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The Absorption of the Shower-Producing Component of Cosmic Radiation in Iron and Lead

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Measurements of the absorption coefficient of the shower-producing component of primary cosmic radiation give 0.35 cm^{-1} in lead and 0.076 cm^{-1} in iron. The atomic absorption coefficients corresponding to these values are nearly in direct proportion to the squares of the atomic numbers of the absorbing materials. The value 0.35 cm^{-1} for lead agrees rather well with that found by Woodward. A slight minimum was found in the curve of the absorption for lead at a point between 8 and 10 cm, confirming similar findings by Rossi and others. No minimum was found in the absorption curve for iron up to a thickness of 20 cm. For the rays received within a given solid angle, the ratio of the shower rate to the vertical coincidence rate falls from 5.1 percent with no shield to 2.6 percent with 15 cm of lead, and to 3.0 percent with 20 cm of iron.

IT is well recognized that most of the electron showers associated with cosmic rays at sea level are produced by a non-ionizing type of radiation. These non-ionizing shower-producing rays very probably consist of photons, which are in turn excited by primary shower-producing particles that may be electrons. The terms A, B, and C will be applied, respectively, to the primary shower-producing particles, the shower-producing photons, and the shower electrons. The present paper is concerned chiefly with a measurement of the absorption coefficient in iron and lead of rays of type A, i.e., the primary shower-producing component of cosmic radiation. A measurement is also made of the relative number of showers and vertical coincidences.

Measurements designed for the same purpose have been performed by Sawyer,[1] Rossi,[2] Woodward,[3] and others. The present experiment has followed Sawyer's procedure of studying showers (C-rays) that are produced in a material that differs from the one in which the shower-producing radiation B itself is excited. Since with this technique the rays of types B and C are always produced in the same substance, a direct comparison is obtained of the absorption of the primary shower-producing radiation A in various absorbing materials. We have replaced the triangular arrangement of three counters used by Sawyer[1] with the fourfold coincidence arrangement of counters shown in Fig. 1. Thus not only is the number of chance counts reduced, but it also becomes necessary for all of the primary rays to pass through the absorbing materials before producing rays which affect the counters.

EXPERIMENTAL PROCEDURE

With the arrangement of counter tubes shown in Fig. 1 coincidence counts are possible only when showers are produced in the lead scatterer S, except for the very rare shower particles which

[1] J. H. Sawyer, Phys. Rev. **50**, 25 (1936).
[2] B. Rossi, Zeits. f. Physik **82**, 151 (1933).
[3] R. H. Woodward, Phys. Rev. **49**, 711 (1936).

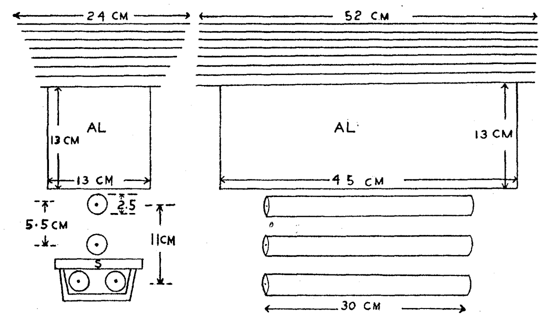

FIG. 1. Arrangement of apparatus in end and side view.

may be able to penetrate 1 cm of lead. Our experiments indicate that the aluminum block placed above the tubes is thick enough to absorb nearly all of the B-type rays entering from above. Thus all of the B-rays which strike the scatterer S are produced in the aluminum block. Above the aluminum block are placed the plates of lead or iron, whose absorption of the A-type of radiation is to be measured. In order to reduce disturbing effects from showers excited in matter in the neighborhood, the apparatus is used under canvass on the roof of Ryerson Laboratory.

The Geiger-Müller tubes are filled with hydrogen to a pressure of 9.6 cm of mercury, and about 0.2 cm of dry air. The center of the plateau of voltage operation is about 1220 volts. Each tube is wrapped in a thin aluminum foil which is grounded. The source of high voltage placed across the counter tubes is a modification of the arrangement given by Street and Johnson.[4] The circuit used with the Geiger-Müller tubes is approximately described by Neher and Harper.[5]

Figure 2 shows in curves A and B the counting rates observed for various thicknesses of iron and lead, respectively. Each datum point represents some thirty hours of readings and the length of the vertical line at each point represents the standard deviation as calculated from the number of counts. Repeated observations at widely separated intervals showed experimental deviations consistent with those to be expected by this statistical calculation. This may be taken as sufficient test of the consistency of the readings.

Except for the last two points of curve B, the data may be represented with sufficient accuracy by the empirical expression

$$N=N_0\epsilon^{-\mu x}+C. \quad (1)$$

The smooth curves in Fig. 2 have been plotted with the values $N_0=20$, $C=10$, $\mu_{\text{Fe}}=0.076\ \text{cm}^{-1}$, $\mu_{\text{Pb}}=0.35\ \text{cm}^{-1}$.

