THE PHYSICAL REVIEW

A Journal of Experimental and Theoretical Physics Established by E. L. Nichols in 1893

VOL. 60, NO. 1 | JULY 1, 1941 | SECOND SERIES

Extensive Cosmic-Ray Showers and the Energy Distribution of Primary Cosmic Rays

NORMAN HILBERRY

University of Chicago, Chicago, Illinois

(Received May 19, 1941)

An experiment is described which determines the variation in the number of extensive cosmic-ray showers per unit time with altitude from sea level up to 4300 m. The number of showers which should have been observed with the apparatus used is calculated on the basis of the cascade theory in which various power law energy distributions for the primary cosmic rays are assumed. Good agreement is obtained between the observations and the calculation at high altitudes for suitable choice of parameters; at low altitudes the observed excess is what would be expected from a mesotron component in the extensive showers. It is found that the same choice of parameters which will give good agreement with the extensive shower data will also describe cosmic-ray observations at much lower energies. It is pointed out that this offers strong support for the hypothesis that there is but one type of primary cosmic-ray particle. The effects of choosing the proton as this primary particle are discussed.

INTRODUCTION

THE prodigious energy associated with extensive cosmic-ray showers is one of their most thought-provoking aspects. Auger and his co-workers[1] have estimated this energy to be above 10^{13} ev. The entire energy of such a shower has been attributed to a single primary particle incident at the top of the atmosphere. The cascade theory[2–5] accounts for the development from a high energy primary of the very large number of ionizing particles observed in these showers. On the basis of scattering in the atmosphere, Euler and Wergeland[6] have derived expressions which determine the spatial distribution of the shower particles about the axis determined by the direction of the incident primary particle. A fairly complete quantitative description is thus given of the number and spatial distribution of the ionizing particles in the shower at different depths in the atmosphere. Obviously, if the cascade theory is correct, the primary particles with energies greater than 10^{13} ev must acquire their energies from some physical process hitherto unknown in kind or at least in order of magnitude. It seems important, therefore, to determine how well the cascade theory does describe the behavior of these extensive showers, and to determine the energy distribution of the incident primary particles as quantitatively as possible.

The simplest attack on the problem is a determination of the variation in the number of extensive cosmic-ray showers as a function of altitude. If the cascade theory is adequate, the energy requisite for a primary incident on the top

[1] Auger, Maze, Ehrenfest and Fréon, J. de phys. et rad. **10**, 39 (1939). Auger, Ehrenfest, Daudin, Robley and Fréon, Rev. Mod. Phys. **11**, 288 (1939).
[2] H. J. Bhabha and W. Heitler, Proc. Roy. Soc. **A159**, 432 (1937).
[3] J. F. Carlson and J. R. Oppenheimer, Phys. Rev. **51**, 220 (1937).
[4] H. Snyder, Phys. Rev. **53**, 960 (1938).
[5] R. Serber, Phys. Rev. **54**, 317 (1938).
[6] H. Euler and H. Wergeland, Naturwiss. **27**, 484 (1939).

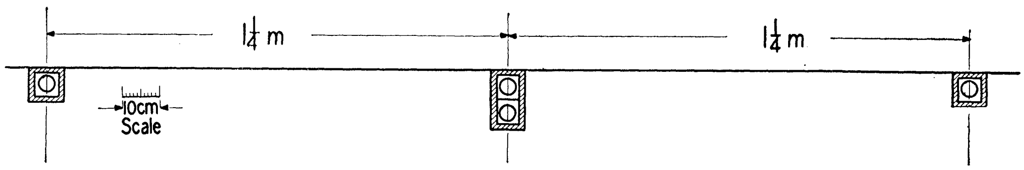

FIG. 1. Counter arrangement under the roof of the station wagon for the measurement of extensive cosmic-ray showers.

of the atmosphere to produce an observable shower at any given depth in the atmosphere is a sensitive function of that depth. Consequently, the number of extensive showers per unit time at any depth is a measure of the number of primary particles incident on top of the atmosphere with energies above a certain "cut-off" value. This latter is determined by the apparatus and by its depth in the atmosphere. Thus the variation of the number of showers with altitude should give definite information not only concerning the validity of the cascade theory but also a fairly quantitative determination of the energy distribution of the incident primary particles as well.

