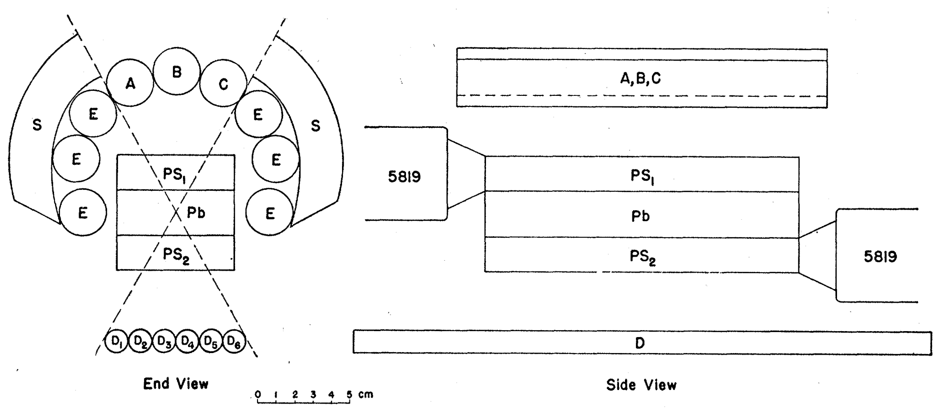

FIG. 1. Experimental arrangement.

* Supported by the joint program of the U. S. Atomic Energy Commission and the U. S. Office of Naval Research.
1 E. J. Williams, Proc. Roy. Soc. (London) A172, 194 (1939).
2 K. Greisen, Phys. Rev. 63, 323 (1943).
3 B. Lombardo, Jr., and W. E. Hazen, Phys. Rev. 68, 74 (1945).
4 J. Clay and E. van Alphen, Physica 17, 711 (1951).
5 L. Jánossy and B. Rossi, Proc. Roy. Soc. (London) A175, 88 (1940).
6 J. Clay, Physica 14, 569 (1949).
7 C. N. Chou, Phys. Rev. 87, 376 (1952).
8 C. N. Chou, Phys. Rev. 87, 903 (1952).

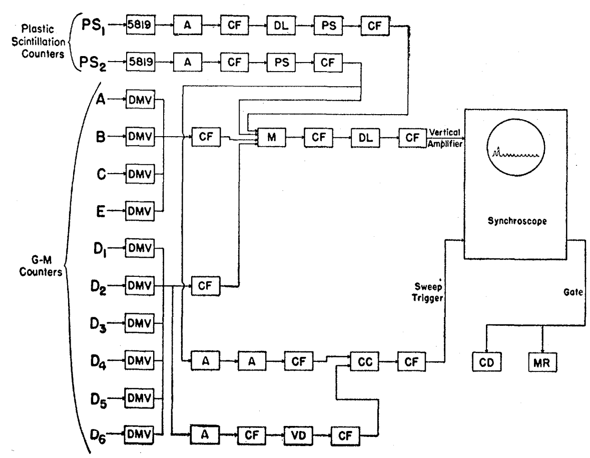

FIG. 2. Block diagram of recording circuits. The abbreviations have the following meanings: *A*, amplifier; *M*, mixer; *CC*, coincidence circuit; *CF*, cathode follower; *DL*, delay line unit; *PS*, pulse shaping unit; *VD*, Schmitt voltage discriminator; *DMV*, delaying multivibrator; *CD*, camera drive unit; *MR*, mechanical register.

delayed with multivibrators by 12, 20, 28, 36, 44, 52, 60, 68, 76, and 84 μsec, respectively. The sweep of the synchroscope was triggered by a coincidence of a pulse of size greater than a "minimum pulse"[9] in PS_2 and simultaneous firing of (a) any one, or (b) at least two of the G-M counters $D_1, \cdots, D_6$. These two kinds of coincidences will be called coincidence PS_2D and coincidence PS_2DD, respectively, and were selected by adjusting the bias setting of the Schmitt voltage discriminator *VD*. The input to the vertical deflection amplifier of the oscilloscope was delayed 4 μsec after the triggering of the sweep. The oscilloscope trace was recorded photographically by a camera which was so

