On Penetrating Showers in Cosmic Radiation

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The mean range of the radiation that generates penetrating showers has been determined in the atmosphere and in water. The results are respectively ~120 g/cm² and ~55 g/cm². The relation between the observed variation of the frequency of penetrating showers with barometric pressure and the absorption law in air for the shower producing radiation has been discussed in some detail. The east-west asymmetry of the radiation that generates penetrating showers has been studied and the results were found to be negative within the experimental errors. The penetrating power of the penetrating showers produced in air has been investigated. No appreciable absorption has been found when the lead protection of the counters has been increased from 18 to 28 cm.

INTRODUCTION

THE present work was done in order to study some of the problems related to penetrating showers in cosmic radiation. The experiments were performed at an altitude of 1750 m in Campos do Jordão from August to December 1948. We investigated the following problems: I. The altitude dependence of the frequency of meson showers. II. The absorption coefficient in water of the radiation that generates penetrating showers. III. The east-west asymmetry of the radiation responsible for penetrating showers. In addition, a complementary experiment to our work on the nature of the mesons in penetrating showers[1] has been performed.

In the following text we shall use the abbreviations *PS* for penetrating shower (meson shower) and *PSPR* for the penetrating shower-producing radiation.

I. DETERMINATION OF THE MEAN RANGE OF THE PSPR IN THE ATMOSPHERE

The study of the variation of the frequency of *PS* with altitude was initiated by Sala and Wataghin[2,3] and later continued by Wataghin.[4] They estimated the mean range of the *PSPR* to be ~100 g/cm², assuming an exponential decrease of the frequency of *PS* with atmospheric pressure. Tinlot,[5,6] working at a geomagnetic latitude of 53°N, confirmed that the dependence of the registered frequency on the barometric pressure is nearly an exponential one and found a mean range of 118±2 g/cm². The barometer effect of *PS* investigated by Janossy and Rochester[7] yields a mean range for the *PSPR* of 116±27 g/cm². The results of Janossy and Rochester can be related immediately to the measurements of the frequency of *PS* at different altitudes. Indeed, both types of experiments consist in measuring the frequency of *PS* at different barometric pressures. The variation of this pressure is obtained either by the meteorological fluctuations at a fixed altitude, or by working with the same apparatus at different altitudes.

The objective of the following discussions is to establish a relation between the registered variation of the frequency of *PS* with barometric pressure and the absorption law for a parallel beam of *PSPR*. In the first place, we ought to consider the generalized Gross-transformation.[8,9] We suppose that the conditions for the validity of the Gross-transformation are satisfied by the *PSPR*, i.e., we assume that there exists isotropy of the incident primary radiation at the top of the atmosphere, and that the *PSPR* does not suffer an appreciable deviation from its initial direction. In order to apply the generalized Gross-transformation we ought to know the efficiency of the *PS*-detector for each direction of incidence of the *PSPR*, but actually we can only say that the detectors used in the above experiments have a maximum of efficiency for the detection of vertical *PSPR*, so that the relative contribution of the inclined *PSPR* to the counting rate is less than for an isotropic detector (which registers the so-called integrated intensity).[10] As the intensity of the inclined radiation decreases with barometric pressure faster than the ver-

TABLE I. Results of Experiment A.

Water thickness above the *PS* detector	Hourly rate of fourfold coincidences
0 cm	3.00±0.17
10 cm	3.59±0.20
22.5 cm	4.10±0.21
32.5 cm	4.87±0.24
42.5 cm	5.48±0.24
50 cm	5.16±0.37
58 cm	5.84±0.22
85 cm	5.11±0.16
114 cm	5.66±0.37
125 cm	5.37±0.17

[1] Meyer, Schwachheim, Wataghin, and Wataghin, Phys. Rev. **75**, 908 (1949).
[2] O. Sala and G. Wataghin, Phys. Rev. **67**, 55 (1945).
[3] O. Sala and G. Wataghin, Phys. Rev. **70**, 430 (1946).
[4] G. Wataghin, Phys. Rev. **71**, 453 (1947).
[5] J. Tinlot, Phys. Rev. **73**, 1476 (1948).
[6] J. Tinlot, Phys. Rev. **74**, 1197 (1948).
[7] L. Janossy and G. D. Rochester, Proc. Roy. Soc. **A183**, 186 (1944).
[8] B. Gross, Zeits. f. Physik **83**, 214 (1933).
[9] L. Janossy, Zeits. f. Physik **101**, 129 (1936).
[10] For definitions and notation see B. Rossi, Rev. Mod. Phys. **20**, 537 (1948).

