Penetrating Particles in Extensive Cosmic-Ray Air Showers

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The number of penetrating particles in extensive air showers has been determined as a function of range of the particles and size of the showers at 3260-m elevation. A measurement with the same apparatus has been made at 260-m elevation, in order to show the altitude variation. It is found that the showers at 3260 m contain many photons and electrons which can be detected under absorbers up to 7-inches lead. The particles penetrating more than this thickness have a very small absorption coefficient in iron, and decrease in density slowly as they traverse the atmosphere. Hence they are thought to be primarily μ-mesons.

IMPROVED measurements have been made, during the summer of 1948, of the penetrating particles present in the extensive air showers at Echo Lake, Colorado (elevation 3260 m), and at Ithaca, N. Y. (elevation 260 m). These measurements, as well as similar measurements made in the past,[1–4] yield numbers for $R(t)$, which is an effective value for the fractional number of shower particles capable of penetrating a thickness t of absorber. It was our intention to improve the precision of determination of R, to study the dependence of R on the size of the showers, and to investigate the nature of the penetrating particles by studying their absorption properties; i.e., the dependence of R on t and on the altitude above sea level.

Three unshielded counter trays, A, B, and C, each of total area S, were disposed in a triangular arrangement in a horizontal plane, with six-meter separation between counter trays at Echo Lake, four-meter separation at Ithaca. Three other counter trays, M_1, M_2, and M_3, each of area S', were placed one above another within a large block of absorber, as shown in Fig. 1. The absorber contained 9 tons of lead plus 3 tons of iron. Simultaneous records were obtained of the coincidences ABC, $ABCM_1$, $ABCM_2$, and $ABCM_3$.[5] The ratio $ABCM_i/ABC$ essentially determines the value of R for the absorber thickness above tray M_i.

The pulses from counters A, B, C were at the same time used in another experiment, on the density spectrum of the electrons in the showers. That experiment is described in an accompanying article in this issue. Further details about the apparatus and precautions taken to eliminate errors are given in that article, and so are omitted here.

* On leave from the University of Catania, Italy.
[1] G. Cocconi, A. Loverdo, and V. Tongiorgi, Phys. Rev. **70**, 852 (1946).
[2] D. Broadbent and L. Janossy, Proc. Roy. Soc. **A191**, 517 (1947); **A192**, 364 (1948).
[3] B. Chaudhuri, Nature **161**, 680 (1948).
[4] J. E. Treat and K. Greisen, Phys. Rev. **74**, 414 (1948).
[5] In part of the experiment, the rate $ABCM_2$ was not recorded.

DEPENDENCE OF R ON SIZE OF SHOWERS

Showers of various mean particle-densities were selected by using different areas S for the unshielded counters. It is well known that the frequency of showers of density greater than Δ follows the empirical law

$$f(\Delta)=K\Delta^{-\gamma},$$

where γ is approximately 1.5 and varies slowly both with Δ and with altitude. Therefore the contribution from showers of density between Δ and $\Delta+d\Delta$ to the coincidence rate of three counters of area S is proportional to

$$g(\Delta)d\Delta=\Delta^{-(\gamma+1)}(1-e^{-S\Delta})^3d\Delta.$$

The contribution per logarithmic unit interval of Δ (i.e., $\Delta g(\Delta)$) is shown in Fig. 2 for $\gamma=1.5$. It is apparent that the choice of a given value of S selects showers that fall in a limited density range, from about $1/10S$ to $10/S$. The slow variation of γ is unimportant over the range of densities that contribute strongly to the coincidence rate. While the present experiment was in progress, careful measurements of γ were simultaneously being carried out by G. and V. Cocconi (see accompanying paper in this issue), so the correct value of γ could be chosen for each of the counter areas S.

In Table I, the data taken at Echo Lake with fixed absorber thicknesses but variable S are presented. Above M_1 the absorber t_1+t_2 was 7 inches of lead (plus 0.15 inch of iron and brass), which is 204 g/cm² or 35 radiation lengths. The experiments with variable absorber, discussed below, show that this is sufficient to exclude essentially all the electrons and photons of the showers. Between M_1 and M_2 was 8 inches of iron ($t_3=155$ g/cm²), while between M_2 and M_3 was another 8 inches of iron, t_4. The momentum losses for mesons of mass 10^8 ev/c² that can barely traverse these absorbers are 3.4, 5.8 and 8.3×10^8 ev/c.

The ratio R for particles capable of traversing the absorbers has been found under the assumption that it is a fixed quantity, independent of the size of the shower or the distance from the shower core.

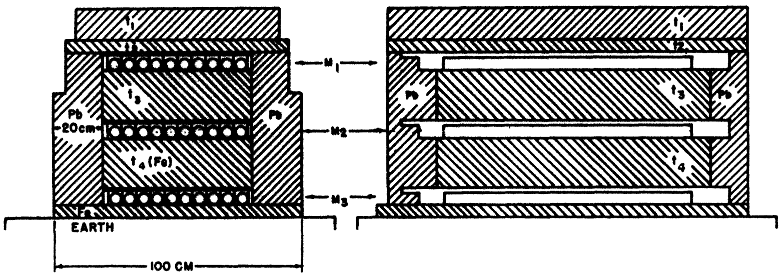

FIG. 1. Arrangement of shielded counters and absorbers.

