(1), the area under such a graph represents the number of shower particles detected under thickness T of absorber, relative to the total number of electrons in the showers. This quantity corresponds to the quantity $R(T)$ measured at 3260 meters elevation by G. Cocconi, V. T. Cocconi, and the author (see accompanying paper). We list for comparison in Table I, (a) the experimental values of the part of $R(T)$ that is due to electrons and photons, (b) the corresponding values of R given by the areas under the solid curves in Fig. 2 (and other similar graphs), and (c) the values of R which would be deduced if the effect of the low energy photons were not considered; i.e., if the probabilities P_0 were used instead of P.

Considering the approximations made both in the present calculations and in the experimental determination of the part of R due to soft component, the agreement between (a) and (b) in Table I is very good. If the low energy photons were not considered, however, it would seem that some of the shower particles were much too penetrating to be photons and electrons. Taking into account the effect of the low energy photons removes the necessity for imagining the existence of new particles.

It is apparent from Fig. 2 that when one increases the absorber thickness beyond about 5 or 6 inches (25 or 30 radiation lengths), one does not detect incident cascade particles of higher average energy. Indeed, beyond 6 inches of lead, practically the only cascade particles detected are the low energy photons that have a slow exponential absorption (a factor 10 in two inches Pb), and may equally well originate from low energy particles as from high energy particles striking the lead.

Note added in proof: It has been pointed out to us that our neglect of post-Compton photons has led us to use too *large* an effective absorption coefficient for the low-energy gamma-rays. Thus we have *underestimated* the effect of the low-energy gamma-rays under large thicknesses of lead. From the work of Hirschfelder *et al.* [Phys. Rev. **73**, 852 and 863 (1948)], we find that an effective absorption coefficient of 0.19 per radiation length is better than the value 0.23 which we have used. Applying this change, Eq. (6) becomes

$$N_\gamma(W,T)=0.9e^{-.19T}(W/12)^{1.23},$$

from which the corrected values of P_γ and P (Eq. (7) and (8)) may be calculated.

The qualitative conclusions in the above article are not affected by this change. Applying it to the air showers, the numbers in column 3 of Table I become $10^{-3}\times 31.5$, 11.0, 4.2, 1.7 and 0.68 for the calculated values of R taking into account the low-energy photons. The agreement with the experimental values is even improved by the present correction. However, such excellent agreement must be regarded as somewhat fortuitous, because the method of calculation is such that the results are only expected to be accurate within a factor of about 2.

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Some Properties of the Cosmic-Ray Ionizing Particles That Generate Penetrating Showers

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The mean free path of the ionizing particles that produce penetrating showers has been measured in various materials at 260 and 3260 m above sea level. It has been found that in both places the mean free path is much larger in Pb than in C, and that it increases with the thickness of the absorbers. Possible interpretations are discussed.

THE experiments described below have been performed in order to study the total cross section in different materials of the ionizing particles of the cosmic radiation which produce penetrating showers. The information thus far acquired concerning such phenomena seems to indicate that the shower-producing particles are likely protons and that penetrating showers are more frequently produced in materials with low atomic number.[1]

EXPERIMENTAL APPARATUS AND RESULTS

The apparatus used is drawn in Fig. 1. The G-M counters were of all-metal type, filled with alcohol-argon mixture, 1″×16″ effective surface, and brass walls 0.5 mm thick. The large surface A, 16″×20″ in area, was realized with 20 counters connected in parallel through the crystal diode mixing circuit described in another paper in this issue.[2] Counters B, C, and D constitute three other groups of counters, each group consisting of three counters

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[1] G. Cocconi and K. Greisen, Phys. Rev. **74**, 62 (1948); H. A. Meyer, G. Schwachheim, and A. Wataghin, Phys. Rev. **74**, 846 (1948).
[2] G. Cocconi and V. Cocconi Tongiorgi, Phys. Rev. **75**, 1058 (1949).

TABLE I. Results of measurements.