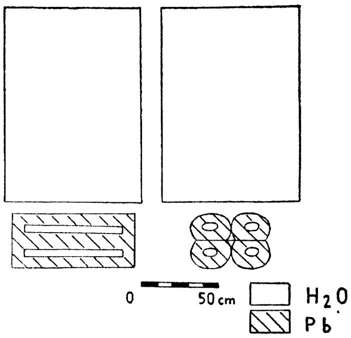

FIG. 1. Experimental arrangement used in the measurements on the transition effect in water (Experiment A).

tical radiation, the actual counting rate decreases with barometric pressure faster than the vertical intensity, but slower than the integrated intensity of the *PSPR*.

In the second place, the interpretation of the observed variation of the frequency of *PS* with barometric pressure requires the knowledge of the origin of the *PS*: We must distinguish the *PS* produced in the lead shielding of the counters from those originated in the air surrounding the detector. In the first case, the frequency of *PS* is proportional only to the intensity of the *PSPR* at the point of observation, whereas the frequency of *PS* produced in the surrounding air is also proportional to the density of the latter, because the frequency of produced *PS* is proportional to the concentration of nuclei with which the *PSPR* collides. The consideration of the density of air for the *PS* produced in it requires supplementary experiments in order to determine the contribution of atmospheric *PS* to the total number of registered *PS*.

We shall show now that the variation of the intensity of a parallel beam of *PSPR* can be represented approximately by an exponential law. We shall use the result that the variation of the registered frequency $f(x)$ of *PS* with barometric pressure x is nearly exponential, as verified by one of us[4] and confirmed by Tinlot.[6] Let us consider, for instance, the limiting case of an isotropic detector. Then we can write

$$f(x)=(k_1+k_2x)J_2(x), \quad (1)$$

where $J_2(x)$ is the integrated intensity, k_1 and k_2 are constants which give the contributions of the *PS* produced in lead and in air, respectively. Since we can write

$$f(x)\cong C\exp(-x/l), \quad (2)$$

C and l being constants, we can deduce from the well-known Gross-transformation the following absorption law $I_v(x)$ for a vertical beam of *PSPR*

$$I_v(x)\cong C(k_1+k_2x)^{-2}[k_1(1+x/l)+k_2x(2+x/l)]\exp(-x/l). \quad (3)$$

In the other limiting case of a detector registering only vertical *PSPR*, one finds

$$I_v(x)\cong C(k_1+k_2x)^{-1}\exp(-x/l). \quad (4)$$

With both types of detectors, $I_v(x)$ can fairly well be represented by an exponential, in the involved range for x, and thus we can reasonably assume that the true absorption law for the *PSPR* is approximately an exponential. Because of the uncertainties due to our lack of knowledge of the true characteristics of the detector used, we can only conclude from Tinlot's experiments that the mean range for a parallel beam of *PSPR* in air lies between the limits 95 and 145 g/cm^2.

In order to avoid at least the uncertainty due to the production of *PS* in air, we studied the variation with altitude of the frequency of *PS* produced locally in a given amount of water. Our detector (Fig. 1) is the same used previously in São Paulo.[11] We observed the following increase of the rate of fourfold coincidences due to 57 cm of water from São Paulo (barometric pressure 950 g/cm^2) to Campos do Jordão (barometric pressure 844 g/cm^2, latitude 23°S): 2.78 ± 0.51. Thus, applying the above considerations, we obtain a mean range of 113 ± 20 g/cm^2 if we suppose our detector to be isotropic, and a mean range of 103 ± 18 g/cm^2 if we admit that our detector registers only vertical *PSPR*.

In the above discussions we have neglected the influence, on the efficiency of the *PS* detector, of the variation with altitude of the *PSPR* energy spectrum.

A possible interpretation of the approximate validity of the exponential absorption law for the *PSPR* in air was recently discussed by one of us.[12] The mechanism of production of *PS* is probably one of cascades of showers of mesons and nucleons. One ought also to take into account that the spectral distribution of energetic nucleons may vary with altitude and that the cross section for production of *PS* is certainly dependent on the energy of the nucleons. All these facts make us think that the exponential absorption law for the *PSPR* has only an approximate validity and is due to a superposition of effects of absorption and production of mesons and nucleons, which are difficult to analyze.

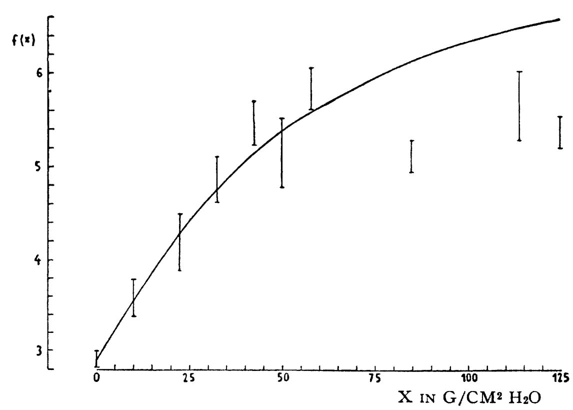

FIG. 2. Frequency of fourfold coincidences against water thickness x in Experiment A. The full curve represents formula (5) with $l=54$ g/cm^2.

