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The Absorption of the Penetrating Component of the Cosmic Radiation*

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The nature of the penetrating component of the cosmic radiation has been studied by making G. M. counter measurements in a cavern at a depth below rock of approximately 60 m water equivalent. Observations on the vertical counting rate were made inside and outside the cavern with various thicknesses of lead between the counters. In agreement with the results of previous investigators the counting rate with no absorber between the counters is approximately one-twentieth of the counting rate outside. The small absorption of the penetrating ionizing radiation at this depth in 550 g/cm^2 of lead shows that the penetrating component is to be associated with an ionizing particle. It is therefore not necessary to assume the transmission of cosmic-ray energy to these large depths by nonionizing particles, e.g., neutrinos. Comparison of the absorption of the penetrating component inside and outside the cavern shows that the penetrating ionizing radiation undergoes a hardening on transmission through large thicknesses of material. The percentage of the radiation of the less penetrating type is very nearly the same inside and outside the cavern (25 percent to 30 percent, respectively). This suggests that such soft radiation is in approximate equilibrium with the penetrating component even at the earth's surface. The character of the absorption curve for the soft component under a depth of 60 m water equivalent shows that it must be possible for the penetrating component to generate secondaries of considerable energy.

INTRODUCTION

It is now quite definitely established that the general cosmic radiation is composed of a soft and a hard component. The experimental data on the soft component, particularly the variation of cosmic-ray intensity with altitude at different geomagnetic latitudes, can be satisfactorily explained if one assumes that it is composed of electrons and photons which behave according to the theory of radiation.[1, 2] It is, however, quite impossible on this view to account for all of the observed intensity at and below sea level so that some of the radiation which reaches low altitudes must be associated with a more penetrating type of radiation. The transmission of cosmic-ray energy through large thicknesses of matter has been extensively studied in a number of depth-ionization investigations. Such measurements have recently been extended by Wilson[3] down to depths of approximately 1500 meters of water equivalent. In order to study some of the properties of the penetrating component we have performed an experiment designed to measure the absorption of the ionizing particles present in the cosmic radiation when filtered by a considerable thickness of material.

* A report on this paper was presented at the Washington Meeting of the American Physical Society, April 1938.
[1] Heitler, Proc. Roy. Soc. **A161**, 261 (1937).
[2] L. W. Nordheim, Phys. Rev. **51**, 1110 (1937); **53**, 694 (1938).
[3] Wilson, Phys. Rev. **53**, 337 (1938). See the literature there cited for earlier intensity *versus* depth measurements.

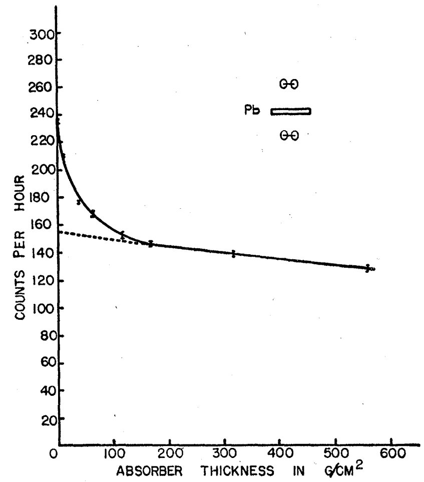

FIG. 1. Counting rate at earth's surface as a function of lead absorber thickness.

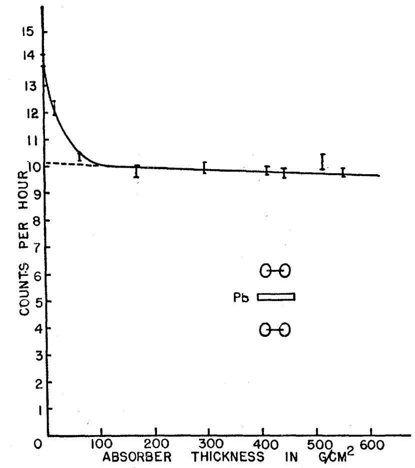

FIG. 2. Counting rate under an additional 60 m water equivalent as a function of lead absorber thickness.