Such an assumption seems necessary, for lack of any information on the production process or scattering of the penetrating particles in the showers. The values of R thus found are true average values only if the assumption is approximately correct; otherwise they are weighted averages, weighted according to the probabilities of detection of the showers. Under this assumption, the counting rates $ABCM$ and ABC are related by

$$\frac{ABCM}{ABC}=\frac{\int_0^\infty \Delta^{-(\gamma+1)}(1-e^{-S\Delta})^3(1-e^{-RS'\Delta})d\Delta}{\int_0^\infty \Delta^{-(\gamma+1)}(1-e^{-S\Delta})^3 d\Delta}.$$

This ratio has been plotted as a function of RS'/S for several values of γ in Fig. 3. The values of R deduced from the graph and from the experimental rates $ABCM$, ABC, are given in the last three columns of Table I. The area S' for all of the measurements was 5000 cm^2.

It may be noted that some sources of error have little or no effect in the above treatment of data. In fact, the data in Tables I and II have been corrected only for the small numbers of chance coincidences (the resolving time was 4 microseconds). The barometric correction has been omitted because it cancels out in the ratio $ABCM/ABC$. The inefficiency of counters A, B, and C, when these trays are composed of single counters, has no effect on the ratio. When the trays are composed of several counters (i.e., for the 1560-cm^2 area only), the inefficiency acts like a small reduction in the area S. The inefficiency of the trays M was very small (less than one percent), and acts as a reduction in the area S'; this, however, compensates almost exactly for the partial effectiveness of the spaces between the counters in the trays. A mixing circuit was employed so that the use of a large number of counters in parallel would not increase the inefficiency. The effective area of the trays M decreases with increasing inclination of the shower axis relative to the zenith. However, the area of the unshielded trays decreases similarly with inclination, and the ratio RS'/S, which determines the relative counting rates $ABCM/ABC$, is unaffected.

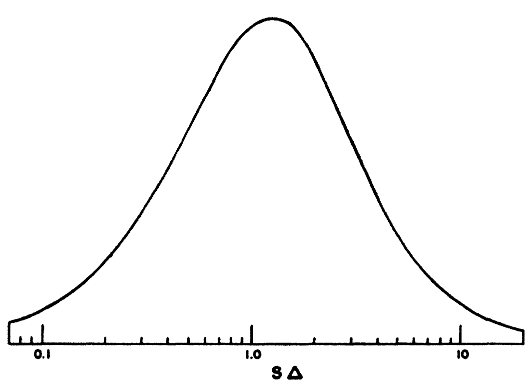

FIG. 2. Contribution to the threefold coincidence rate, made by showers of different densities, per logarithmic density interval.

The values of R_1, R_2, and R_3 in Table I indicate that the "penetrating particles" are really penetrating in character, and hence are (mostly, at least) not photons or electrons. The average ratio $R_1/R_2/R_3$ is 1.00/0.90/0.79. In this ratio the errors are smaller than one would conclude if one considered R_1, R_2, and R_3 as statistically independent, for in fact they are not so. The area of the trays was so large compared with the separation, that many of the particles crossing one of the trays crossed the other trays also.

The values of R_1 and R_3 from Table I are shown in the graph of Fig. 4, which is a logarithmic plot of R against reciprocal counter area. Since the mean electron density in the showers is proportional to $1/S$, the proportion of penetrating particles is observed to decrease as the electron density increases, going approximately as

$$\frac{\text{Pen. Part.}}{\text{Electrons}}\sim(\text{Electrons})^{-0.13}$$

or

$$\text{Pen. Part.}\sim(\text{Electrons})^{0.87}.$$

The explanation for this is probably as follows. When one selects higher densities, one selects, on the average, showers of higher primary energy. In these, the electrons are not as far beyond the maximum of the multiplication curve as in showers of lower primary energy; hence the number of electrons per unit primary energy is larger in the

TABLE I. Data for determination of R *vs.* mean density of showers at Echo Lake, elevation 3260 m. $t_1+t_2=204$ g/cm² Pb, $t_3=t_4=155$ g/cm² Fe. R_i is the fraction of the shower particles that can penetrate to the layer i of shielded counters.

Counter area S (cm²)	γ	Time (hours)	ABC	$ABCM_1$	$ABCM_2$	$ABCM_3$	$R_1\times 100$	$R_2\times 100$	$R_3\times 100$
9	1.56	372.4	70	64	—	61	0.93 ± 0.36	—	0.64 ± 0.21
29	1.51	190.0	215	148	—	141	0.71 ± 0.10	—	0.62 ± 0.08
98	1.46	169.2	1187	602	—	537	1.08 ± 0.07	—	0.87 ± 0.05
500	1.39	38.5	2967	646	582	538	1.27 ± 0.06	1.10 ± 0.05	1.00 ± 0.05
1560	1.34	30.6	11,520	1334	—	1076	1.56 ± 0.05	—	1.20 ± 0.04
1560	1.34	44.9	17,735	1888	1761	—	1.41 ± 0.04	1.29 ± 0.03	—

denser showers. The penetrating particles are not so strongly absorbed, so their transition curve is much more flat and they are more likely to be proportional in number to the primary energy. Hence the relative number of electrons should be greater in the denser showers.

