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A Study of Penetrating Cosmic-Ray Showers in Water*

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Penetrating showers produced locally by non-ionizing radiation were studied using counter techniques. The collision length in water of the non-ionizing component which is capable of producing penetrating showers was found to be (98±13) g/cm². Comparison of this collision length with that expected from the geometrical cross section seems to indicate that the hydrogen nuclei in water have a rather small cross section for the production of penetrating showers by neutral radiation. Results obtained at two elevations were used to calculate the absorption length in air of the neutral penetrating shower producing component. The absorption length measured, (115±19) g/cm², agrees with that obtained by others for the total penetrating shower producing component.

I. INTRODUCTION

THE experiment described below was designed to measure, in water, the collision length, or mean free path for one nuclear collision producing a penetrating shower, of that non-ionizing component of cosmic-rays which is capable of producing penetrating showers. Water was chosen as the absorbing material in order to compare the collision length in a hydrogenous material with those obtained by other investigators in light elements. Such a comparison may allow some conclusion to be drawn about the cross section for production of penetrating showers in hydrogen. Pomeroy,[1] with non-ionizing primaries, and George and Jason,[2] with ionizing primaries, have measured the collision length in paraffin, while Meyer *et al.*,[3] have measured the collision length of the total penetrating shower producing component in water. Their results, as well as those obtained here, may be compared with values found in carbon by Walker *et al.*,[4] and in aluminum by George and Jason.[2] The effectiveness of hydrogen in the production of penetrating showers has not been measured uniquely, although recently Vidale and Schein[5] have shown that π-mesons are produced in proton-proton collisions in cosmic rays.

II. APPARATUS

Details of the equipment are shown in Figs. 1 and 2. Penetrating showers produced in the small water tank σ_2 were counted by means of four trays of counter tubes, A, B, C, and D. The two crossed trays A and B were separated by six inches of lead σ_3, from two more crossed trays, C and D. A fivefold coincidence among the four trays was required to record a shower. At least one counter tube in each of the trays A, B, and D and at least two neighboring counter tubes in tray C had to be simultaneously discharged. A single particle inclined enough from the vertical to discharge two tubes in tray C would not strike tray A.

In order to better limit the solid angle, tubes B-1 and B-2 were connected in parallel (see Fig. 2), and pulses from either of the two could form coincidences with pulses from D-1, D-2, or D-3, also connected in parallel. An analogous arrangement existed for the other tubes in trays B and D. An examination of Fig. 2 discloses that the solid angle subtended by this arrangement is fully covered by the anticoincidence tray E.

In the case of trays A and C, allowed threefold coincidence combinations were selected in such a manner as to keep the solid angle within the limits of the anticoincidence tray E. There were six threefold arrange-

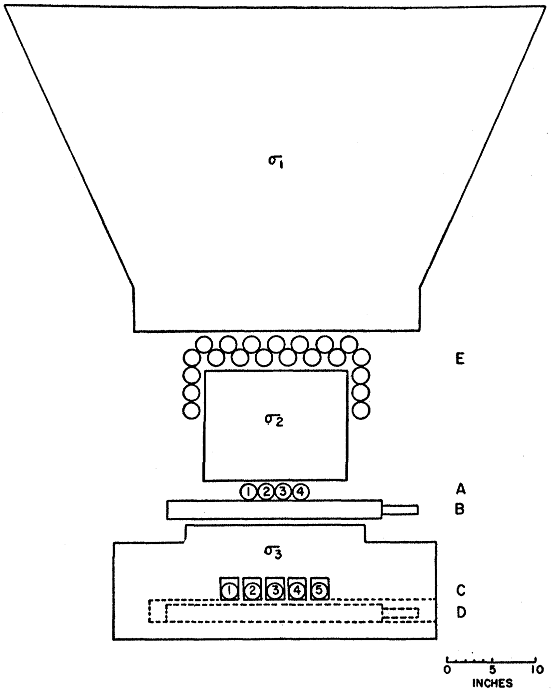

FIG. 1. Front view of experimental arrangement.

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[1] D. Pomeroy, Phys. Rev. **84**, 77 (1951).

[2] E. P. George and A. C. Jason, Proc. Phys. Soc. (London) **A63**, 1081 (1950).

[3] Meyer, Schwachheim, Wataghin, and Wataghin, Phys. Rev. **76**, 598 (1949).

[4] Walker, Walker, and Greisen, Phys. Rev. **80**, 546 (1950).

[5] M. L. Vidale and M. Schein, Phys. Rev. **84**, 593 (1951).