THE EXPERIMENT

The experiment was carried out in Linville Caverns in western North Carolina at an altitude of approximately 2500 feet. The depth of rock above the experimental site was approximately seventy-five feet measured by a surveyor's transit. The rock is of a limestone formation. We have calculated the depth to be sixty meters water equivalent, assuming the specific gravity of the rock to be 3.28. This calculation must necessarily be only a rough approximation because of a possible inhomogeneity in the rock and because of the sloping contour of the mountain overhead. The solid angle defined by the rays which pass through the counters was such that the minimum distance to the mountain side was approximately sixty-four feet; the maximum distance was, of course, considerably more than seventy-five feet. There is apparently a transition effect in the first 20 m water equivalent in going from air to rock[3] or from air to water.[4] By making measurements at a depth of 60 m water equivalent we are fairly certain of avoiding complications due to such transition effects. The counters and counter circuits were essentially the same as used in previous investigations.[5] Insofar as possible the apparatus was mounted in paraffin covered ply-wood boxes in which drying agents were placed to safeguard against difficulties due to excessive dampness. The flexible leads to the sealed counter tubes were wound with rubber tape. In this work we have operated four counters in pairs as shown in the inset of Fig. 1. The two groups of counters were placed vertically above each other with their axes parallel. The distance between the center of the upper and the center of the lower pair of counters was 63 cm.

Measurements were made of the counting rate with various thicknesses of lead between the counters outside and inside the cavern. The efficiencies of the counters outside the cavern were measured by the method of Street and Woodward.[6] From such measurements we estimate the over-all efficiency of the apparatus for detection of coincidences to be approximately 80 percent.

RESULTS AND DISCUSSION

The curve of Fig. 1 shows the data observed outside the cavern. The data obtained inside are shown in Fig. 2. The counting rates at the two locations with no lead between the counters are 235 c/hr. and 14 c/hr., respectively. The ratio of the corrected outside counting rate (293 c/hr.) to that inside[7] is in approximate agreement with

[4] Ehmert, Zeits. f. Physik **106**, 751 (1937).

[5] K. Z. Morgan and W. M. Nielsen, Phys. Rev. **52**, 564 (1937).

[6] Street and Woodward, Phys. Rev. **46**, 1024 (1934).

[7] No attempt was made to measure the counting efficiency of the apparatus inside the cavern. The error made by assuming that it recorded all rays which passed through both groups of counters will not appreciably affect the ratio indicated above.

the measurements of Wilson[3] and Ehmert[4] who observe a reduction of about twenty-fold between ground level and a depth of 60 m water equivalent.

It is obvious from the curves of Fig. 1 and Fig. 2 that the ionizing radiation both outside and inside the cavern consists of a soft and a hard component. Observations similar to those shown in Fig. 1 have been made by a number of investigators[8] with essentially similar results. There are, however, several important conclusions which may be drawn from a comparison of the curves and we shall therefore discuss them in some detail.

The absorption coefficient of the penetrating component calculated from the data of Fig. 1 is 0.0004 cm^2/g, a value in reasonable agreement with the results of previous investigators.[8]

The straight line of Fig. 2 has been drawn to correspond to an absorption coefficient of 0.0002 cm^2/g, a value slightly smaller than that given by the data of Wilson at approximately the same depth. Obviously, the absorption coefficient is not here accurately measured. It is to be emphasized, however, that the value obtained applies to the ionizing particles present in the cosmic radiation after filtering through a considerable layer of material. The large penetrating power of such particles as here observed, makes it unnecessary to assume that the cosmic radiation is to any appreciable extent, transmitted down to these large depths by a nonionizing and penetrating type of radiation, e.g. neutrinos.[9] It seems clear that our results indicate that practically all this energy is carried down by ionizing rays and that the role played by neutral particles must be a minor one.

A comparison of the data contained in the two curves shows that the ionizing radiation undergoes a hardening as it penetrates to lower depths. A decrease in the absorption coefficient of the cosmic radiation with increasing depth below sea level has generally been observed in ionization chamber[10] and counter[3, 4] measurements. Such observations in the past have been concerned with the change in slope of the depth-intensity curve obtained by measurements of the cosmic-ray intensity for various depths of absorbing material above the sensitive portion of the apparatus. It is clear that such measurements give no direct information on the penetrating power of the observed ionizing radiation. It is, therefore, of some interest to point out that the results of the present investigation show that the hardening of the radiation is directly to be associated with the penetrating ionizing particles. This conclusion also follows immediately if one accepts the well established depth-ionization curves of others and if, as shown above, the cosmic radiation is transmitted through the large depths of material by penetrating ionizing particles.