Since the number of showers observable with a given apparatus increases rapidly with decreasing depth in the atmosphere, it is important that the observations be extended to as high an altitude as possible. With this in mind, an experiment was so designed that observations could be made on the number of extensive showers over a range of altitudes from sea level at Chicago to 4300 meters at Mt. Evans, Colorado.

EXPERIMENT

To measure the number of these showers per unit time at various altitudes, a set of four argon and petroleum-ether filled Geiger-Müller tubes were mounted permanently just beneath the light wood and fabric roof of a Ford station wagon. All readings were taken in the open to eliminate any possibility of scattering from material above the counter set. Each counter was placed in an individual sheet-metal shielding can together with the first amplifier tube of the coincidence circuit. A one-half inch layer of Celotex was placed around each counter tube unit to furnish thermal insulation. One counter tube was mounted at the extreme forward end of the car, one at the extreme rear and the other two in vertical II-fold (twofold) coincidence midway between the extreme counters. The distance between the extreme counters was 2.5 meters (Fig. 1). Each counter had a diameter of 4 cm and an active length of 48 cm, giving an active area of 196 cm^2.

The counters were connected in fourfold coincidence by a conventional coincidence circuit and the usual precautions were taken to maintain constant working potentials on the G-M tubes and constant plate and grid potentials on the amplifier itself.

The counter tubes were mounted permanently in the station wagon to guarantee constant geometry throughout the experiment and thus facilitate alternation in the measurements at the various altitudes. The observational procedure was to take a run at one altitude for a period of from twelve to twenty-four hours; next, to take a run at a second station for a similar period; finally, to return to the first station for a final run to complete the set. This continual alternation of the observations at different altitudes with a fixed apparatus tends to eliminate errors due to slow variations in the cosmic-ray intensity or in the circuit itself. Actually, the latter effect was extremely small for the observations made in Chicago at the start of the expedition differed from those made after the return by less than the standard statistical deviation for the entire Chicago set.

The average depth below the top of the atmosphere for each observation station was determined by taking barometric readings for each run and averaging over the total counting interval.

The accidental counting rate was determined from the onefold counting rates for each G-M tube as measured with a scale 16 scaling circuit, from the twofold counting rate for the central pair and the twofold counting rate for the extreme G-M pair. The twofold rate for the extreme pair was assumed to be entirely accidental, and this together with the onefold rate for each extreme counter gave the observed resolving time for the circuit. This procedure gives a maximum value and in all cases the value of the resolving time so measured was less than 10^{-4} sec. This resolving time was then used to compute the accidental counting rate for the present counter arrangement, which was treated as an effective threefold coincidence set with the onefold counting rates for the extreme counters and the vertical twofold rate of the central pair of counters as the onefold rate for a single effective central counter. In all cases the true fourfold accidental rate was completely negligible. The accidental rates so determined were, of course, also maximum values so that the accidental rate at Mt. Evans was less than the 0.1 count per hr. and that at Chicago was less than the 0.01 count per hr. computed for each respectively.

Table I gives the observed counting rates with their standard statistical deviations obtained by the above procedure.

Comparison with the Cascade Theory and Determination of the Energy Distribution

In order to interpret the experimental curve in terms of the validity of the cascade theory and to derive from it an expression for the energy distribution of the incident primary particles, it is necessary to carry through a complete calculation of the cascade process for all showers which can be detected by the counter system used. Since the validity of any conclusions based upon such a calculation depend upon the way in which the calculation is carried out, the method followed in the computation will be outlined in detail.

The computation is separable into three major parts: (1) the cascade computation itself for the development of the showers arising from a single incident primary particle of energy E, (2) the introduction of an energy distribution which will give the variation of counting rate with depth for vertically incident primary particles, and (3) the zenith angle calculation which then furnishes a quantitative description of the observed decrease of counting rate with depth in the atmosphere for a suitable choice of the parameters in the arbitrarily chosen energy distribution expression.