In support of this hypothesis, Fig. 5 shows a graph of number of electrons, N, in showers at 15 radiation lengths depth, as a function of primary photon energy W_0. It is seen that over the range of N that contributes most to the counting rates (200 to 10^5, allowing for some multiplicity of the primary photons), the number of electrons is proportional to $W_0^{1.14}$. If the number of penetrating particles is proportional to W_0, we then have

$$\frac{\text{Pen. Part.}}{\text{Electrons}}\sim W_0^{-0.14}\sim(\text{Electrons})^{-0.12}.$$

The good agreement with the data of Fig. 4 lends support to the assumption that the number of penetrating particles in a shower is proportional to the primary energy.

DEPENDENCE OF R ON ABSORBER THICKNESS

In order to investigate the nature of the particles absorbed in less than 204 g/cm² lead, further data were taken at Echo Lake with constant area S (1560 cm²) but with different thicknesses and kinds of absorber in t_1 and t_3. These data, along with the deduced values of R, are given in Table II.

The results in Table II have been plotted in Fig. 6, with the abscissas equal to the momentum limits set by the absorbers for ordinary μ-mesons traveling in the vertical direction. Such a scale is similar to an ionization-loss scale for particles heavier than mesons also. It is immediately obvious from this graph that the particles that can penetrate the smaller absorbers (4 to 7 inches of lead, or 6 inches iron plus 2 to 5 inches lead) are not all mesons. Indeed, a large fraction consists of particles that are stopped much more effectively by lead than by iron. Such behavior suggests that they are high energy electrons and photons.

It is also obvious that beyond 8 inches of lead, or 8 inches iron plus 6 inches lead, the penetrating particles are *not* electrons or photons. In fact, the absorption is extremely small. The straight line drawn on the graph has a slope equal to 4×10^{-6} per g/cm² Fe, which is 3×10^{-4} relative to the intercept. In other words, if the absorption of this hard component is exponential, the mean free path is about 3600 g/cm² Fe, which is about 25 times the mean free path of high energy protons (or other heavy particles with strong nuclear interactions). The data of course do not permit the slope to be

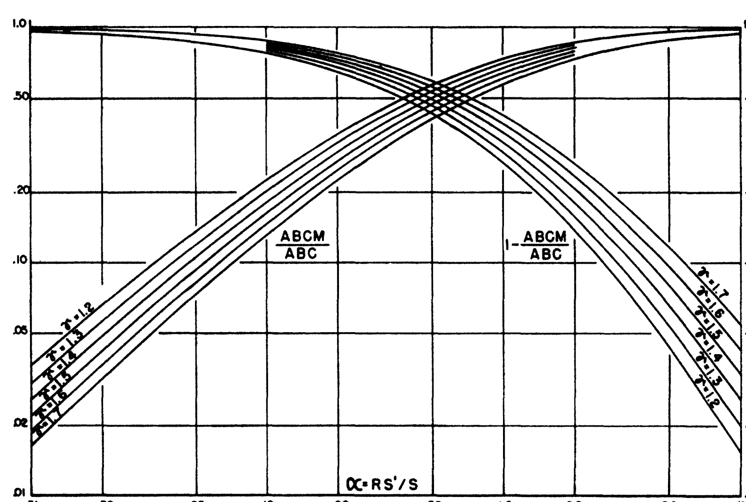

FIG. 3. $(ABCM/ABC)$ *versus* RS'/S for several values of γ.

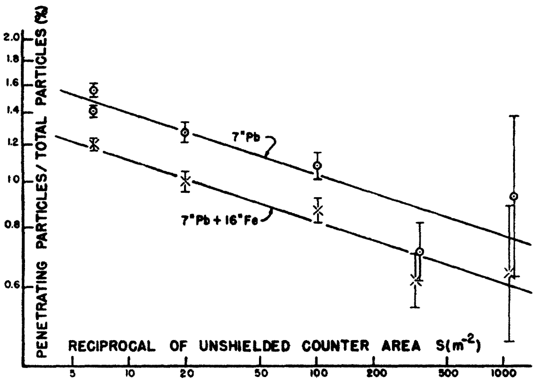

FIG. 4. *R versus* $1/S$, for penetrating particles capable of penetrating 7″ Pb and 7″ Pb+16″ Fe.

determined with precision, but the above value can hardly be too low by as much as a factor two.

Therefore we think that the hard component of the showers is composed mainly of ordinary μ-mesons, rather than other types of heavy particles. This conclusion must be considered tentative, because the properties of the absorption curve for protons plus their secondaries are not known. A high energy proton has a relatively short mean free path for nuclear interaction, but in this act it produces further penetrating particles. These are presumably not μ-mesons, but again strongly interacting particles, that produce more nuclear interactions after short free paths. Such a process of multiplication should exhaust the primary energy rapidly, not giving an exponential absorption curve in the first two or three mean free paths (i.e., in our experiment), but yet giving a faster absorption than 3×10^{-4} per g/cm² Fe.

