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On the Absorption of Penetrating Showers

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Several experiments on the absorption in lead of the particles of penetrating showers have been performed under different geometrical conditions. The penetrating showers produced in air are shown to have a high penetrating power, whereas those produced locally are strongly absorbed. An interpretation is given by the study of the selection of the penetrating showers by our apparatus. The cross section for nuclear absorption of the π-mesons of the locally produced penetrating showers was measured and shown to be smaller than half the geometrical one. Some data on the structure of the penetrating showers and on the presence of photons were obtained.

I. INTRODUCTION

A SERIES of experiments has been performed to study the absorption of the ionizing particles of penetrating showers (PS). We studied the absorption in lead of the particles of the PS produced in the air as well as those produced in a material located above the arrangement. We call the former atmospheric PS and the latter local PS. The frequency of atmospheric PS is given by the recorded frequency without the producing material (background), since accidental coincidences and coincidences due to mesons and their knock-on secondaries are negligible.[1] Moreover, the lead shields are thick enough to absorb soft showers (a point that is checked in each experiment), and the position of these shields is such that the registration of a PS produced in them would be very improbable. As we observed that the absorption of the atmospheric PS is very small, in general, their absorption in the producing material will be small, and the frequency of local PS will be given by the difference between the frequencies with and without the producing material.

Experiment I was performed in Campos do Jordão (844 g/cm^2) during the last months of 1949. The others were performed in São Paulo (950 g/cm^2) in 1950. The G-M counters used in our experiments, with sensitive area of 2.9 cm$\times$45 cm$=$130 cm^2, had glass walls with an external cathode of conducting paper. All statistical errors given below are standard deviations.

II. EXPERIMENT I

Experiment I is a refinement of an experiment described earlier.[2] We recorded coincidences between four trays of counters (Fig. 1). Each tray consisted of three counters in parallel. Figure 1 shows that at least two particles with sufficient energy to penetrate 19 cm of lead were needed in order to record a coincidence. The PS were absorbed in layers of lead, 5 and 10 cm thick, placed in position A between the trays of each telescope. In order to be recorded, a PS produced in these layers must contain at least one energetic particle going upwards. We believe, therefore, that the recorded frequency of PS produced in these layers is negligible. The local PS are produced in 29 g/cm^2 of carbon located above the arrangement, as shown in Fig. 1. Our results are collected in Table I. We see that the atmospheric PS are not appreciably absorbed by the additional layers of lead, while the locally produced showers are strongly absorbed in 5 cm of lead. These results are in agreement with those of the earlier experiment.[2] In the

TABLE I. Experiment I: Hourly rate of fourfold coincidences.

Lead thickness in position A	Background (atmospheric PS)	With carbon	Production in carbon
0 cm	1.79±0.16	2.21±0.15	+0.42±0.22
5 cm	1.70±0.13	1.53±0.13	−0.17±0.18
10 cm	1.39±0.10	1.50±0.10	+0.11±0.14

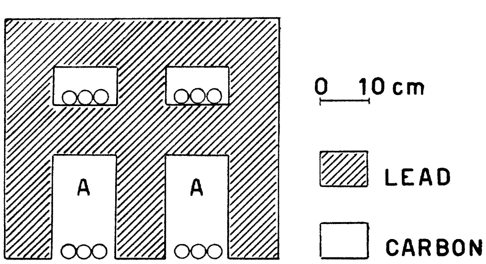

FIG. 1. Arrangement used in Experiment I. The PS were absorbed placing different thicknesses of lead in the cavities A.

[1] Cicchini, Meyer, Schwachheim, and Wataghin, Comm. Ass. Fis. Arg. 23 (May 1949).

[2] Meyer, Schwachheim, Wataghin, and Wataghin, Phys. Rev. 75, 908 (1949).

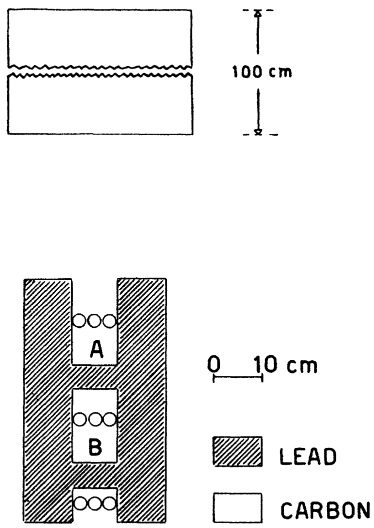

FIG. 2. Arrangement used in Experiment II. The small angle PS were absorbed by lead placed in positions A and B.