1 $\Sigma+\Sigma'$ (g/cm²)	2 P showers (h⁻¹) $A+B+C+D+1E$	3 (h⁻¹) $A+B+C+D+2E$	4 (h⁻¹) $A+B+C+D+3E$	5 $\frac{A+B+C+D+2E}{A+B+C+D+1E}$	6 $\frac{A+B+C+D+3E}{A+B+C+D+1E}$
Echo Lake					
0+0=0	9.90±0.24	2.60	4.67	0.26	0.47
115+0=115 Pb	4.95±0.24	1.61	6.94	0.32	1.40
284+0=284 Pb	2.31±0.15	0.74	5.52	0.32	2.40
284+116=460 Pb	1.32±0.10	0.595	5.25	0.45	4.00
284+321=605 Pb	0.892±0.07	0.455	4.68	0.51	5.25
200+0=200 Fe	2.72±0.15	0.68	6.50	0.25	2.40
200+200=400 Fe	1.18±0.09	0.48	5.38	0.40	4.55
46+0=46 C	6.41±0.26	1.91	8.07	0.30	1.26
46+51=97 C	3.85±0.18	1.65	10.08	0.43	2.80
Ithaca					
0+0=0	1.04±0.045	0.26	0.51	0.25	0.49
30+0=30 Pb	0.92±0.09	0.84	0.602	0.91	0.66
147+0=147 Pb	0.66±0.06	0.166	0.753	0.25	1.14
250+0=250 Pb	0.47±0.045	0.145	0.71	0.31	1.51
250+176=426 Pb	0.32±0.04	0.09	0.54	0.28	1.69
46+0=46 C	0.708±0.04	0.235	0.685	0.33	0.97
46+64=110 C	0.52±0.03	0.213	0.925	0.41	1.78

in parallel. Coincidences $A+B+C+D$ were recorded with a resolving time of 1.2 μsec. (blocking oscillators and crystal diode coincidences) and were presumably due to penetrating showers. In fact, the lead P all around the counters B, C, and D was 6″ thick on all sides and above the counters, and each counter of the trays B, C, D was separated from the neighbors by 1″ of Pb.

The showers can be generated either in the lead P, or in the absorbers Σ, Σ', or in the roof of the room in which the experiments were performed (5 g cm^{-2} in all stations), or in the atmosphere. In order to select only the showers generated in the lead P, 20 counters were placed in E, and their pulses were fed into a circuit able to discriminate how many counters E were simultaneously discharged, within 10 μsec. Actually this discriminating circuit was able to select coincidences $A+B+C+D$ accompanied by the discharge of either one, or two, or more than two of the counters E. We consider the coincidences $A+B+C+D$ accompanied by the discharge of only *one* of counter E (coincidences $A+B+C+D+1E$) as due to penetrating showers generated by a single ionizing particle in the lead P (showers P).

Of course, the distance of Σ from the counters was chosen large enough so that any shower generated in Σ would have to strike more than one of the counters E in order to strike B, C, and D. Chance coincidences were always negligible. The rate of the P showers had been measured, varying the amount and the nature of the absorbers Σ and Σ' both at Ithaca (260 m above sea level, mean pressure 1007 g cm^{-2}) and at Echo Lake (3260 m, 708 g cm^{-2}). The results are reported in Table I. Column 2 refers to P showers (coinc. $A+B+C+D+1E$), column 3 to showers which discharged two of the counters E (coinc. $A+B+C+D+2E$), and column 4 to showers which discharged three or more counters E (coinc. $A+B+C+D+3E$). The frequencies of P showers *versus* the thickness of absorbers $\Sigma+\Sigma'$ are plotted on a logarithmic scale in Figs. 2 and 3. From Fig. 2 one observes:

(a) At 3260 m, the initial slopes of the absorption curves correspond to the following mean free path of the shower-producing particles for absorption and production of penetrating showers:

$$\begin{array}{ll} \text{In Pb} & \lambda_{\mathrm{Pb}}=160\pm15 \text{ g cm}^{-2}, \\ \text{in Fe} & \lambda_{\mathrm{Fe}}=135\pm15 \text{ g cm}^{-2}, \\ \text{in C} & \lambda_{\mathrm{C}}=100\pm5 \text{ g cm}^{-2}, \end{array} \tag{1}$$

$$\lambda_{\mathrm{Pb}}/\lambda_{\mathrm{C}}=1.60\pm0.17.$$

(b) The absorption curves for Pb and Fe, which are continued up to large thicknesses, are not purely exponential; the mean free paths increase with the thickness, so that under about 500 g cm^{-2} of absorber they become:

$$\begin{array}{ll} \text{In Pb} & \lambda_{\mathrm{Pb}}=380\pm60 \text{ g cm}^{-2}, \\ \text{in Fe} & \lambda_{\mathrm{Fe}}=310\pm60 \text{ g cm}^{-2}. \end{array} \tag{2}$$

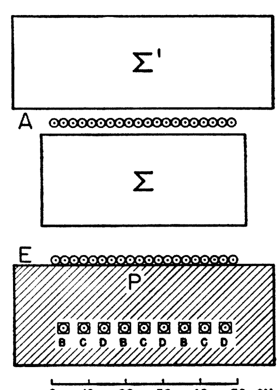

FIG. 1. Arrangement of counters and absorbers.