1. Cascade computation

(a) The first step in the cascade computation for a single incident ionizing particle is the solution of the cascade equations to determine the total number of ionizing particles, $n_{z,E}$ at a given depth z in the atmosphere, for a primary particle with a given incident energy E. For this purpose the cascade equations as given by Serber[5] and Snyder[4] were used. These equations express the number of ionizing particles as a function of the depth z below the surface of the atmosphere, the logarithm ϵ of the ratio of the incident energy to the critical energy in air, and an arbitrary parameter y. Values of the parameter ϵ were used corresponding to energies of the incident primaries of 1×10^{12} ev, 5×10^{12} ev, 1×10^{13} ev, $\cdots$, 1×10^{16} ev. The depth equation was then solved for each of these values of ϵ, to determine the values of the remaining parameter, y, corresponding to the depths 630 g/cm^2, 700 g/cm^2, 800 g/cm^2, $\cdots$, and 1100 g/cm^2. The equation for the number of ionizing particles, when solved for the above values of the parameters y and ϵ, yields the desired total numbers of ionizing particles, $n_{z,E}$ at each of the chosen depths due to incident primaries of each of the chosen energy values.

(b) *Determination of the spatial distribution* of the $n_{z,E}$ particles about the axis of the shower in the plane of observation. The axis of the shower is the direction of incidence of the primary particle. For this calculation the scattering formulas given by Euler[6] were used. While they are strictly valid only in the region of maximum development of the shower, the approximation is sufficiently good for the depths and energies here

Table I. *Extensive shower counting rate as a function of altitude.*

Place	Altitude Meters	Depth Below Top of Atmosphere in g/cm²	Counting Rate Counts/hr.
Mt. Evans	4320	628	24.1 ±0.3
Summit Lake	3900	658	20.5 ±0.5
Echo Lake	3100	709	14.0 ±0.5
Idaho Springs	2190	795	7.3 ±0.8
Denver	1610	854	5.0 ±0.4
Chicago	91	1025	1.47±0.15

considered. The values of the "half-width" of the shower in Euler's expression for the radial distribution were determined for each of the chosen depths and the expressions normalized to yield the proper values of $n_{z,E}$ when integrated over the entire plane of observation. These expressions then give the mean values of the surface densities of ionizing particles, $\rho_{z,E,r}$, at any distance r from the axis of a shower having a total number of particles at the depth z of $n_{z,E}$. Of course the actual distribution is statistical about this mean value.

(c) *Probabilities of observing extensive showers.* The probability ${}^{\mathrm{I}}P_{z,E,r}$ that a single G-M counter tube of active area A will be struck by an ionizing particle when the counter tube is at any given distance r from the axis of the shower can be calculated readily from the mean particle density $\rho_{z,E,r}$. In the present case, the counter arrangement was not symmetrical about a vertical axis through its center. Consequently, to determine the probability of registering a threefold coincidence ${}^{\mathrm{III}}P_{z,E,r}$ it was necessary to average over all orientations Φ of the counter set in the particle field. To do this the distance from the center of the counter arrangement to the axis of the shower was kept fixed at some value of r and the distances to each counter then determined for orientations of 0°, 30°, 60° and 90° between the radius vector from the counter set to the shower axis and the axes of the G-M tubes. The threefold coincidence probability was then calculated as:

$$ {}^{\mathrm{III}}P_{z,E,r} = [{}^{\mathrm{I}}P_{z,E,r'}] \times [{}^{\mathrm{I}}P_{z,E,r}] \times [{}^{\mathrm{I}}P_{z,E,r''}] $$

for each orientation, and the mean of these values (determined by a Simpson's rule calculation of the area under the ${}^{\mathrm{III}}P_{z,E,r}(\phi)$ curve when necessary) gave the mean value of ${}^{\mathrm{III}}P_{z,E,r}$. This orientation average was carried out in all cases for values of r of $\frac{1}{2}$, 1, 2, 3, 4 and 5 meters. For greater values of the radius the effect of the orientation was in general negligible and except in a few cases no appreciable error was introduced by computing ${}^{\mathrm{III}}P_{z,E,r}$ as $[{}^{\mathrm{I}}P_{z,E,r}]^3$. The orientation calculation was made for larger values of r in those cases where any sensible error would be introduced by the omission. The values of ${}^{\mathrm{III}}P_{z,E,r}$ were extended in this fashion for values of r of 10, 15, 20, $\cdots$ out to 100 m in the case of the high energy primaries.

This means, of course, that there is a definite probability that a shower whose axis falls a distance r from the center of the counter arrangement will register a threefold coincidence. There is thus an "area of incidence" at the top of the atmosphere over which an incident particle of energy E will be effective in producing coincidences, and this area increases with the energy of the incident primary.