INTERPRETATION

If we assume that the primary cosmic rays A are electrons of an absorption coefficient (μ_1), the secondary rays B are photons of an absorption coefficient (μ_2), and the tertiary rays C are shower particles of an absorption coefficient (μ_3), it can be shown that the counting rate N should be given by the following equation.

$$N=\frac{C}{(\mu_3-\mu_1)(\mu_2-\mu_1)} \times\left\{\epsilon^{-\mu_1 x}-\frac{(\mu_3-\mu_1)}{(\mu_3-\mu_2)}\epsilon^{-\mu_2 x}+\frac{(\mu_2-\mu_1)}{(\mu_3-\mu_2)}\epsilon^{-\mu_3 x}\right\}. \quad (2)$$

The curve shown in Fig. 3 is plotted with the values $\mu_1=0.3\ \text{cm}^{-1}$, $\mu_2=0.7\ \text{cm}^{-1}$, $\mu_3=5.0\ \text{cm}^{-1}$ of lead. The shape of the portion AB of this curve is determined primarily by the coefficient μ_3, the portion BC by the coefficient μ_2, and from C to D by the coefficient μ_1. The fact that the data shown in Fig. 2 are on the downward sloping part of the curve thus indicates that the aluminum block is adequate to absorb most of the secondary photons that come from above. This in

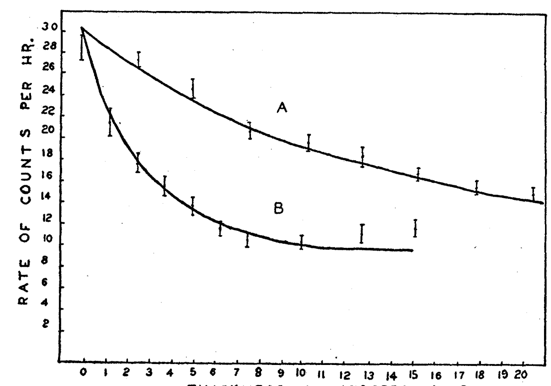

FIG. 2. Counting rates as functions of thickness of iron (curve A) and of lead (curve B).

[4] J. C. Street and T. H. Johnson, J. Frank. Inst. **214**, 155 (1932).

[5] H. V. Neher and W. W. Harper, Phys. Rev. **49**, 940 (1936).

turn gives assurance that B-type rays reaching the scatterer S are those produced in the aluminum block. Thus we may provisionally identify the absorption coefficient measured by the arrangement of Fig. 1 with the absorption coefficient of the primary shower-producing particles A in iron and lead.

The constant C is due at least in part to the showers produced in the air and in the wood structure placed above the tubes to support the iron and lead. It is noteworthy, however, that the data associated with curve B show a minimum at about 9 cm of lead. This result confirms similar findings by Rossi[6] and others. It is not impossible that the rise beyond 9 cm of lead may represent the excitation of a penetrating cosmic ray by a less penetrating primary ray.[7] In this case the rising datum points at the end of curve B should correspond to the portion of the curve of Fig. 3 lying between B and C. The base line of curve B should then not have the constant value $C=10$, but should rather be sloping upward from the origin. In view of the speculative character of this hypothesis, we preferred to use the simpler assumption represented by Eq. (1). Had the alternative of an upward sloping base line been taken, the value of N_0 would have been increased by roughly fifty percent. The value of μ, however, would not have been greatly altered.

On the basis of the relative absorption in iron

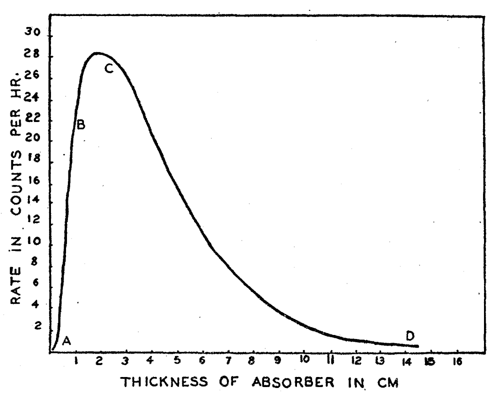

FIG. 3. Theoretical curve, plotted according to Eq. (2), for the variation of counting rate with absorber thickness.