We have made an estimate of the amount of soft radiation in the two sets of data by subtracting the contribution due to the penetrating component as shown in Fig. 1 and Fig. 2. We thus find the percentage of soft radiation to be very nearly the same outside and inside the cavern (30 and 25 percent, respectively). This suggests that even at approximate sea level the penetrating component must be very nearly in equilibrium with its secondaries. The parallel variation in the intensity of the soft and the hard components suggest rather strongly that a large percentage of the soft component at both levels is generated by the more penetrating type of radiation. The fact that a soft component is observed at all at large depths implies that it must be generated by a more penetrating type of radiation which as we have shown is of an ionizing character.

An examination of those portions of the curves which correspond to the absorption of the softer component shows that the half-value thickness corresponds to a thickness of 20 g/cm^2. Any difference in this respect between the soft component inside and outside the cavern is not large enough to be disclosed by the experimental data. There can hardly be any doubt but that the soft component is closely associated with showers. We are therefore forced to conclude that showers are generated either directly or indirectly by the ionizing penetrating component. It would also appear that the complexity at any rate of the smaller showers under heavy layers of

[8] Auger, Leprince-Ringuet and Ehrenfest, J. de phys. **7**, 58 (1936) and others.
[9] Heisenberg, Zeits. f. Physik **101**, 533 (1936).
[10] Rossi, *La Radiation Cosmique* (Hermann, Paris 1935).

matter is approximately the same as that of the showers observed at sea level. The general features of this conclusion are in agreement with the results of an earlier investigation[5] on shower production under thick layers of various materials. We observed transition effects which indicated that the showers were electronic in character. We suggested that such showers might have their origin in the generation of shower producing radiation (possibly secondary electrons and photons) by the penetrating component. It also follows from these transition curves that some of such secondary particles must have considerable energy.

We wish to thank Mr. J. Q. Gilkey of Marion, North Carolina for his kindness in making Linville Caverns available for these measurements and to acknowledge the interest of Professor L. W. Nordheim and his helpful suggestions in our work.

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The Formation of Deuterons by Proton Combination

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The probability of the astrophysically important reaction $H+H=D+\epsilon^+$ is calculated. For the probability of positron emission, Fermi's theory is used. The penetration of the protons through their mutual potential barrier, and the transition probability to the deuteron state, can be calculated exactly, using the known interaction between two protons. The energy evolution due to the reaction is about 2 ergs per gram per second under the conditions prevailing at the center of the sun (density 80, hydrogen content 35 percent by weight, temperature $2\cdot10^7$ degrees). This is almost but not quite sufficient to explain the observed average energy evolution of the sun (2 ergs/g sec.) because only a small part of the sun has high temperature and density. The reaction rate depends on the temperature approximately as $T^{3.5}$ for temperatures around $2\cdot10^7$ degrees.

§1. Introduction

It seems now generally accepted that the energy production in most stars is due to nuclear reactions involving light elements. Of all the elements, hydrogen is favored by its large abundance, by its large internal energy which makes a considerable energy evolution possible, and by its small charge and mass which enable it to penetrate easily through nuclear potential barriers. Again, of all reactions involving hydrogen, the most primitive is the combination of two protons to form a deuteron, with positron emission:

$$H+H=D+\epsilon^+. \qquad (1)$$

In fact, this reaction must stand in the beginning of any building up of chemical elements; it has already been discussed in this connection by v. Weizsäcker.[1] However, there seems to be a general belief that reaction (1) is too rare to account for any appreciable fraction of the energy production in stars and that it can serve only to *start* the evolution of elements in a star which will then be carried on by other, more probable, processes. It is the purpose of this paper to show that this belief is unfounded but that reaction (1) gives an energy evolution of the correct order of magnitude for the sun.

On the other hand, we do not want to imply that reaction (1) is the only important source of energy. An analysis of all possible nuclear reactions with light elements[2] shows that the capture of protons by carbon and nitrogen will also play an important role. It is more important

[1] v. Weizsäcker, Physik. Zeits. **38**, 176 (1937).
[2] Bethe, to appear shortly in the Physical Review.