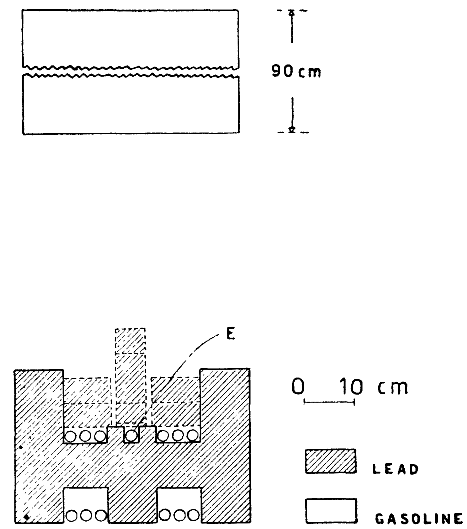

FIG. 3. Arrangement used in Experiment III. The two telescopes selected the PS, and a counter E located between them detected associated particles. The dotted rectangles represent the various lead absorbers.

present experiment we use carbon as the producing material because the atomic weight of carbon is close to the mean atomic weight of the air. The similarity of the results of this experiment and of the earlier one, in which we used gasoline instead of carbon, justifies the indiscriminate use of both materials in our experiments.

III. EXPERIMENT II

The purpose of this experiment is to repeat Experiment I under different geometrical conditions; we wanted to study the absorption of local PS with an appreciably smaller angular aperture.

The PS were selected by three trays of three counters each (Fig. 2). The two outer counters in each tray were connected in parallel. We recorded sixfold coincidences. For a coincidence to be recorded there had to be at least two particles able to penetrate 10 cm of lead. The local PS were produced in carbon. In the cavities A and B, we placed different thicknesses of lead absorbers. Our results are collected in Table II.

The high background counting rate without absorber is due to the fact that electron showers are still recorded. From 2.5 cm to 10 cm of lead the background rate shows only a slight variation. This arises from a small absorption of the atmospheric PS. The locally produced PS are strongly absorbed, however, as in Experiment I.

TABLE II. Experiment II: Hourly rate of sixfold coincidences.

Thickness of lead absorbers (cm)	Background (atmospheric PS)	With carbon	Production in carbon (local PS)
0	1.106±0.069	1.455±0.082	~0.7
2, 5	0.656±0.056	1.000±0.077	0.344±0.095
5	0.562±0.037	0.728±0.037	0.166±0.052
10	0.443±0.043	—	—

IV. EXPERIMENT III

In Experiment III the PS are selected by two vertical telescopes, and variable thicknesses of lead are placed above a counter, E, located between the telescopes (Fig. 3). We measure, in this way, the penetrating power of one particle of the shower. Each tray of the telescopes consisted of three counters in parallel. Between the trays of each telescope was a permanent layer of 10 cm of lead. We recorded both the coincidences among the four trays of the telescopes and the fivefold coincidences among these four trays and counter E.

In a preliminary measurement, without absorber above counter E, we placed 5 cm of lead absorber above the upper trays of the telescopes and the fourfold coincidence rate of the background decreased appreciably, as shown in Table III. This suggests that, with only the permanent lead absorber, some electron showers were still recorded. When we further increased the absorber above the telescopes by 5 cm of lead, the

TABLE III. First part of Experiment III: Hourly rates of coincidences.

Lead thickness		0 cm	5 cm	10 cm
Background (atmospheric PS)	fourfold rate	1.493±0.083	0.853±0.031	0.978±0.070
	fivefold rate	0.930±0.066	0.518±0.024	0.643±0.057
With gasoline	fourfold rate	2.009±0.106	1.175±0.056	1.084±0.090
	fivefold rate	1.181±0.082	0.672±0.042	0.693±0.071
Production in gasoline (local PS)	fourfold rate	~0.8	0.322±0.064	0.106±0.114
	fivefold rate	~0.6	0.154±0.049	0.050±0.091

TABLE IV. Second part of Experiment III: Hourly rates of coincidences.