Pictures taken this summer with a cloud chamber under thick lead, triggered by air showers,[6] show the occasional presence of a heavy particle that produces a star, or a penetrating shower, or a local burst of cascade radiation. V. Cocconi Tongiorgi[7] has also demonstrated that heavy particles in the showers frequently produce neutrons. The heavy particles that do these things are not μ-mesons. The slow absorption in lead can be understood, however, if the strongly interacting particles are a minor fraction of the penetrating component in the showers near sea level, not more than about 25 percent.

In order to test the conclusion that the particles absorbed in less than 7 inches of lead are photons and electrons, the parts of R which were due to penetrating particles (as read from the straight line drawn in Fig. 6) have been subtracted from the values of R in Table II, and the differences have been plotted in Fig. 7 as a function of the total absorber thickness in radiation lengths (in the vertical direction). The points for iron-and-lead absorbers as well as those for the pure lead absorbers are seen to fall approximately on a single smooth curve. The slight discrepancies are in the right direction to be accounted for by the errors in the simplified cascade theory which predicts that all materials should be equivalent in radiation units. More specifically, the low energy photons have a much longer range (in radiation lengths) in lead than in iron; hence the counting rates are slightly greater under the lead absorbers than under the lead and iron.

It should be noted that all the data in Table II, taken with absorbers thin enough that some electrons and photons are included in R, were obtained with at least ten radiation units of lead directly above the counters (except for one point, which is enclosed in parentheses in the table and not plotted in the graphs of either Fig. 6 or Fig. 7). The layer of constant material above the counters ensures that the particles of low energy in the cascades always have the same spectrum. Without

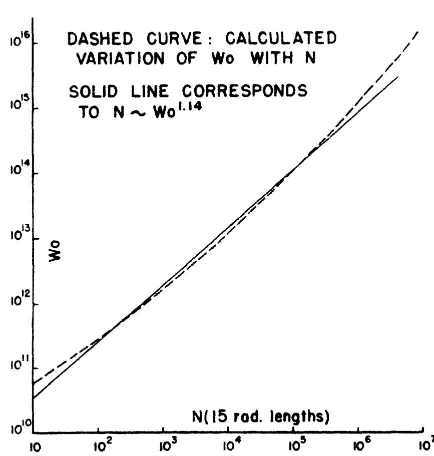

FIG. 5. Numbers N of electrons generated after 15 radiation lengths in air by a photon of energy Wo.

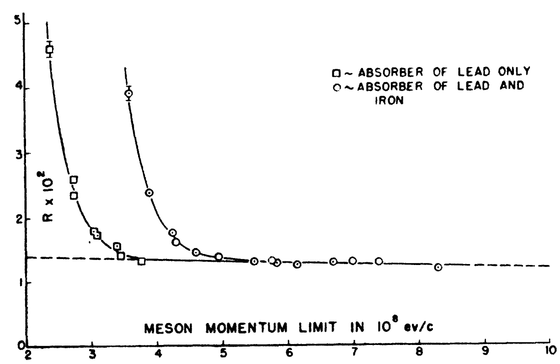

FIG. 6. *R versus* total absorber thickness, expressed in terms of the meson momentum limit. The points enclosed in squares refer to lead thicknesses from 4 to 8 inches. The least absorber including iron was 2 inches lead plus 6 inches iron.

[6] Experiments performed by W. W. Brown and A. S. McKay; results to be published soon.

[7] V. T. Cocconi, Phys. Rev. **74**, 226 (1948).

TABLE II. Data for absorption curve at Echo Lake. Areas = 1560 cm² (unshielded counters), 5000 cm² (shielded counters).

Absorbers (g/cm²) t_1	t_2	t_3	t_4	Time (hours)	ABC	Counts recorded $ABCM_1$	$ABCM_2$	$ABCM_3$	Fraction of particles $R_1\times 100$	$R_2\times 100$	$R_3\times 100$
57 Pb	60 Pb	60 Pb	155 Fe	23.6	8784	2279	1106	886	4.59±0.12	1.73±0.06	1.31±0.05
114 Fe	60 Pb	60 Pb	155 Fe	22.7	8465	1960	1008	847	3.91±0.11	1.62±0.06	1.30±0.05
86 Pb	60 Pb	60 Pb	155 Fe	44.9	17,735	2823	1888	1761	2.35±0.06	1.41±0.04	1.29±0.03
114 Fe	89 Pb	60 Pb	155 Fe	35.6	13,993	2256	1533	1404	2.39±0.06	1.46±0.04	1.31±0.04
86 Pb	60 Pb	41 Fe	155 Fe	47.0	18,445	3186	2349	1884	2.61±0.06	(1.76±0.04)	1.33±0.04
115 Pb	60 Pb	60 Pb	155 Fe	22.3	8631	1107	883	843	1.78±0.06	1.33±0.05	1.26±0.05
114 Fe	89 Pb	60 Pb	155 Fe	21.5	8063	1028	852	803	1.77±0.06	1.39±0.06	1.30±0.05
144 Pb	60 Pb	155 Fe	155 Fe	30.6	11,520	1334	——	1076	1.56±0.05	——	1.20±0.04

such a constant layer, absorbers of iron and lead would not be even approximately equivalent in radiation units for the cascade showers.