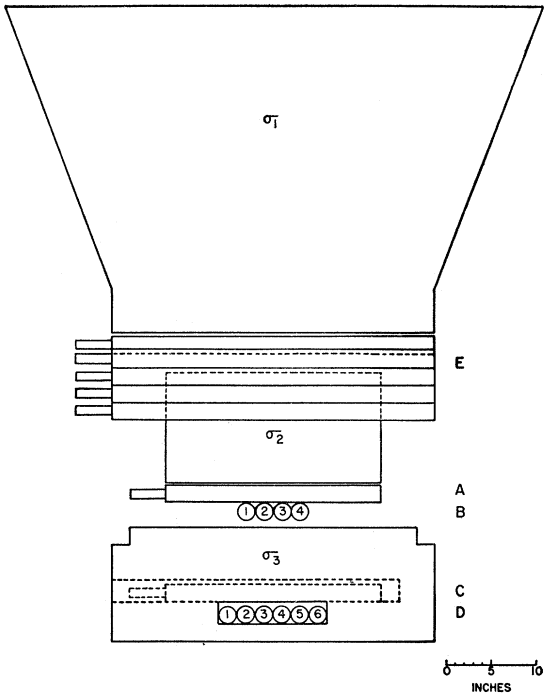

FIG. 2. Side view of apparatus.

ments; A-1 with C-1 and C-2; A-2 with C-1 and C-2; A-2 with C-2 and C-3; A-3 with C-3 and C-4; A-3 with C-4 and C-5; and A-4 with C-4 and C-5. The threefold coincidences from trays A and C were brought into coincidence with the twofold coincidences from trays B and D to give a fivefold coincidence $(A+B+2C+D)$.

The lead block σ_3 insured the penetrating nature of the shower particles, since they had to traverse six inches of lead. The lead also shielded the lower trays of tubes to prevent the registering of soft showers from the side. Each of the tubes in tray C was separated from its neighboring tubes by one-half inch of lead to keep knock-on electrons accompanying mesons from causing a background count.

An anticoincidence counter tray E was situated between σ_2 and a large water tank σ_1 on top of the equipment. An anticoincidence event, $PSN=(A+B+2C+D-E)$, was interpreted as due to a penetrating shower produced in σ_2 by non-ionizing radiation.

In order to determine the collision length of the non-ionizing radiation which produces penetrating showers, the counting rate PSN was measured for various thicknesses of σ_1. This method was first employed by Janossy and Rossi[6] and later by Rossi and Regener.[7]

The efficiency of the anticoincidence tray was tested weekly by moving counter tray B above tray E. The PSN rate should have been zero with tray B in this position. There was an auxiliary recorder which counted all fivefold coincidences $(A+B+2C+D)$. The PSN rate was always 1 percent of the fivefold rate, within statistical limits, during these weekly tests.

The counters used were large brass-walled tubes,[8] two inches in diameter and 24 in. or 36 in. long.

III. POSSIBLE SOURCES OF ERROR

The experimental arrangement was designed to minimize errors due to poor geometry. Any line drawn through allowable combinations in the penetrating shower telescope would pass through counter tray E and the absorber tank σ_1. It would be possible for an ionizing particle to come in at a large angle from the zenith and produce a penetrating shower having a large angular spread which would count as a PSN. However, Walker[9] found a very strong zenith angle dependence of penetrating showers ($\cos^7\theta$ at Echo Lake). Walker also found that the shower particles are projected in the direction of an ionizing primary with little spread, so that very few events of the above type could be recorded.

There will be some fivefold coincidences which are caused by knock-on processes, in spite of the lead plates between the counters of tray C. It seems unlikely, however, that any of the anticoincidence events recorded as PSN are simulated by knock-on processes, because the primary ray causing the knock-on event would have had to be non-ionizing when passing through tray E.

Extensive air showers which could penetrate σ_3 would, with a high degree of certainty, also strike tray E with at least one particle, no matter from which direction they came. For a photon to trigger the apparatus, it would have to produce, in σ_2, a cascade capable of traversing the 170 g/cm² of lead in σ_3. Photons of such a high energy would not be expected to enter the equipment without being accompanied by the ionizing particles of an air shower.

There was some possibility that chance coincidences between one of the counters in tray C and a fourfold coincidence $A+B+C+D$ would cause an appreciable error. Tests performed at the time of construction of

TABLE I. Anticoincidence counting rate as a function of absorber thickness, σ_1, with standard deviations.

Absorber thickness σ_1 (g/cm²)	*PSN* $\sigma_2=0$ g/cm² Counts	Time (hr)	Rate/hr	*PSN* $\sigma_2=30$ g/cm² Counts	Time (hr)	Rate/hr
0	68	34.5	1.97±0.24	526	91.5	5.75±0.25
12.5	44	20	2.20±0.35	452	79.5	5.69±0.27
25	48	24	2.00±0.29	420	82.5	5.09±0.25
37.5	...	...	...	410	90.5	4.53±0.22
50	60	35.5	1.69±0.22	404	95.5	4.23±0.21
90	78	42.5	1.84±0.21	498	141	3.53±0.16
Total:	298	156.5	1.90±0.11			

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[6] L. Janossy and B. Rossi, Proc. Roy. Soc. (London) **A175**, 88 (1940).

[7] B. Rossi and V. H. Regener, Phys. Rev. **58**, 837 (1940).

[8] V. H. Regener, Rev. Sci. Instr. **18**, 267 (1947).