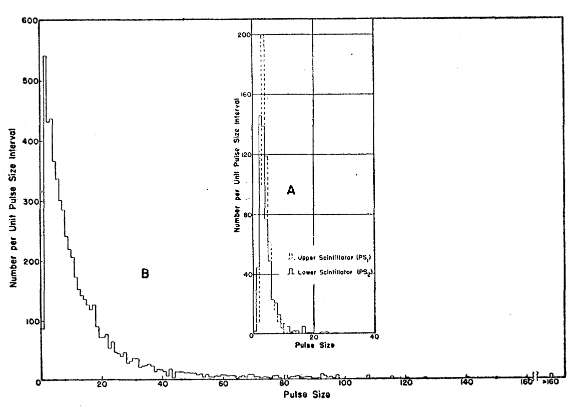

FIG. 3. The differential pulse-size distributions for minimum ionizing particles A, and for photon-produced showers B in experiments of Series 1. Histogram B refers to the lower scintillator only. Both the ordinate and the abscissa are in arbitrary units. For the abscissa, the same arbitrary unit is used in both A and B.

[9] A "minimum pulse" means a pulse of size of about 5 percent of the most probable pulse size produced by a minimum ionizing particle in passing through the scintillator.

equipped that the gate output from the oscilloscope automatically moved the film ahead for another event. A Tektronix Type 513-D oscilloscope was used in these experiments.

Two series of experiments were carried out. In Series 1, the lead shielding *S* was in the position shown in Fig. 1. In Series 2, the shielding was removed. This enabled one to estimate the contributions of photons coming from directions making large angles with the vertical and to test the effect of the geometry adopted in the present experiment on the experimental results. Altogether, more than 25 000 useful events were recorded, with about equal number of events in each of the two series of experiments.

II. EXPERIMENTAL RESULTS

In both series of experiments, events in which the sweep was triggered by coincidence PS_2D and by co-

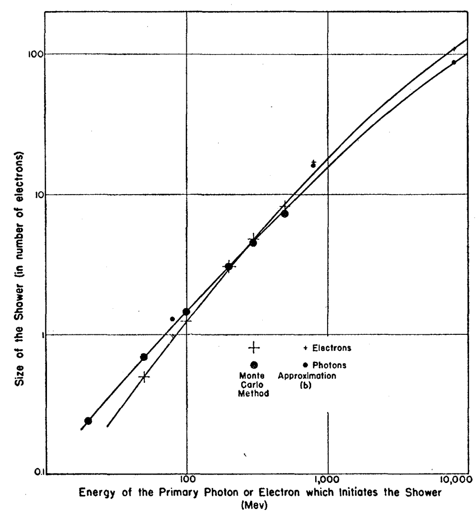

FIG. 4. Theoretical relationship between the size of a shower (in number of electrons) and the energy of the primary photon or electron initiating it. Large symbols indicate Monte Carlo method (see reference 15); small symbols indicate approximation (b) (see references 12–14).

incidence PS_2DD were recorded. In the PS_2D triggered events, we considered those recorded with only one upper G-M counter (any one of the counters *A*, *B*, or *C*) and only one lower G-M counter (any one of the counters $D_1, \cdots, D_6$) fired as predominantly caused by the passage of μ-mesons. The number *vs* pulse-size distributions in both plastic scintillators PS_1 and PS_2 for these events were obtained. They are expected to show a distribution which is the superposition of Landau distributions corresponding to various path lengths of minimum ionizing particles in either scintillator in the geometrical arrangement adopted in the present experiments. As typical examples the distribution histograms for both scintillators PS_1 and PS_2 in experiments of Series 1 with coincidence PS_2D are shown in Fig. 3A. As expected the width of the distribution is wider than that normally observed,[10,11] because of the comparatively large effective solid angle in the present arrangement, which was adopted in order to be able to test this new method of shower measurement with reasonably good statistical accuracy.

In the PS_2DD triggered events those with only one upper G-M counter fired are considered as predominantly caused by electrons, and those with no upper G-M counter fired, as mostly caused by photons. In about 80 percent of these latter events, no trace was registered by the upper scintillator. This was expected from the geometry. Corrections have been made to allow for the finite wall thickness of the upper G-M counters and spurious effects due to the geometrical arrangement of the counters. As a typical example, the number *vs* pulse-size distribution of photon-produced showers in the lower scintillator (PS_2) in the experiments of Series 1 is shown in Fig. 3B.