From Fig. 3 one finds:

(c) At 260 m above sea level the mean free path of the shower-producing particles are:

$$\begin{aligned} &\text{In Pb} \quad \lambda_{\mathrm{Pb}} = 310 \pm 30 \text{ g cm}^{-2}, \\ &\text{in C} \quad \lambda_{\mathrm{C}} = 140 \pm 20 \text{ g cm}^{-2}, \end{aligned} \tag{3}$$

$$\lambda_{\mathrm{Pb}}/\lambda_{\mathrm{C}} = 2.20 \pm 0.45.$$

(d) From the ratio of the intensity of the P showers observed at Echo Lake and at Ithaca with lead absorber, one deduces, assuming in air an exponential decrease:

$$\begin{aligned} &\text{With} \quad 0 \text{ g cm}^{-2} \quad \lambda_a = 133 \pm 7 \text{ g cm}^{-2}, \\ &\text{with} \quad 200 \text{ g cm}^{-2} \quad \lambda_a = 169 \pm 10 \text{ g cm}^{-2}, \\ &\text{with} \quad 400 \text{ g cm}^{-2} \quad \lambda_a = 191 \pm 15 \text{ g cm}^{-2}. \end{aligned} \tag{4}$$

Before discussing the meaning of these results, we wish to point out that no other phenomena, except penetrating showers, seem to be recorded by our apparatus. It might be supposed that an appreciable percentage of knock-on electrons, by the meson component, notwithstanding the complete screenings of the counters with lead, may discharge the counters A, B, C, D, and that their number, decreasing with the thickness of the absorber less than the number of the penetrating showers, may vary the slope of the absorption curve and increase, at the greater thickness, the apparent free path of the radiation which produces penetrating showers. If this happened, one would have to expect, increasing Σ, a decrease of the ratio $(A+B+C+D+2E/A+B+C+D+1E)$ as well as of the ratio $(A+B+C+D+3E/A+B+C+D+1E)$, because no electron shower able to discharge A, B, and C can be produced in the absorber Σ. From columns 5 and 6 of the table, one observes, instead, the opposite behavior, which indicates, on the other hand, that the number of showers created in Σ increases with its thickness. Furthermore, if such an effect existed, the difference between λ_{Pb} and λ_{C} would decrease at sea level, and here too we observed the opposite.

Another strong argument in favor of the reliability of our results is the following. Consider the absorption curves in Pb; the frequency of the P showers at Echo Lake with $\sim$550 g cm^{-2} (see Fig. 2) is 1.04 h^{-1}; the same frequency we observed at Ithaca with $\Sigma+\Sigma'=0$. If we continue the curve of Fig. 2 with the curve of Fig. 3, beginning the second at 550 g cm^{-2}, we obtain the smooth curve of Fig. 4, which demonstrates that the variation in slope observed at Echo Lake is real, since the same behavior is found after 300 g cm^{-2} of air.

Finally, we observe that the mean free path (4) deduced for the air with $\Sigma+\Sigma'=0$ is well in agreement with the mean free path measured by other authors.[3] The question naturally arises as to why the frequency of the penetrating showers decreases exponentially with the thickness of the atmosphere, over thicknesses of air corresponding to many mean free paths, while in lead it does not decrease exponentially. We may only observe that in the case of the measurements taken in the atmosphere the λ deduced does not represent a mean free path for absorption of the shower producing radiation, because it may happen, as it is shown by many cloud-chamber pictures, that some of the particles in the penetrating showers generated in the air have energy big enough for generating another penetrating shower, and hence are not eliminated; this cannot happen in our measurement because, if the incoming particle generates a penetrating shower in Σ or Σ', very likely more than a single particle reaches counters E, and the eventual secondary shower is not recorded. A second alternative is the possibility of radioactive decay in the atmosphere, which is unlikely to occur in our apparatus because of the short path.