[11] Meyer, Schwachheim, and Wataghin, Phys. Rev. **74**, 846 (1948).
[12] G. Wataghin, Phys. Rev. **74**, 975 (1948).

II. DETERMINATION OF THE MEAN RANGE OF THE PSPR IN WATER

The absorption of *PSPR* in various materials can be studied on the basis of the so-called transition effect. After some measurements of this effect in São Paulo,[11] we performed, in Campos do Jordão, more complete measurements on the transition effect in water. We used a *PS* detector consisting of two telescopes of Geiger-Müller counters completely shielded by lead (Fig. 1), so that a particle, in order to be registered by a telescope, should produce a coincidence through at least 18 cm of lead. The counter trays had an area of 600 cm^2 each and were connected in fourfold coincidence. The few accidental coincidences were taken into account in our results. The water was contained in a vessel of light material having a wall thickness of ~ 2 g/cm^2. In Experiment A, the water tank was placed right above the *PS* detector, as shown in Fig. 1. We increased the thickness of water to 125 cm. Our results are shown in Table I and in Fig. 2.

Experiment B was essentially the same as experiment A with the only difference that the water-containing tank was placed 90 cm higher. The results are given in Table II.

The curves obtained in Experiments A and B are the results of several factors. The first one is the exponential absorption of the *PSPR* in water. If this were the only factor, we should expect a curve given by the formula,

$$f(x)=f(0)+f_1[1-\exp(-x/l)], \qquad (5)$$

where $f(x)$ denotes the hourly rate of fourfold coincidences as a function of the water thickness x; l is the mean range of *PSPR* in water; $f(0)$ and f_1 are constants. As is well known, formula (5) describes the transition effect of a parallel beam incident normally on a plate of thickness x.

A second factor is the variation of the probability of registration of the *PS* with the position of their center of production. Experiment *B* shows the importance of this factor. Indeed, as we can see from Tables I and II, for a given amount of water, the registered rate of production in Experiment B is only half the rate in Experiment A. This geometrical factor introduces a deviation from the saturation law (5). A third factor determining the experimental curve of the measurements is the absorption of the produced *PS* in water.

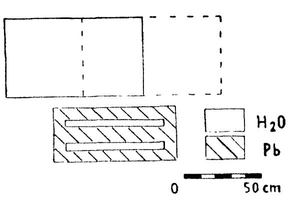

FIG. 3. Experimental arrangement for the investigation of the east–west asymmetry of the *PSPR*. The two symmetrical positions of the water containing vessel in Experiment A are represented by the the full and by the dotted rectangles.

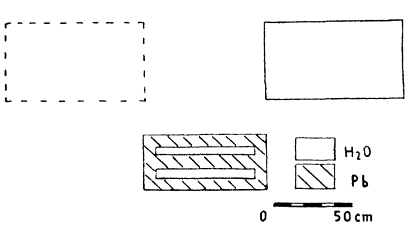

FIG. 4. Positions of the vessel in Experiment B.

TABLE II. Results of Experiment B.

Water thickness above the *PS* detector	Hourly rate of fourfold coincidences
0 cm	3.32±0.24
10 cm	3.98±0.29
30 cm	4.23±0.32
40 cm	4.49±0.25
57 cm	4.67±0.33

TABLE III. Results of Experiment C.

	Hourly rate of fourfold coincidences	
	Series 1	Series 2
No water in either tank (A_0)	3.00±0.17	3.23±0.12
Water in the lower tank (A_1)	5.81±0.29	5.11±0.16
Water in the upper tank (A_2)	4.67±0.33	4.49±0.25
Water in both tanks (A_{12})	5.66±0.37	5.37±0.17

TABLE IV. Results of the measurements on the east–west asymmetry.

	Hourly rates of fourfold coincidences	
	Experiment A	Experiment B
Background	2.79±0.14	2.79±0.14
Water at east	5.11±0.35	3.06±0.15
Water at west	4.70±0.35	3.25±0.17
Difference west–east	−0.41±0.50	0.19±0.23
Average production in water	2.11±0.29	0.36±0.18