Lead thickness above counter E (cm)	Background fourfold coincidences	Background fivefold coincidences	With gasoline fourfold coincidences	With gasoline fivefold coincidences
0	0.834±0.051	0.518±0.026[a]	1.301±0.074	0.730±0.034[a]
5	0.805±0.058	0.548±0.029[a]	1.195±0.069	0.751±0.034[a]
15	0.906±0.074	0.496±0.034[a]	1.234±0.073	0.669±0.036[a]
20	0.911±0.080	0.499±0.029[a]	1.186±0.064	0.679±0.030[a]
Average rate[b]	0.853±0.031	0.518±0.024	1.226±0.035	—
1	0.876±0.081	0.539±0.038[a]	1.198±0.080	0.706±0.040[a]

[a] These statistical errors can be used only when comparing measurements in the same column.
[b] The measurements with 1 cm were not included when computing the average.

background rate did not change appreciably. This shows that no more electron showers are recorded with 15 cm of lead and confirms that the absorption of the atmospheric PS is weak. Repeating the same measurements with a producing material (38 g/cm^2 of gasoline) we observed that the locally produced PS recorded by the two telescopes are strongly absorbed (Table III). This is in agreement with the results of Experiments I and II.

Afterwards, with a permanent absorber of 15 cm of lead in the telescopes and with 67 g/cm^2 of gasoline as producing material, we placed various thicknesses of lead above counter E. The fivefold coincidence rates with different thicknesses of lead are shown in Table IV.

Let us notice that the absorber covers only counter E, so that its presence cannot change the rate of fourfold coincidences due to either background or local production of PS. This is confirmed by Table IV. Also, by Table IV, we see that there is no absorption of the fivefold coincidences without the producing material, in agreement with Experiments I and II. Taking into account that the fivefold coincidences are not statistically independent of the fourfold coincidences, we normalized all our data for fivefold coincidences to the common fourfold coincidence rate and accordingly reduced the statistical errors of the fivefold rates. It is observed from Table IV that the absorption of the locally produced particles is very small.

We investigated whether or not counter E was struck by photons resulting from the decay of neutral mesons of the PS, which constitute about half of the number of charged mesons.[3] As the thickness of the wall of counter E measured in radiation lengths is much smaller than unity, this counter has a very low efficiency for the registration of photons. When covered with 1 cm of lead its efficiency will approach unity, in our range of energies. We thus expect the difference between the fivefold coincidence rates with and without 1 cm of lead to yield the frequency of these photons. Table IV shows that this frequency is low. We believe that this happens because the angular dispersion of the two photons into which the neutral mesons decay is so large that few of them strike counter E. This sets an upper limit of about 1 Bev to the mean energy of the mesons which go in the direction of counter E, if we assume the number of photons to be about equal to the number of charged mesons.[3]

V. DISCUSSION

In our experiments the absorption of atmospheric PS is weak. The atmospheric PS must be produced in a mass of air at least of the order of the mass of the producing material used in our experiments because the counting rates are of the same order. By geometrical considerations we see that the center of this mass of air must be tens of meters above our arrangement. The largest part of the recorded atmospheric PS should consist of groups of particles having a very small angular dispersion and in consequence large energy, and should consist mainly of μ-mesons resulting from the decay of π-mesons. For these reasons these particles should neither disappear appreciably by ionization nor suffer nuclear interactions. It is interesting to notice that the predominant factor in the selection of the atmospheric PS is the small angular divergence rather than the thickness of lead used in our experiments so that the recorded particles of the atmospheric PS selected by our arrangement have an energy much larger than the minimum energy necessary to cross the lead shielding.

The results of Experiments I and II, and the absorption of the fourfold coincidences in Experiment III indicate that, in the conditions of these experiments, the absorption of the locally produced PS is strong, even if we take into account the fact that in order to record the absorption of a PS it is sufficient that only one particle be absorbed. However, the absorption of the particles which strike counter E in the locally produced PS (Experiment III) is weak. Because of this fact and because the cross section for nuclear absorption would need to be larger than the geometrical cross section, we do not believe that the contribution of nuclear interactions to the observed absorption of the fourfold coincidences due to the local PS is important. Thus, the principal contribution to the absorption of the PS comes from particles stopped in the lead absorber after having lost their energy by ionization. Our experimental results indicate that the main part of the particles of the local PS recorded by the two telescopes have an energy just above the minimum energy required to cross the lead absorber. We believe that the local PS are not selected by the requirement of a particularly small angular divergence but by the thickness of the lead absorber, which means that the minimum energy of the recorded particles of the local PS should be just the energy necessary to penetrate this absorber. Because the spectral distribution of these particles is believed to fall off rapidly with increasing energy, the local PS would be easily absorbed.