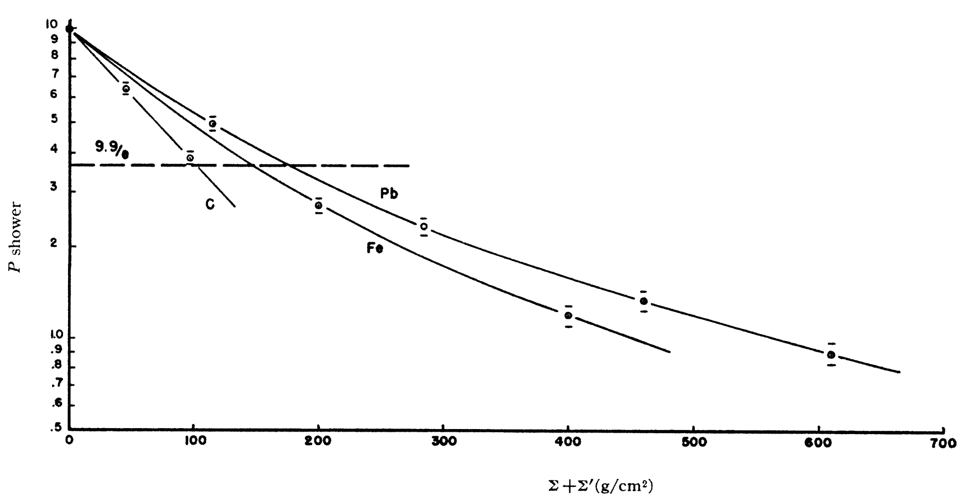

FIG. 2. P showers *versus* thickness $\Sigma+\Sigma'$ at Echo Lake.

[3] G. Wataghin, Phys. Rev. **71**, 453 (1947); J. Tinlot, Phys. Rev. **73**, 1476 (1948).

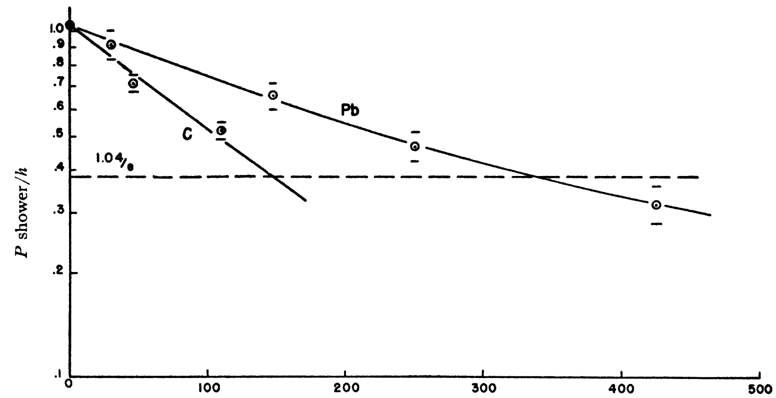

FIG. 3. P showers *versus* thickness $\Sigma+\Sigma'$ at Ithaca.

$\Sigma+\Sigma'$(g/cm²)

DISCUSSION

We may begin by discussing the mean free paths (1) deduced from the initial slopes of the curves at Echo Lake. The obvious explanation for the decrease of λ with atomic number is that the primaries generating penetrating showers interact with the nucleons with a cross section of the order of magnitude of the geometrical cross section of the nucleons. In this case, in heavy nuclei the number of inside nucleons screened by the nucleons on the surface is larger than in light nuclei (packing effect), and the heavy nuclei have a smaller stopping power, per nucleon, then the light ones. If the nuclei were completely opaque, the mean free path λ_0 of the penetrating shower producing radiation in a substance of atomic number A would be:

$$\lambda_0=(A/\pi R^2 N)\text{ g cm}^{-2}, \qquad (5)$$

where N is Avogadro's number and R is the radius of the nucleus. Assuming $R=rA^{\frac{1}{3}}$, one finds immediately the well-known $A^{\frac{1}{3}}$ law.

If instead the nucleus is not completely opaque, the mean free path becomes:

$$\lambda_A=\lambda_0/(1-P_A), \qquad (6)$$

where P_A is the probability for the penetrating shower-producing radiation to cross the nucleus without being absorbed. If α is the mean free path *in nuclear matter* of the shower-producing radiation,

$$P_A=\int_0^R(2\pi x/\pi R^2)\exp[-(2(R^2-x^2)^{\frac{1}{2}}/\alpha)]dx$$
$$=(\alpha^2/2R^2)[1-(1+(2R/\alpha)/\exp(2R/\alpha))]. \qquad (7)$$

With

$$R=rA^{\frac{1}{3}}=1.5\times10^{-13}\times A^{\frac{1}{3}}\text{ cm}, \qquad (8)$$

one deduces the curves of Fig. 5. The values (1) for λ, fit quite well the calculated ones, if one assumes $\alpha=\sim 4r$.