In order to avoid the influence of the geometrical factor, we devised a third experiment (Experiment C). We placed above the shielded counter arrangement described two superposed tanks. The experiment consisted in studying the influence of the water placed in the superior vessel on the production of *PS* in the water of the lower one. The diminution of the rate of production in the water of the lower tank due to the absorption of the *PSPR* allows us to calculate the mean range of the *PSPR* in water. Two series of measurements were performed. In series 1 we used 57 cm of water in both tanks. In series 2 we used 85 cm of water in the lower tank, and 40 cm in the upper one. We present our results in Table III. The mean range l is given by the relation:

$$(A_{12}-A_2)/(A_1-A_0)=\exp(-x/l), \qquad (6)$$

where x is the water thickness in the upper tank. Series 1 yields a mean range of 55±27 g/cm^2 for the *PSPR*, and series 2 a mean range of 53±25 g/cm^2. The average value resulting from series 1 and 2 is 54±19 g/cm^2. However in this experiment the influence of the absorption of the *PS* in water is not excluded, but it can be shown that a mean range much larger than 55 g/cm^2 would be incompatible with the data of Experiments A and B. We should notice that in the latter experiment the geometrical factor is less important. In Fig. 2 we have drawn $f(x)$ with the values for the parameters: $f(0)=2.9\ h^{-1}$; $f_1=4.1\ h^{-1}$; $l=54$ g/cm^2. This curve is in good agreement with the experimental points if we take into account the distortion due to the geometrical factor.

We wish to point out that the mean range l measured in our experiments is only a value averaged over the energy and eventually over the types of particles constituting the *PSPR*. We should also notice that the mean range thus determined is the true mean range for absorption of *PSPR* in water. Indeed, an eventual secondary production of *PSPR* in water cannot influence our results since the secondary showers are simultaneous with the primary ones and are registered as a single event

In conclusion, there is a definite difference between the mean range $35<l<75$ g/cm^2 for the absorption of *PSPR* in water and the value $95<l<145$ g/cm^2 for the absorption of *PSPR* in air. This difference was interpreted by one of us[12] as due to a process of secondary production of *PSPR* in the air, which would result in an apparent mean range larger than the mean range for absorption of *PSPR* in the atmosphere.

III. EAST-WEST ASYMMETRY OF THE PSPR

In order to study the east–west asymmetry of *PSPR* we performed a series of measurements using the same *PS* detector described in the preceding section. A water tank was located alternatively to the east and to the west of the *PS* detector. It seems plausible to assume that, in the average, the direction of a *PS* is the direction of the generating particle.[13] Thus, if there existed an asymmetry in the *PSPR*, we should expect different frequencies of *PS* for the east and the west positions of the tank.

We performed two experiments, A and B (Figs. 3 and 4). The asymmetry of the position of the tank was greater in Experiment B. Our results are collected in Table IV.

Neither of the experiments showed an asymmetry greater than the experimental errors. However there exist several effects which could have masked a possible magnetic deflection of the *PSPR*. In the first place, already in experiment A an asymmetry $\sim$25 percent would be masked by statistical errors. Besides, it is possible that the *PSPR* we study are not the primaries of cosmic radiation but are secondary particles. This would attenuate any asymmetry of the primary radiation. However, at higher altitude an eventual asymmetry may become observable.

[13] G. Wataghin, Phys. Rev. **70**, 787 (1946).

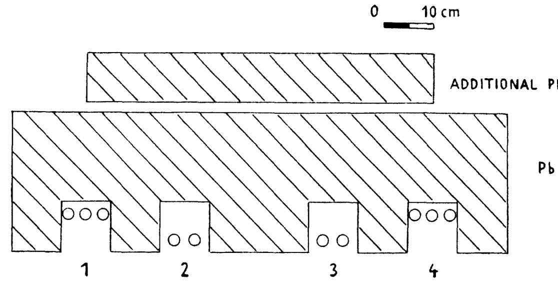

FIG. 5. Arrangement used for the study of the penetrating power of *PS* produced in the air.

IV. COMPLEMENTARY EXPERIMENT ON THE PENETRATING POWER OF PS

In a previous work[1] we discussed our experiments on the nature of the particles constituting the *PS*. We were led to conclude that the produced mesons should be π-mesons rather than μ-mesons. An essential point in our argument was the fact that when the lead protection of the counters was increased from 18 to 28 cm the rate of fourfold coincidences remained unaltered. The interpretation we gave was that the showers produced in the atmosphere were not absorbed by the additional layer of lead. We ruled out the alternative interpretation that there was a compensation between a production of *PS* in the lead and an absorption of atmospheric *PS* in this additional layer. In order to prove this point we investigated the effect of an additional layer of 10 cm of lead above the counter trays 2 and 3, on the rate of threefold coincidences due to *PS* detected by the counter arrangement shown in Fig. 5. The trays 1 and 4 were connected to the same line of the coincidence circuit. The accidental coincidences were negligible. Each counter indicated in Fig. 5 had an area of 120 cm^2. The geometrical disposition was planned in order to make the registration of a *PS* produced in the lead shielding of the counters more improbable than in the experimental arrangement of our previous measurements.[1] The rate of coincidences without the additional lead was $5.15\pm0.54\ h^{-1}$ and with the lead $5.00\pm0.16\ h^{-1}$. This confirms our argument.

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