DEPENDENCE OF R ON ALTITUDE

The proportion of penetrating particles in air showers has also been determined at Ithaca, N. Y. (elevation 260 m), with the same apparatus as that used at Echo Lake. The separation between counters A, B, and C was 4 meters (corresponding to the 6-meter separation used at Echo Lake). The absorbers were the same as for the Echo Lake data of Table I: namely, $t_1+t_2=204$ g/cm² Pb, $t_3=t_4=155$ g/cm² Fe. The area of the unshielded counters was 1680 cm², and of the shielded counters was 5000 cm².

In 202.1 hours the following counts were recorded (corrected only for chance coincidences): ABC, 8863; $ABCM_1$, 1370; $ABCM_2$, 1251; $ABCM_3$, 1144. The value of γ appropriate to 1680-cm² area of the unshielded counters is 1.38. From these data we deduce for the relative number of penetrating particles

$$R_1\times 100=2.60\pm 0.09,$$
$$R_2\times 100=2.31\pm 0.08,$$
$$R_3\times 100=2.06\pm 0.07.$$

The values of R_1, R_2, and R_3 are found to be in the ratio 1.00/0.89/0.79, almost exactly the same as at Echo Lake under the same absorbers. But all three values of R are larger than at Echo Lake, which indicates that the density of the penetrating particles varies less than the density of the electrons as the showers cross the atmosphere.

Indeed, from interpolation between the data of Table I, one finds that the showers ABC recorded at Ithaca have the same frequency as the showers recorded at Echo Lake with counters A, B, C smaller in area by a factor 5.0. Hence the electron density in these showers decreases by an average factor 5.0 between Echo Lake and Ithaca. The relative density of penetrating particles, meanwhile, changes from 1.21 percent at Echo Lake to 2.60 percent at Ithaca (for particles that can traverse 7 inches Pb), or from 0.96 percent at Echo Lake to 2.06 percent at Ithaca (for particles that can traverse 7 inches Pb plus 16 inches Fe). The density of the penetrating particles in the showers, therefore, is reduced by a factor 2.33±0.1 between Echo Lake and Ithaca. This factor is found to be independent of the absorber thickness within the statistical errors (all absorbers in this comparison were thick enough to exclude practically all the photons and electrons).

These results exclude the possibility that most of the penetrating particles are locally produced in the absorbers, either by the photons in the showers or by strongly interacting heavy particles. If they were all locally produced, the number of penetrating particles should be proportional to the local intensity of the producing particles. The soft component of the showers decreases by an average factor 5.0, and the strongly interacting heavy particles must be reduced by a factor about 10 between Echo Lake and Ithaca. Both of these factors are much greater than the factor 2.3 measured for the penetrating particles.

The density-reduction factor 2.3 represents the combined effect of many possible processes: (a) further scattering in the air, (b) increase in spread due to previous angular divergence, (c) ionization loss, (d) nuclear interactions, (e) radioactive decay in the air, and (f) absorption, in the air, of the shower particles that may produce penetrating particles in the local absorbers—all of which processes tend to reduce the density—plus (g) further production of penetrating particles in the

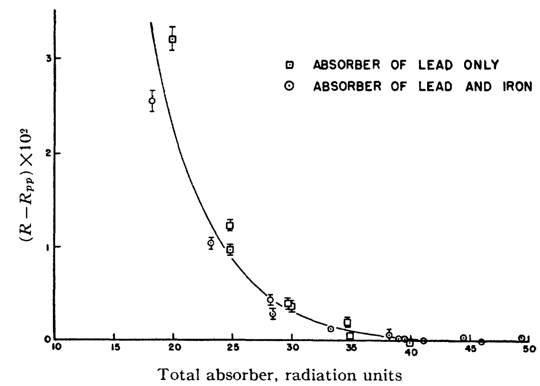

FIG. 7. The part of R not due to penetrating particles, plotted *versus* total absorber thickness, measured in radiation units.

TABLE III. Dependence of measurements on the separation of counters A, B, C. Area of unshielded counters = 1680 cm², that of shielded counters = 5000 cm². Effective value of $\gamma = 1.38$. $t_1 + t_2 = 204$ g/cm² Pb, $t_3 = t_4 = 155$ g/cm² Fe.

Mean separation of counters ABC	Time (hours)	ABC	$ABCM_1$	$ABCM_2$	$ABCM_3$	$R_1 \times 100$	$R_2 \times 100$	$R_3 \times 100$
1.3 m	206.4	11002	1588	1380	1312	2.38 ± 0.07	1.99 ± 0.06	1.87 ± 0.06
4.5 m	202.1	8863	1370	1251	1144	2.60 ± 0.09	2.31 ± 0.08	2.06 ± 0.07
15.0 m	231.8	8020	1313	1227	1197	2.81 ± 0.09	2.57 ± 0.09	2.48 ± 0.09

air, which tends to increase the density. As pointed out above, the small net reduction factor indicates that local production is comparatively unimportant. Hence the decrease in amount of local production in the absorbers (process *f*) and the production in the air (process *g*) are small factors which approximately cancel each other and may therefore be neglected.