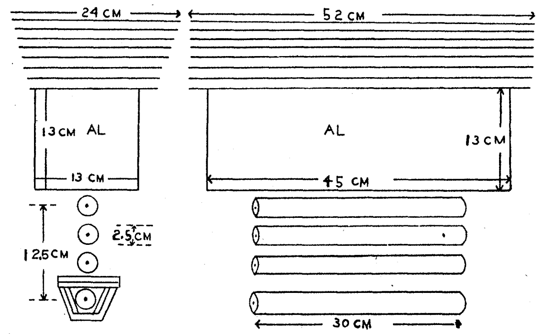

FIG. 4. Arrangement of apparatus to determine ratio of shower-producing rays to the total vertical cone of cosmic rays.

and lead we should not expect a similar minimum in curve A until a thickness of 35 to 45 cm of iron is reached. This is in accord with the observed absence of such a minimum in the data for iron, and indicates the importance of using great thicknesses of absorber for measuring this highly penetrating secondary radiation.

The value of μ required for the empirical formula (1) should thus differ little from the true absorption coefficient of the primary shower-producing ray in iron and lead. The atomic absorption coefficients corresponding to the values of $\mu_{Pb}=0.35$ cm^{-1} and $\mu_{Fe}=0.076$ cm^{-1} are, respectively, 1.05×10^{-23} and 0.08×10^{-23}. These values for lead and iron are approximately in direct proportion to the squares of the atomic numbers of the absorbing materials. This result does not agree with that found by Sawyer.[1] The value for the absorption in lead is in good agreement with the corresponding value of 0.33 cm^{-1} found by Woodward.[3]

THE RELATIVE NUMBER OF SHOWER-PRODUCING RAYS

A rough estimate of the ratio of shower-producing rays to the total vertical cone of cosmic rays was made possible by counting the coincidence rate with four counters in line as shown in Fig. 4. With no absorber above the aluminum block the observed rate of shower coincidence was 11.7 percent as great as that of the observed vertical coincidence. Because, however, of the greater separation of the tubes in vertical arrangement, the solid angle of the vertical cone was less than in the shower arrange-

[6] B. Rossi, *International Conference on Physics* (London, 1934).

[7] Thus, Heitler, Proc. Roy. Soc., June, 1938, suggests that the primary electrons may excite alternatively penetrating barytrons or less penetrating electron pairs through the medium of secondary photons.

ment by a factor of 2.3. Thus for the rays within a given solid angle the shower rate is 5.1 percent as great as the vertical coincidence rate. For the full shield of 15.24 cm of lead the corresponding ratio is reduced to 2.6 percent, and for 20.48 cm of iron to 3.0 percent. These fractions of the primary rays which produce showers are approximately the same as those found by Geiger.[8]

The ratio of the number of recorded showers to the total number produced somewhere along the path of the primary shower-producing rays is unknown. The smaller percentage of the observed showers suggests, however, that the shower-producing component constitutes the smaller part of the primary cosmic radiation.

It gives me great pleasure to acknowledge my indebtedness to Professor A. H. Compton for his constant inspiration and helpful advice throughout this investigation. I wish also to express my sincere appreciation to the General Education Board for the fellowship aid given to me during this time.

[8] H. Geiger, Zeits. f. Physik **97**, 300 (1935).

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The Capture of Orbital Electrons by Nuclei

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The simple theory of electron capture is outlined and three general methods for its detection are suggested. The first experimental evidence for the process (in activated titanium) is described. A rigorous experimental proof of the hypothesis is given for the case of Ga^{67}. A summary of several isotopes whose properties are best explained on this hypothesis is appended. The properties of Ga^{67} are described in considerable detail, and include the first evidence for internal conversion in artificially radioactive atoms.

INTRODUCTION

THE suggestion that positron emitters might decay by the alternate process of electron capture was first advanced by Yukawa[1] from considerations based on the Fermi theory of beta-ray emission. In this theory, the electrons and positrons are pictured as being created at the moment they are ejected, during neutron-proton transitions. The continuous beta-ray spectrum and the conservation of spin are explained by the simultaneous emission of a neutrino and electron. One may represent the transition involved in electron and positron decay by the following equations:

$$N \rightarrow P + e^- + \nu \qquad (1)$$

$$P \rightarrow N + e^+ + \nu. \qquad (2)$$

On the basis of Dirac's theory, however, the positron is merely the "hole" left in the continuum of negative energy electrons when one of these electrons is given a positive energy by the addition of at least $2mc^2$. The proton in (2) does not transform into a neutron and positron, but rather captures a negative energy electron, and turns into a neutron, leaving the hole in the negative energy sea, or positron. Eq. (2) may then be written

$$e^- + P \rightarrow N + \nu. \qquad (3)$$

The experimental observation that positrons may be annihilated (a positive energy electron falling into the hole), shows that there is no essential difference between electrons in the two energy states. Therefore, there is no *a priori* reason why Eq. (3) demands the use of a negative energy electron. In fact, when the energy difference between parent and daughter nucleus is less than $2mc^2$, it would be impossible for the relation to be satisfied unless a proton could capture an ordinary electron. Since there are many cases of negative beta-ray decay with an

[1] Yukawa and Sakata, Proc. Phys. Math. Soc. Japan **17**, 467 (1935); **18**, 128 (1936).