If, now, there are incident vertically on the top of the atmosphere N_E particles of energy E per cm² per sec., their contribution to the threefold counting rate of this counter set when incident at a distance between r and $r+dr$ will be

$$ N_E \, {}^{\mathrm{III}}P_{z,E,r} \times 2\pi r dr $$

and the total contribution to the threefold counting rate will be

$$ {}^{\mathrm{III}}R'_{z,E} = N_E \int_0^\infty {}^{\mathrm{III}}P_{z,E,r} \times 2\pi r dr. $$

Since the integrand is an empirical function, this integration was carried out by a Simpson's rule determination of the area under the curve of ${}^{\mathrm{III}}P_{z,E,r} 2\pi r$ as a function of r. These numerical integrations were extended out to such values of r that contributions for still greater values of the radius were negligible. For the low energies the calculation could be stopped at 5 m or 10 m, while for the high energy primaries it was necessary to carry the calculation out to 90 m.

This process was repeated for each of the values of E at each depth z. The families of curves of ${}^{\mathrm{III}}R'_{z,E}$ as a function of E for each z, and of ${}^{\mathrm{III}}R'_{z,E}$ as a function of z for each E, were plotted as a check for possible arithmetical errors. Also, from these families of curves, values of ${}^{\mathrm{III}}R'_{z,E}$ were interpolated for values of E intermediate between the values for which the computation had been carried out. The nature of the curves was such as to make this readily possible and sufficiently accurate. Thus the cascade computation has yielded a set of values of ${}^{\mathrm{III}}R'_{z,E}$ for each of the energies (1, 2, 3, 4, 5, 6.25, 7.50, 8.75) $\times 10^{12}$ ev, $(1, \cdots) \times 10^{13}$ ev $(1, \cdots) \times 10^{14}$ ev, $(1, \cdots) \times 10^{15}$ ev, 1×10^{16} ev at each of the chosen depths. The above values of the intermediate energies were chosen to facilitate a Simpson's rule integration over the energy intervals from 1×10^{12} ev-5×10^{12} ev, 5×10^{12} ev -1×10^{13} ev, $\cdots 5\times10^{15}$ ev-1×10^{16} ev at the next stage of the computation.

2. Vertical counting rate *vs.* depth curves

For this it is necessary to make some assumption concerning the nature of the energy distribution of the incident primary particles. The usual form was adopted, that is

$$dN'_{0,\alpha}=N'_{0,\alpha}E^{-\alpha}dE,$$

where $dN'_{0,\alpha}$ represents the number of particles per sec. with energies between E and $E+dE$ incident vertically on each cm^2 of surface at $z=0$, the top of the atmosphere. $N'_{0,\alpha}$ and α are arbitrary parameters to be chosen to give the best possible quantitative description of the experimental observations. Various values have been used for α in the literature under various circumstances. In the present calculation, values of dE/E^{α} were computed for all of the above energies, including the interpolated values, for each value of α. The values of α chosen were 2.5, 2.6, $\cdots$3.0.

The total vertical extensive shower counting rate at each depth is now

$$^{\text{III}}R'_{z,\alpha}=N'_{0,\alpha}\int_0^{\infty}{}^{\text{III}}R'_{z,E}E^{-\alpha}dE.$$

Again the integrand is an empirical function and the integration was carried out by using a Simpson's rule determination of the area under the curve of $^{\text{III}}R'_{z,E}N'_{0,\alpha}E^{-\alpha}$ as a function of E. The calculation was extended to a value of E of 5×10^{15} ev which was sufficiently large to make the contributions from still higher energy groups negligible for the present counter arrangement.

3. Zenith angle computation

The calculation to this point gives a set of relationships between the vertical counting rate, $^{\text{III}}R'_{z,\alpha}$ and the depth z, for each of the chosen values of the exponent α. These relationships do not represent the variation of total counting rate with depth, however. The above relationships show that the variation of counting rate with depth is extremely rapid, so that a given change of zenith angle at small depths will produce a much smaller change of counting rate than the same change of zenith angle at a relatively great depth. Consequently, it is essential to make a computation of the zenith angle effect. This calculation is complicated for the present counter arrangement since the entire upper hemisphere of incidence is not open to threefold coincidences due to the fact that unless a single particle can produce a twofold coincidence in the central pair a true fourfold rather than a threefold coincidence is required in order to register a count. The geometry is simple, however, so that it is possible to determine the effective depths corresponding to any zenith angle across any chosen zone on the hemisphere of incidence, and the fraction of each such total zone which is open to threefold coincidences. For the present counter arrangement and depths, the contributions due to fourfold coincidences were negligible from the portion of the hemisphere of incidence closed to threefolds.