For the strongly interacting particles that produce penetrating showers (in general not associated with extensive showers), the reduction due to ionization loss and nuclear interactions, minus the creation in the air, is a factor 10 between Echo Lake and Ithaca (see accompanying article by G. Cocconi on penetrating showers). Hence it is inconceivable that the penetrating particles in extensive showers should be mostly of the strongly interacting type, such as high energy protons. For μ-mesons not associated with extensive showers, on the other hand, the reduction in number, arising from ionization loss and decay, minus the effect of local production, is a factor 1.74 between the two elevations. The increase in geometrical separation of the particles, caused by scattering and previous angular divergence, can easily account for a further density-reduction of $2.33/1.74 = 1.34$. Therefore the penetrating particles are probably μ-mesons, created in the air high above the apparatus.

The experimental results given above may be summarized as follows. The particles in the showers, capable of penetrating rather thick absorbers, consist (*a*) of electrons and photons, which are not fully absorbed until 40 radiation lengths of absorber, and (*b*) of penetrating particles that are very slowly absorbed in large thicknesses (absorption coefficient $\approx 3 \times 10^{-4}$ per g/cm² Fe). The penetrating particles in the showers are primarily μ-mesons.

COMPARISON WITH PREVIOUS EXPERIMENTS

The results and interpretation of the present experiments are somewhat at variance with the results and interpretation of a similar experiment performed by J. E. Treat and K. Greisen[4] at Echo Lake in 1947. From that experiment, it was concluded that the penetrating particles were about three percent of the shower particles (rather than about one percent), and were rather easily absorbed; moreover, that the penetrating particles varied in density even more rapidly than the electrons as the altitude was changed. The reason for the errors in these conclusions is now obvious: Treat and Greisen did not use quite enough lead above the counters to exclude all the electrons and photons. In their "Experiment *A*" the absorber was 14-cm thick; we see from the graph in Fig. 6 or 7 that under this thickness, about $\frac{1}{3}$ of the "penetrating" particles are photons or electrons. Their lead shielding was also not quite complete at the ends of the counters, so that perhaps as many as $\frac{1}{2}$ of their "penetrating" particles were soft component. When they changed the elevation, the number of high energy electrons and photons increased more rapidly than the number of low energy electrons. And when they increased the amount of absorber, the soft component was absorbed. Under their maximum absorber, 39 cm Pb, they found $R = (83 \pm 7)^{-1} = 1.20 \pm 0.10$ percent at Echo Lake, in excellent agreement with our present results.

From the experiments of Cocconi, Loverdo, and Tongiorgi,[1] one may deduce $R \times 100 = 2.2 \pm 0.2$ at 2200-m elevation under 16 cm Pb. We see now that this figure included some electrons as well as penetrating particles. Broadbent and Janossy,[2] at sea level, have found $R \times 100 = 2.0 \pm 0.5$ under very thick absorbers, with the result independent of the atomic number of the absorber. B. Chaudhuri,[3] also at sea level, has found $R \times 100 = 2.0 \pm 0.2$. The latter two results are in good agreement with those of the present experiment at sea level.

PLACE OF ORIGIN OF THE PENETRATING PARTICLES

The question has frequently been raised,[2, 8–11] whether the penetrating particles observed in extensive showers are created in the absorbers of the detecting apparatus, or arrive on the absorbers from the air. The information accumulated by now allows a fairly complete answer to this question. In the first place, production of penetrating particles in the lead plates of a cloud chamber has been seen[6] in association with air showers; hence, *some* of the penetrating particles observed under lead are locally produced. This implies that production

[8] G. Cocconi and C. Festa, Nuovo Cimento **3**, 293 (1946).
[9] D. Broadbent and L. Janossy, Proc. Roy. Soc. **A190**, 497 (1947).
[10] G. Salvini and G. Tagliaferri, Phys. Rev. **73**, 261 (1948).
[11] G. Cocconi and K. Greisen, Phys. Rev. **74**, 62 (1948).

can also occur in the air. Several experiments[8–10] have shown that the number of penetrating particles observed is independent of the atomic number of the absorber. Hence, either the particles are mostly *not* locally produced, or the amount of production is independent of atomic number. Finally, we observe that the penetrating particles have very small average absorption coefficients in lead and iron, and increase in number slowly with elevation. Therefore the particles can be produced in air, even at a great height above the apparatus, and still be observed. The number produced in the air is in general much greater than the number produced locally, because the weight of air above the apparatus is greater than the weight of absorber, and the average intensity of the producing agents is greater in the air.

The penetrating particles produced in the air, however, are separated from each other because of their initial angular divergence and their scattering, so they are only rarely found close together. If one designs a counter arrangement that exerts a strong bias in favor of close-packed groups of penetrating particles, one may record most frequently those groups of penetrating particles that are locally produced, even though these are a small fraction of all the penetrating particles in the showers. If, however, one uses a single shielded counter or a group of widely separated counters, one will detect most frequently the penetrating particles that were produced in the air above the apparatus. This explanation accounts fairly well for the differences among the experimental results in the references given above.