Following this scheme, the increase of λ_{Pb} with the thickness of $\Sigma+\Sigma'$ may be interpreted as due to a decrease of the cross section of the penetrating shower-producing radiation due to a hardening of the filtered radiation (perhaps as a result of a change in the average energy). But as a consequence

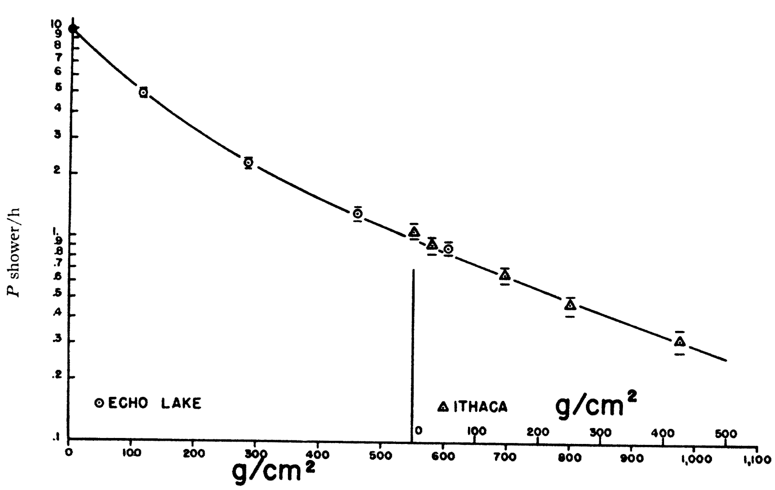

FIG. 4. Absorption curve in P showers at Echo Lake, continued with the absorption curve at Ithaca.

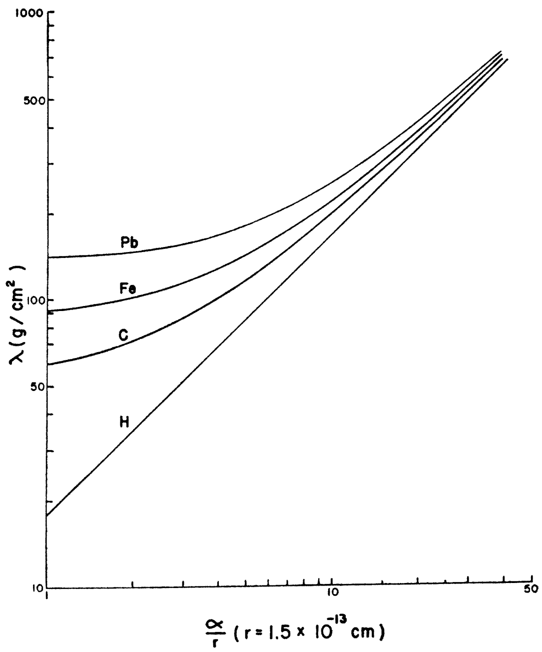

FIG. 5. Theoretical mean free path λ in Pb, Fe, C, and H of the P shower-producing radiation, *versus* mean free path α in nuclear matter.

of such an hypothesis, as shown by Fig. 5, one has to expect a decrease of the ratio λ_{Pb}/λ_C; in fact, if the Pb nuclei become more transparent, the difference in behavior between Pb and C must decrease. From the results (3) at Ithaca, instead, λ_{Pb}/λ_C seems to increase.

If the discrepancy is real, as we believe, then the problem is more complex, but we think that our knowledge of the mechanism of such phenomena is too poor for us to suggest any explanation. We wish, instead, to emphasize the following experimental results: (a) The mean free paths of the ionizing radiation which produces penetrating showers show a strong dependence on the atomic number of the absorber both at Ithaca and at Echo Lake. Perhaps this dependence is stronger at Ithaca than at Echo Lake. (b) The mean free path of this radiation increases with the thickness of the absorber, and this has been proved both for condensed material (Pb) and for air.

We want, finally, to point out that a decrease of λ with the atomic number of the absorber has also been observed for a quite different kind of phenomenon—the stars observed in photographic plates[4]—and interpreted as an indication of packing effect for the particles which produce stars. Besides that, it has been shown[5] that neutrons of few Mev, and very likely stars, are associated with penetrating showers. As pointed out in reference 5, it is possible that the two phenomena are more closely related than it was thought before, and that the variation of λ observed for stars must really be ascribed to the variation of λ for the radiation which produces penetrating showers.

The author wishes to thank Professors K. Greisen and H. Bethe for many helpful suggestions and discussions. He is very grateful to the Research Corporation for a grant which covered the expenses of performing the experiment at Echo Lake. The cost of constructing the apparatus was provided through a Navy contract. The facilities of the Inter-University High Altitude Laboratories, and the help of Professors Cohn and Iona of Denver University were an invaluable aid in performing the experiment.

[4] E. P. George, Nature **162**, 333 (1948); G. Bernardini, C. Cortini, and A. Manfredini, Phys. Rev. **74**, 845 (1948).
[5] G. Cocconi, V. Cocconi Tongiorgi, and K. Greisen, Phys. Rev. **74**, 1876 (1948).