At the depth corresponding to the summit of Mt. Evans, the hemisphere of incidence was broken into zones at zenith angles of 0°, 21°6′, 30°, 36°58′, 42°57′, 48°19′ and 53°16′. The depth corresponding to this last zenith angle is 1050 g/cm^2 and the contribution from greater depths is negligible. Each of the first two zones was completely open to the threefold arrangement. Sixty-seven percent of the third zone was open, as was 48 percent of the fourth, 38 percent of the fifth and 31 percent of the sixth. At the 1000 g/cm^2 depth the contributions from zones beyond the second were negligible.

The contribution to the total counting rate from each zone was now determined from the vertical counting rate curves and the effective values of $z \sec \theta$ across the zone. Again this was done by a Simpson's rule computation of the mean value. This mean value was multiplied by the value of the solid angle for that part of the zone open to the threefold arrangement and this gave the contribution from that zone to the total counting rate. The sum of these contributions from the various zones then gave the total counting rate at that depth. This, of course,

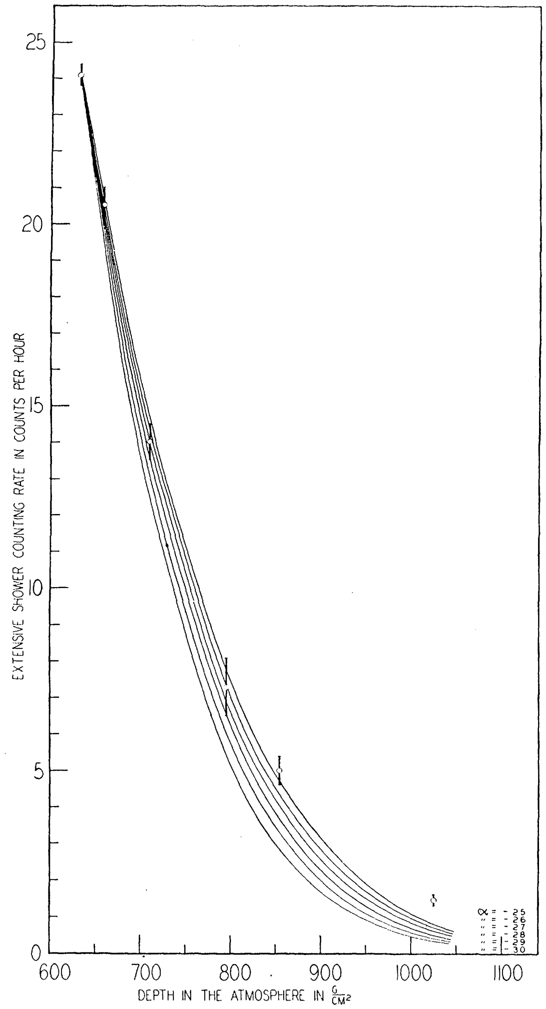

FIG. 2. The variation in the number of extensive cosmic-ray showers per unit time with depth in the atmosphere. The curves give the calculated variation for various choices of the power law exponent.

assumes that the primary particles are isotropically distributed in angle at the top of the atmosphere, which should be justified for the energies here involved ($>10^{13}$ ev).

Six such sets of values of counting rate as a function of depth were determined, one for each value of α used. Each contains a single undetermined constant, $N_{0,\alpha}$, which now represents the number of particles per cm² per sec. per unit solid angle incident at the top of the atmosphere. This constant was then adjusted so that the counting rate at Mt. Evans was the experimentally observed value of 24.1 counts per hr. These curves for ${}^{\text{III}}R_{z,\alpha}$ as a function of z for the various values of the exponent are shown in Fig. 2.