APPENDIX I

Dependence of the Measured Value of R on the Separation of Counters A, B, and C

The dependence of R on counter separation has been investigated experimentally at Ithaca, by repeating the measurement with different distances between the counters A, B, C. The big absorber surrounding the counters M was always located a few meters below the plane of counters A, B, C, under a point near the center of the triangle formed by those counters. The data (corrected for chance coincidences) are given in Table III, and the ratios $ABCM/ABC$ have been plotted in Fig. 8 *versus* the mean separation of counters A, B, and C. The three curves correspond to the same three absorber thicknesses as were used to obtain the data at Echo Lake, given in Table I and Fig. 4. Figure 8 also shows, on a different scale, the variation of the coincidence rate ABC with counter separation.

The coincidence rate ABC is observed to be 21 percent greater at 1.3 meters, and 21 percent less at 15 meters, than the rate with 4.5-meter separation. The decrease of ABC with separation is due to elimination of the small showers striking very nearby, which have sufficient density to discharge the counters only over a small area. The magnitude of the effect would indicate that about $\frac{1}{3}$ of the showers that discharge the counters having 1.3-meter separation strike with their cores within about 10 meters of the counters.

The ratios $ABCM/ABC$ do not change by such a large percentage, but nevertheless show a significant increase with distance between the counters. From the extrapolated values of the ratio at zero counter separation, we obtain the following values of R:

$$R_1\times 100=2.28,$$
$$R_2\times 100=1.93,$$
$$R_3\times 100=1.70.$$

These are less than the values found at 4.5-meter separation by about 15 percent. Presumably a similar difference would be found at Echo Lake between zero and 6-meters counter separation.

In computing the above values of R and the values in Table III, however, we have assumed the effective value of the exponent γ in the density spectrum to be constant at the value (1.38) measured with 4-meter counter separation. Recent data by Loverdo and Daudin[12] and by R. W. Williams[13] indicate that γ increases with counter separation. This implies that a more correct evaluation of R would show an even stronger increase with counter separation than is indicated above.

One may conclude that the following assumptions, used in our evaluation of R, are not accurate: (1) that the showers have the same density at each of the counters (this is wrong for the large fraction of showers that strike nearby), (2) that R is independent of shower size, and (3) that R is independent of distance from the shower core.

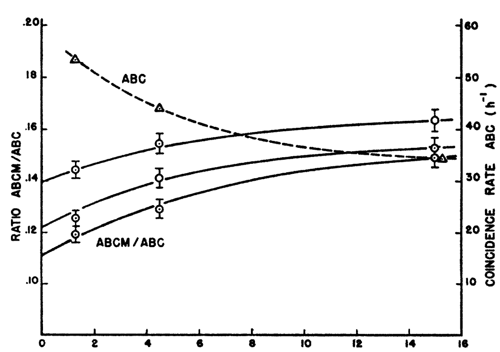

FIG. 8. ($ABCM/ABC$) and ABC *versus* separation of the unshielded counters ABC.

[12] A. Loverdo and J. Daudin, J. de phys. et rad. **9**, 134 (1948).

[13] Robert W. Williams, Phys. Rev. **74**, 1689 (1948). We are grateful to the author for communicating his data to us before publication.

It seems unlikely that the error in the assumption of uniform density could have produced an effect as large as that which was found. The weak dependence of R on shower size has been discussed above (Fig. 4). Since R decreases with shower size, and the average shower size increases with counter separation, this effect would make R decrease with separation of counters A, B, C. That would be opposite to the observed variation of R. Therefore it seems probable that R increases rather strongly with distance from the shower core, because the average distance to the core of the showers increases with counter separation. In other words, it seems likely that the mesons are not concentrated as strongly near the core of a shower as are the electrons.

It should not be concluded that measurements of R made with extremely small counter separation are more accurate than measurements made with several meters separation. Indeed, if counters A, B, C are placed too close to each other, they will be sensitive not only to extensive showers, but to small local showers and stars as well. Rather, it must be recognized that any values of the relative number of penetrating particles, measured as in the present experiments, are effective values, averaged over a wide range of shower sizes and distances from the shower core. R is not a constant, but in principle should be measured as a function of these parameters.

APPENDIX II

On the Existence of λ-mesons

It has been suggested[14] that the particles of the extensive showers which are absorbed in thicknesses between 3 and 7 inches of lead are too penetrating to be electrons and too soft to be μ-mesons, but must represent another particle, the λ-meson, of mass between 3 and 10 times the electron mass. While we have no proof of the non-existence of λ-mesons, we think the evidence for their existence has been misinterpreted and does not require new particles for its explanation.

The chief causes of the misinterpretation were probably two: (1) an underestimate of the relative number of high-energy electrons and photons in the large air showers, and (2) an underestimate of the "range" of a cascade shower in lead. The latter error was also what led Treat and Greisen to use too little lead above their shielded counters.

The relative abundance of high-energy particles in the extensive showers is much greater than in the smaller showers which constitute the bulk of the soft component in the atmosphere. In fact, the total soft component in the atmosphere is known to have an energy spectrum (at high energies) that goes approximately as dE/E^3. The extensive showers, on the other hand, are mostly observed only slightly beyond their maximum development. The energy spectrum under these conditions goes about as dE/E^{s+1} with $s+1\approx 2.1$ or 2.2. The relative abundance of particles above 10^{10} ev therefore is greater by a factor of order 10^2 in the extensive showers, as compared with the soft component observed independently of extensive showers.