It is very important to know the criterion by which

[3] Carlson, Hooper, and King, Phil. Mag. 41, 701 (1950).

the PS are selected with a given arrangement. Indeed, the PS are really "penetrating"; i.e., their frequency does not depend, within large limits, on the thickness of the lead absorber, except if they are selected by a special requirement, such as their small angular divergence. This is why showers resulting from high energy nuclear explosions (high energy stars) discovered in the atmospheric PS may be called "penetrating." The registered local PS, though of the same nature as the recorded atmospheric PS, are not really "penetrating" in the sense given above, for reasons we have already discussed; but they are penetrating, of course, in the sense that some of their particles are able to cross large thicknesses of lead.

The small absorption of the locally produced PS in the absorber placed above counter E shows that the largest part of the particles of the PS which strike this counter have an energy larger than that necessary to penetrate any of the absorbers. This fact indicates that the particles in the center of the local PS (which have the direction of the primary particle) have in the mean a larger energy than the lateral particles. This is easily understood by the laws of conservation of momentum. If ionization does not contribute to the observed absorption, the absorption length observed by us will be caused by nuclear absorption and will be of the order of or greater than 400 g/cm^2 of lead. There is a correction arising from the fact that counter E is sometimes struck simultaneously by more than one particle. Taking into account this correction and the statistical errors of the measurements, we are still able to state that the nuclear absorption length in lead cannot be shorter than 350 g/cm^2. However, because of the possible contribution of ionization, and because of the statistical errors, we cannot give an upper limit to the nuclear absorption length.

Notice that since counter E was not struck by photons, we are measuring the absorption length for charged particles. In the rather high energy region involved it is plausible to assume that, in the center of the locally produced PS, π-mesons constitute the main part of the total number of ionizing particles, while the protons which constitute the remainder could not change our results appreciably, because their absorption length in lead is of the order of 300 g/cm^2. As the distance from the producer to counter E is too small to allow the decay of the π-mesons initially produced, we can conclude that the cross section for nuclear absorption of π-mesons in lead, in our range of energies, is less than half the geometrical cross section. This conclusion is in agreement with the results of other workers.[4–9]

However, our results do not allow us to make a definite statement on the value of the nuclear interaction length in lead of the π-mesons. Our arrangement is not sensitive to small-angle scattering with a small energy transfer to the lead nucleus. But it is believed that nuclear interactions should produce, on the average, rather large angle scattering, and these were shown by Brown and McKay[4] to be 4 or 5 times less frequent than catastrophic interactions. Besides, our arrangement has a reasonable efficiency for detecting large angle scattering. Another fact which could mask a possible nuclear interaction is the production by the π-meson of penetrating secondaries in lead. It is rather difficult to meet this argument but we may remember that the energy of the particles striking counter E cannot exceed about 1 Bev. In order to reconcile our results with a geometrical cross section for nuclear interaction (this corresponds to a mean range in lead of about 150 g/cm^2), as found by the Bristol group,[10] more than half of all interactions should result in the production of a PS able to strike counter E with high efficiency. We do not know whether this can happen in our range of rather low energies.

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[4] W. W. Brown and A. S. McKay, Phys. Rev. **77**, 342 (1950).
[5] Butler, Rosser, and Barker, Proc. Phys. Soc. (London) **63**, 145 (1950).
[6] J. B. Harding and D. H. Perkins, Nature **164**, 285 (1949).
[7] W. B. Fretter, Phys. Rev. **76**, 511 (1949).
[8] Lovati, Mura, Salvini, and Tagliaferri, Phys. Rev. **77**, 284 (1950).
[9] O. Piccioni, Phys. Rev. **77**, 6 (1950).
[10] Camerini, Fowler, Lock, and Muirhead, Phil. Mag. **41**, 413 (1950).

Announcement: Publication Charge for Letters to the Editor

At the meeting of the Publication Board of the American Institute of Physics on January 30, 1951, a proposed publication charge for Letters to the Editor (and similar sections) was approved. The charge will be effective with the July issues and will be at a flat rate of $10.00 for each Letter. As in the case of regular articles, the charge will be made against the institution rather than the individual author and will be on a voluntary basis. When honored, 100 reprints will be provided without further cost.

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Review of Scientific Instruments (Laboratory and Shop Notes)
Journal of Chemical Physics
Journal of Applied Physics