Discussion of Results

It will be seen from Fig. 2 that there is excellent agreement between the cascade computation and the experimental observations at the high altitudes, that is at Summit Lake and at Echo Lake, for values of the exponent lying between 2.6 and 2.8. At the lower altitudes, particularly at Chicago, there is definite disagreement for all values of the exponent. As pointed out in a recent note,[7] this discrepancy can be explained qualitatively on the basis of a mesotron component accompanying these extensive showers. With this in mind, the choice of the best value of the exponent must be made from the high altitude observations. Here the electron-photon component is most fully developed and consequently the relative contribution of the mesotron component to the total spatial distribution of ionizing particles in the shower is very small. The Echo Lake observation is at an altitude sufficiently high for the mesotron correction to be small and yet far enough below Mt. Evans for the differences between the calculations for the different values of the exponent to become appreciable. Basing the choice, therefore, on this point, the best value of the exponent would appear to be 2.70 or somewhat larger, although any value from 2.6 to 2.8 is permissible.

The selection of a particular value of the exponent based on the present data alone is not as well defined as could be desired. On the other hand, the value of the coefficient which must be associated with any given choice of the exponent is much more precisely determined. This arises from two facts; first, that the Mt. Evans observation is the best determined of the experimental counting rates; and second, that the cascade computation itself is most completely valid at high altitudes where the showers are most fully developed. The relationship between the coefficient and the exponent as determined by the present data and computations is

$$\log_{10}(N_{0,\alpha}) = 12.146 + 14.55(\alpha - 2.5) - \tfrac{1}{2}\times 1.1 \times(\alpha-2.5)(\alpha-2.4) \quad 2.5 \leqq \alpha \leqq 3.0.$$

[7] N. Hilberry, Phys. Rev. 59, 763 (1941).

If numerical agreement with the extensive shower observations at the top of Mt. Evans is to be obtained, this expression must be satisfied for any choice of the exponent. To obtain good agreement with the Echo Lake observations α is limited to the range between 2.6 and 2.8.

Figure 3 shows in the full curve the graph of $d(NE)/dE$ over the energy range up to 5×10^{10} ev as predicted by this energy distribution expression with α equal to 2.75. It should be emphasized that this expression has been derived from observations involving primary particles chiefly in the energy range from 5×10^{13} ev to 5×10^{15} ev. In this case, the energy distribution expression becomes:

$$dN=5.4_5\times10^{15}E^{-2.75}dEd\omega.*$$

The dotted curve in Fig. 3 is that published by Bowen, Millikan and Neher[8] and the blocks represent their experimental observations. The broken curve in Fig. 3, for energy values less than 1.0×10^{10} ev, has been obtained in the same manner as that of Bowen, Millikan and Neher by adjusting it so that the areas under the curve are kept equal to those of the corresponding blocks. As will be seen, the present curve fits the experimental observations remarkably well. In obtaining it, it has been assumed that over the major part of the observed energy range the particles are isotropically distributed at the top of the atmosphere.

Integration of the energy distribution expression to determine the energy per cm^2 per sec. carried into the top of the atmosphere from all directions by particles in various energy bands gives a value of 9.7×10^8 ev for those particles with energies above 1.7×10^{10} ev as compared with the Bowen, Millikan and Neher observation of 9.4×10^8 ev. In the band from 0.67×10^{10} ev to 1.7×10^{10} ev, the present expression gives 9.8×10^8 ev as compared with the experimental observation of 8.7×10^8 ev. Since the observed distribution has already dropped well below the power law in the lower part of this energy range, this agreement is also satisfactory.

If 2.74 is used for α, the energy which should be carried in by particles with energies above 1.7×10^{10} ev drops to 9.0×10^8 ev but it then becomes very difficult to fit a smooth curve to the experimental observations below 1.0×10^{10} ev. On the other hand, the choice of 2.76 for α makes possible a smooth fit below 1×10^{10} ev but the energy which particles above 1.7×10^{10} ev should carry in then becomes 10.5×10^8 ev and this is definitely in poorer agreement with the observations than the result given by the expression with $\alpha=2.75$.

It would seem, therefore, that a single power law expression is capable of describing the distribution of the number of primary cosmic-ray particles per unit energy range from energies of 10^{16} ev down to energies of 10^{10} ev.