To obtain the energy spectra we proceed in the following way: (a) A smooth curve assumed to represent the pulse-size distribution due to a single minimum ionizing particle is fitted to the histogram represented by the solid line of Fig. 3A. (b) A combination of various curves derived from it corresponding to different numbers of particles is fitted to a smooth curve drawn through the histogram of Fig. 3B. This enables one to obtain a curve corresponding to the frequency *vs* shower size (in number of electrons) for showers initiated by photons in experiments of Series 1. Procedures (a) and (b) are repeated to analyze the data of Series 2, and also the data of electron-initiated showers in both series. To express the shower size in terms of the energy of the primary which initiated the shower, we make use of the results of existing shower theories.[12–16] The theoretical calculations yield the known relationship between the size of the shower (in number of electrons) and the energy of the photon or electron producing it as shown in Fig. 4 for the particular thickness of lead (4.4 radiation lengths) used. From Fig. 4 and the frequency *vs* shower size curves obtained by procedure (b) we obtain the energy spectra of the photons and electrons initiating the showers. The resulting differential energy distributions are shown in Fig. 5 and Fig. 6. The ordinates of the two distributions from the two series of experiments have been normalized for comparison.

The curve of Fig. 5 yields for photons in the energy range of 0.3–2.0 Bev, a differential energy distribution which can be represented by a power law of the form E^{-s}, with $s=2.71\pm0.13$. The good agreement shown in Fig. 5 demonstrates that the experiments of Series 1

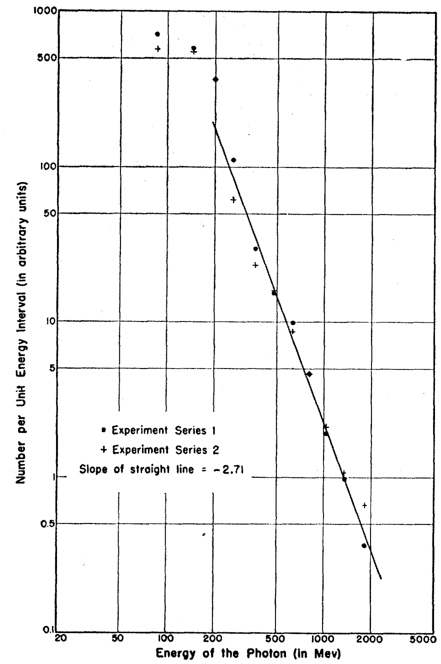

FIG. 5. Differential energy spectrum of cosmic-ray photon at Chicago (600 ft above sea level and 51° N geomag. lat).

and Series 2 led to essentially the same results in the energy range of 0.3–2.0 Bev. This indicates that the difference in geometry in the two series of experiments did not have a strong effect on the energy distribution of photons in this energy range.

For the energy distribution of electrons of the same energy range of 0.3–2.0 Bev (Fig. 6), a power law E^{-s}

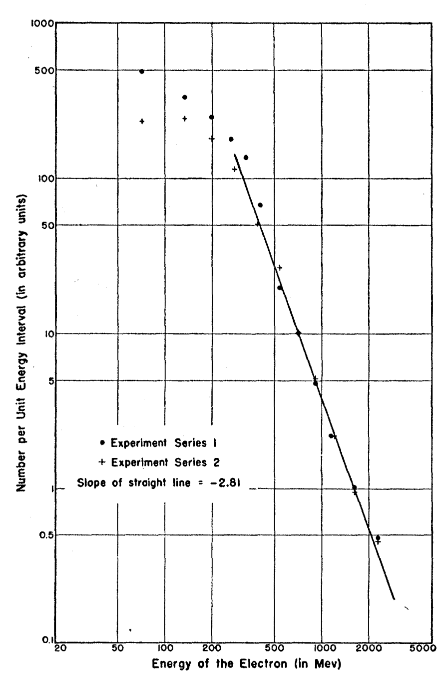

FIG. 6. Differential energy spectrum of cosmic-ray electrons at Chicago.

[10] T. Bowen and F. X. Roser, Phys. Rev. **85**, 992 (1952).
[11] A. Hudson and R. Hofstadter, Phys. Rev. **88**, 589 (1952).
[12] L. Jánossy and H. Messel, Proc. Roy. Irish Acad. **A54**, 217 (1951).
[13] H. S. Snyder, Phys. Rev. **53**, 960 (1938).
[14] B. Rossi and K. Greisen, Revs. Modern Phys. **13**, 240 (1941).
[15] R. R. Wilson, Phys. Rev. **86**, 261 (1952).
[16] H. Messel and R. B. Potts, Phys. Rev. **86**, 847 (1952).

holds with $s=2.81\pm0.13$, which is, within experimental errors, almost the same as that for the photons. It was also found that in the experiment of Series 1 (with shielding S in position) photon- and electron-initiated showers occur at the same absolute rate within 10 percent at energies 0.3–2.0 Bev. In Series 2, there were about 30 percent more photon-initiated than electron-initiated showers observed. This is probably essentially because the side counters E excluded electrons with good efficiency, whereas photons from the sides were registered by the apparatus.