Furthermore, the "range" of a cascade in lead, initiated by a photon or electron, is a concept almost entirely without meaning in experiments where the cascades are detected by single counters under the lead. This is because of the large number of low-energy photons produced, some of which have a mean free path greater than 4 radiation units in lead. The low-energy photons do not contribute much to the development of the cascade, but may produce a pulse in a G-M-counter at a depth far beyond what is normally considered the range of the shower. This effect is considered in an approximate quantitative calculation by Greisen in an accompanying article. The result is that at large depths, the probability of detecting a cascade particle is a rather slowly increasing (rather than abruptly increasing) function of the primary energy. This increase is counterbalanced by the relative frequency of shower particles striking the lead, which decreases with energy. The counts recorded at large depths, it is found, are mostly due to rather low-energy incident particles, whose cascades have died out but are survived by some low-energy photons. The counting rate is much greater than one would predict by ignoring the low-energy photons and considering that each cascade had a fixed range.

According to Greisen, if one detects the extensive air showers near their maximum, the number of particles (photons and electrons) detected under 6-inches Pb (30 radiation lengths), as compared with the total number of electrons in the shower, should be about 2×10^{-3}. This is in approximate agreement with the experimental value of the part of R due to soft component, as seen in Fig. 7. Hence it is not necessary to assume the existence of a new type of particle slightly more penetrating than electrons.

Perfect agreement between the calculations and the experimental values of the part of R due to soft component should not be expected, not only because of the approximations in the calculation, but because of the experimental method of determining R, which assumes R to be a fixed quantity at all points in the shower. Actually, the density of high-energy photons and electrons, relative to the low-energy

[14] P. Auger, J. Daudin, A. Fréon, and R. Maze, Comptes Rendus **226**, 169 (1948); **226**, 569 (1948).

electrons in the air showers, changes strongly with distance from the shower core. Hence the experimental numbers of high-energy cascade particles are strongly weighted averages and should be considered only approximate in absolute value.

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Range of Cascade Showers in Lead

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A calculation has been made of the probability of a cascade particle being detected under large thicknesses of lead, taking into account the effect of the low energy photons produced in the lead. The low energy photons increase the probability of detection very greatly, and make the concept of "range" of a cascade shower in lead very indeterminate. The results have been applied to the case of large air showers, where general agreement is found between the calculated and experimental counting rates under large thicknesses.

In this paper, an attempt is made to calculate the expected counting rate in a G-M counter under a large thickness of lead, when a known spectrum of photons and electrons is incident on the lead. The solution is of importance in the interpretation of many cosmic-ray experiments, and may be useful in work with high energy synchrotron beams.

If we express the incident spectrum $f(W)$ as the number of particles per logarithmic interval of energy W, the counting rate C is given by

$$C(T)=\int_0^\infty f(W)P(W,T)d(\log W) \tag{1}$$

where $P(W, T)$ is the probability of obtaining a count under T radiation lengths of lead when a particle of energy W strikes the lead. Thus the problem is reduced to a computation of $P(W, T)$.

In this paper, we consider only large values of T, greater than about 20 radiation lengths (4 inches of Pb); and the probabilities P have been evaluated only for the case of photons striking the lead. Indeed, for energies W large compared with the critical energy of lead, the result does not depend strongly on whether the incident particle is a positron, electron or photon: while if W is less than the critical energy, the probabilities P are large only for incident photons. Also, the number of low energy photons is large compared with the number of low energy electrons, both in cosmic rays and in a beam emerging from a synchrotron.

Solutions have already been computed, according to the cascade theory, for the function $\pi(W, O, T)$, which is the average number of electrons above zero energy at a depth T in a cascade initiated by a photon of energy W. In first approximation, then, our solution for P may be written

$$P_0=1-e^{-\pi}. \tag{2}$$

This formula assumes a Poisson form for the fluctuations in the number of shower particles, which is admittedly an underestimate of the fluctuations in the case $\pi\gg 1$. But in this case P is large anyway, and the error is not serious. For $\pi<1$, the physical explanation for the long tail of the shower curve is that one of the photons may survive beyond the depth where the rest of the shower is practically exhausted, and release an electron in the neighborhood of T. This accounts for the shape of the tail, which is approximately $\pi\sim e^{-\sigma T}$, σ being the nearly constant absorption coefficient of high energy photons. In this case, which is the one of importance in the present calculations, Eq. (2) represents the fluctuations correctly.

Our problem would be completely solved by Eqs. (1) and (2) if the quantity π had been completely and correctly evaluated. This has not been done, however, for an arbitrary depth T in the shower, but only for the thickness corresponding to the maximum, or integrated over the shower length. The solutions which have been given for arbitrary T have taken the collision loss of electrons into account, but have ignored the variation of the absorption coefficient of the photons with their energy. This simplification is not serious for materials of low atomic number, in which the absorption coefficient is never much less than its asymptotic value. It is very bad, however, at large depths