The question immediately arises as to why a deviation from this power law should set in at 1×10^{10} ev, since this is a very high energy value to be affected by the solar magnetic field.[9] A *Letter to the Editor* by Carlson and Schein[10] now in press suggests that a large amount of energy is carried away by neutrinos in the disintegration of the mesotrons. If some such hypothesis is correct, the present power law may be valid down to energies even lower than 1×10^{10} ev. Thus if the total energy carried into the top of the atmosphere at Omaha be computed from the present

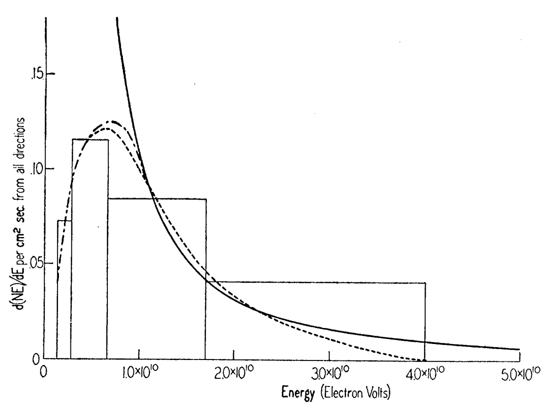

FIG. 3. The energy distribution curve in the region of 10^{10} ev. The full curve gives the present power law expression. The dotted curve is the curve of Bowen, Millikan and Neher and the blocks represent their experimental observations. The broken curve is the present power law distribution adjusted below 10^{10} ev to fit the experimental observations.

* The value of the coefficient, 5×10^{15} given in the previous note[7] was taken from a linear logarithmic graph of coefficient against exponent. In re-evaluating the coefficient-exponent relationship, the more precise formulation seemed justified.

[8] Bowen, Millikan and Neher, Phys. Rev. **53**, 855 (1938).

[9] P. Epstein, Phys. Rev. **53**, 862 (1938).

[10] J. F. Carlson and M. Schein, Phys. Rev. **59**, 840 (1941).

expression, the value is 3.54×10^9 ev per cm^2 per sec. from all directions as compared with the experimental observation of Bowen, Millikan and Neher of 2.25×10^9 ev per cm^2 per sec. There is then a discrepancy of 37 percent between the energy carried into the atmosphere as calculated and that observed, as compared with the loss of approximately 40 percent given by Carlson and Schein for the neutrino loss in the same energy range. On this basis it would seem possible that the power law given here may hold down to an energy considerably below 10^{10} ev.

The validity of a single energy distribution expression over an energy range from 10^{16} ev to 10^{10} ev or lower indicates strongly that there is but one predominant type of primary cosmic-ray particle. The recent experiments of Schein, Jesse and Wollan[11] indicate that these particles are protons. This suggestion has been made previously by R. Gunn[12] and W. F. G. Swann.[13] Others[14,15] have emphasized protons as responsible for the penetrating component. It must now be determined whether or not primary protons obeying the energy distribution given here are capable of accounting for the soft component of cosmic rays, the observed mesotron energy distribution and the extensive shower phenomena. The recent discussions by Swann[13] and by Carlson and Schein[10] describe the way in which the soft component can arise from such incident protons, and the mean energies used in their calculations are in good agreement with those computed from the present expression.

As pointed out in the previous note,[7] this energy distribution is capable of accounting qualitatively, likewise, for the mesotron distribution observed by V. C. Wilson[16] in his deep mine measurements.

The choice of the proton as the primary cosmic-ray particle has also certain advantages[7] from the point of view of the mesotron component in extensive showers. On the other hand, for the analysis presented here to furnish a valid description of the primary energy distribution, it is essential that practically the entire energy of a primary proton in the range above 10^{13} ev be transferred to electrons and photons very near the top of the atmosphere. It is possible that the radiation cross section of the proton in this energy range may prove to be sufficiently large to account for this energy transfer directly. If, however, the hypothesis of the explosive production of mesotrons by protons[12,10] proves to be justified, it would seem possible that it is this process which forms the first step in the genesis of an extensive shower. In the latter case, a large multiplication with a consequent large division of energy occurs in a single event practically at the top of the atmosphere. This would leave a group of extremely high energy mesotrons very near the top of the atmosphere as the second stage in the development of an extensive shower.