The interpretation of the results at energies lower than 0.2 Bev is complicated because the arrangement used was not very sensitive in this region. A more elaborate apparatus is now being constructed with the purpose of carrying out energy measurements of high energy photons and electrons with increased precision.

III. CONCLUSION

The results of this work show that a suitable scintillation counter arrangement making use of large plastic scintillators provides a new method of measuring the energies of high energy photons or electrons, or the energy distribution of a spectrum of high energy photons or electrons with satisfactory precision. The energy spectra of cosmic-ray photons and electrons at ground level obtained by this method are not inconsistent with previous results obtained by others.[1–6]

The author wishes to express his hearty thanks to Professor Marcel Schein for many valuable discussions and for the privilege of working in the Cosmic Ray Laboratory at Chicago. He also thanks Mr. T. Bowen for numerous constructive discussions and for his valuable cooperation.

PHYSICAL REVIEW VOLUME 90, NUMBER 3 MAY 1, 1953

On the Damping of Virtual Nucleon-Pair Formation in Pseudoscalar Meson Theory*

K. A. BRUECKNER, *Indiana University, Bloomington, Indiana*

AND

M. GELL-MANN AND M. GOLDBERGER, *University of Chicago, Chicago, Illinois,*

(Received January 15, 1953)

The modifications of the propagation characteristics of a nucleon which result from the presence of a strongly coupled mesonic self-field are estimated from the consideration of a simple subset of radiative corrections to the nucleon propagation function. It is found that reactive effects markedly inhibit nucleon pair formation so that the contributions from the pseudoscalar coupling term which do not involve nucleon pairs are strongly enhanced relative to those involving pair formation. In addition, the meson pair coupling term, which results from nonrelativistic approximations to the relativistic linear coupling term and is intimately connected with nucleon pair formation, is strongly damped. The relation of this result to the nonrelativistic theory of Wentzel is discussed.

ONE of the most characteristic features of pseudoscalar meson theory with pseudoscalar coupling is the large value of the matrix elements of the interaction for processes in which a nucleon pair is produced. This effect is usually stated qualitatively by noting that the operator γ_5 has matrix elements of the order of v/c (v the nucleon velocity) for processes in which no nucleon pairs are produced but of the order of unity for nucleon pair production. The consequences of this effect are well known for a number of important phenomena, particularly (1) meson-nucleon scattering, where the contribution to the scattering involving nucleon pair production in the intermediate states gives rise in the weak coupling limit to very large s wave scattering,[1] and (2) nuclear forces where the fourth-order potential[2] arises almost entirely from nucleon pair formation in the intermediate states.

A convenient method which exhibits these features of the theory is that given by the transformations of Dyson[3] and of Foldy,[4] which show that the pseudoscalar coupling term

$$H_{ps}=ig\bar{\psi}\gamma_5\tau_\alpha\psi\varphi_\alpha \quad (1)$$

may be transformed into an expression nonlinear in the meson field variables, which in the nonrelativistic limit has as leading terms in g,

$$(g/2M)\boldsymbol{\sigma}\cdot\nabla(\tau\cdot\varphi)\rho(r)+(g^2/2M)\varphi^2\rho(r), \quad (2)$$

where $\rho(r)$ is the nucleon source density. The first term is the usual pseudovector coupling term; the second is a meson pair coupling which is very closely associated with nucleon pair formation, arising as it does from the pairing of two pseudoscalar interaction terms H_{ps} in which the two pairs of nucleon operators create or annihilate a nucleon pair with the result that the native elements of the two γ_5 operators are of the order of unity. This meson-pair term gives rise to large s wave

* This work was supported in part by a grant from the National Science Foundation.

[1] Ashkin, Simon, and Marshak, Progr. Theoret. Phys. (Japan) **5**, 634 (1950).

[2] K. M. Watson and J. V. Lepore, Phys. Rev. **76**, 1157 (1949); H. A. Bethe, Phys. Rev. **76**, 191 (1949); M. Lévy, Phys. Rev. **86**, 806 (1952); J. V. Lepore, Phys. Rev. **88**, 750 (1952).

[3] F. J. Dyson, Phys. Rev. **73**, 929 (1948).

[4] L. L. Foldy, Phys. Rev. **84**, 168 (1951).