The next phase in the growth of the shower would depend on the behavior of the mesotron at these extremely high energies. Little is known with certainty from the theoretical standpoint concerning the nature of the mesotron. Experimentally, however, some information can be deduced from the absorption curves of V. C. Wilson.[16] If the decrease in intensity of the mesotrons with depth is due mainly to ionization loss as is almost certainly true, Wilson's absorption curve gives the integrated energy distribution for the very energetic mesotrons and, as pointed out before, this agrees well with the present primary proton distribution assuming a fairly constant production cross section at these high energies. There is a sudden change in this mesotron energy distribution, however, at a depth of about 250 m water equivalent, corresponding to an energy in the neighborhood of 10^{11} ev. For greater depths, the change of intensity with depth is much more rapid. The actual exponents for Wilson's absorption curve are -1.77 corresponding to energies less than 10^{11} ev and -2.52 for energies greater than this value. This marked break in the mesotron energy distribution indicates either that many fewer mesotrons are formed above this energy value or else that those formed in this range lose energy rapidly until they fall below this critical value.

---

[11] Schein, Jesse and Wollan, Phys. Rev. **59**, 615 (1941).
[12] R. Gunn, Terr. Mag. **38**, 247 (1933).
[13] W. F. G. Swann, Rev. Mod. Phys. **11**, 251–254 (1939); Phys. Rev. **58**, 200 (1940).
[14] A. H. Compton and H. A. Bethe, Nature **134**, 734 (1934).
[15] T. H. Johnson, Rev. Mod. Phys. **10** (1938); **11**, 208 (1939).
[16] V. C. Wilson, Phys. Rev. **53**, 337 (1938); Rev. Mod. Phys. **11**, 230 (1939).

There appears to be no reason why mesotrons should not be formed at high energies unless the radiation cross section of the proton in this energy range becomes large in comparison with the mesotron production cross section, which itself must be very great. In such a case the radiation of the mesotron would not be required as an intermediate process in the transfer of the energy from the proton to the shower particles. The proton itself would then be the shower-producing particle.

If the high energy mesotrons are formed abundantly, radiation from those with energies over 10^{11} ev must be assumed. This is in accord with the conclusion arrived at by Christy and Kusaka[17] in their analysis of bursts. The value of the radiation cross section must become large above approximately 10^{11} ev to account for the magnitude of the break in Wilson's energy distribution. On this basis, the third step in the formation of an extensive shower would be the transfer of energy from the energetic mesotrons to photons by successive radiation until the mesotron energy has dropped below the 10^{11} ev value. Since the minimum initial energy of the mesotrons in the present case would have been above 5×10^{12} ev this means that all but one or two percent of the energy of the softest mesotrons entering into extensive shower production would go into photons and electrons. This would mean that even for the lowest energy protons which make any appreciable contribution to the counting rates observed in the present experiment, all but some ten percent of the energy of the initial proton eventually would go into typically developing shower particles. For the majority of the protons, the energy carried off by the mesotrons would be very much smaller.

It is probably true that a certain fraction of the photon energy is also converted back into slow mesotrons,[18–20] but this again should have but a relatively small effect upon the total energy appearing in shower particles at high altitudes, and consequently in the total number of ionizing particles reaching the plane of observation.

It would thus seem quite possible for a primary proton to generate an extensive shower which would differ from an electron generated shower of the same initial energy at depths of sixteen or more cascade radiation units below the top of the atmosphere by less than the errors in the present observations and those inherent in cascade computations of the kind here carried out. Consequently, it would still appear justifiable to assume that the expression here given does represent approximately the energy distribution of the primary protons in the energy range from 10^{16} ev to 10^{10} ev.

In conclusion, the author wishes to express his indebtedness to Professor A. H. Compton for his advice and encouragement throughout the progress of this work, and to thank Professor Bruno Rossi for his advice on the arrangement of the experiment and for discussion of results during the expedition. To Professor Joyce Stearns of Denver University, whose unfailing thoughtfulness and assistance play such a large part in the success of any Mt. Evans expedition, the author is deeply grateful.

[17] R. F. Christy and S. Kusaka, Phys. Rev. **59**, 414 (1941).

[18] M. Schein and V. C. Wilson, Rev. Mod. Phys. **11**, 292 (1939).

[19] Schein, Jesse and Wollan, Phys. Rev. **57**, 847 (1940).

[20] L. Janossy and P. Ingleby, Nature **145**, 511 (1940).