[9] W. D. Walker, Phys. Rev. **77**, 686 (1950).

the apparatus indicated that this occurrence was rare, accounting for less than 0.5 percent of the *PSN* counting rate.

IV. EXPERIMENTAL RESULTS

The equipment was housed in an instrument shelter at the High Altitude Observatory of the University of New Mexico Physics Department. The observatory is atop Capillo Peak (elevation 2770 meters) in the Manzano Mountains of New Mexico.

It was expected that the counting rate with no water in σ_2 would be independent of the water level in σ_1 and that this counting rate could be subtracted as a background. Several runs were made at various absorber depths σ_1, with $\sigma_2=0$. The rates obtained are shown in the first part of Table I, along with their standard deviations. Since the counting rates were the same within the statistical accuracy, the total number of counts and the total time were taken to give a background rate of (1.90±0.11) counts/hr for all values of σ_1.

The one percent inefficiency of the anticoincidence tray could have necessitated a correction to the *PSN* rate, since the fivefold rate with tray *B* in its normal position was from 7 to 24 times that of the uncorrected *PSN* rate. This would make an error of from 6 percent to 20 percent in the *PSN* rate. However, since the background rate (no water in σ_2) for *PSN* contained very nearly the same number of counts due to the inefficiency as the corresponding *PSN* rates with σ_2 full, the error almost cancels when the background is subtracted, leaving a maximum error of one percent. Since the maximum statistical accuracy was 5 percent, this correction was neglected.

In order to minimize the effect of time variations in the radiation and in the performance of the equipment, the depth of the water in σ_1 was changed daily during the actual experiment. Each depth was used for at least five different runs. The counting rates obtained are given in the second part of Table I. Figure 3 shows the data, after correction for background, on a semilogarithmic scale. A least squares calculation of the collision length of the non-ionizing penetrating shower producing radiation gives

$$\lambda=(98\pm13)\ \mathrm{g/cm^2}.$$

This result is discussed in Sec. V.

Prior to the installation of the equipment at Capillo Peak, it was set up on the grounds of the University of New Mexico (elevation 1570 meters). While this was was not part of the main experiment, it allowed a comparison of the counting rates obtained from identical arrangements at the two elevations. A calculation was made of the absorption length in air of the non-ionizing radiation which produces penetrating showers. The counting rate, corrected for background, with no water in σ_1 was (1.41±0.28) counts/hr at 1570 meters, while that at Capillo Peak was (3.85±0.27) counts/hr.

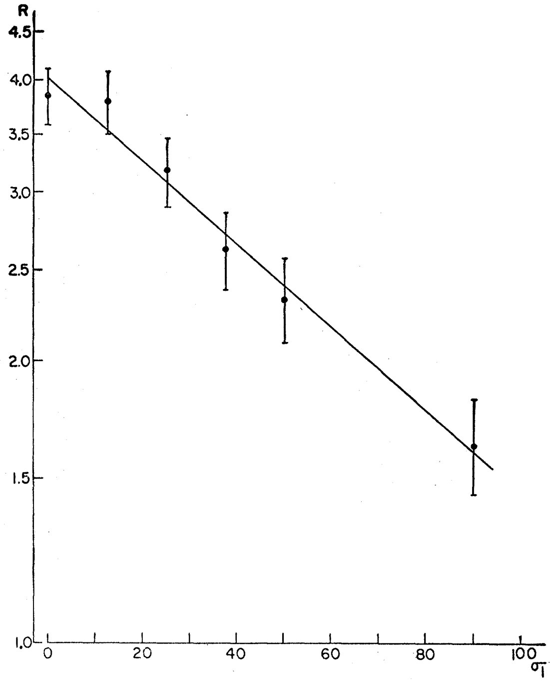

FIG. 3. Corrected rate of anticoincidence events (*PSN*) per hour, as a function of the absorber thickness σ_1 (g/cm²).

Assuming an exponential decrease in counting rate with atmospheric depth, these rates give an absorption length of

$$\lambda=(115\pm19)\ \mathrm{g/cm^2}.$$

This value agrees with that obtained by Pomeroy[1] for non-ionizing primaries and also with the results of others[3,9–11] for combined non-ionizing and ionizing primaries.

V. DISCUSSION OF THE COLLISION LENGTH

The collision length obtained here can be compared with that calculated from the geometrical cross section of the nucleus according to the formula $\lambda=A/N\sigma$. In this formula the cross section σ is calculated from $r=(1.4\times10^{-13})A^{\frac{1}{3}}$. The calculated collision length is 58 g/cm², which makes the ratio between measured and calculated collision lengths 1.7.

However, this ratio seems high when compared with the results of other investigators who measured the collision length in elements. Walker, Walker, and Greisen[4] measured the collision length of the non-ionizing radiation in carbon and obtained (80±7) g/cm², a ratio of 1.3 with the calculated collision length. George and Jason[2] with aluminum, Cocconi[12] with iron, and Sitte[13] (among others) with lead, each obtained a measured collision length for the ionizing radiation which was from 1 to 1.3 times that calculated from the

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[10] J. Tinlot, Phys. Rev. **74**, 1197 (1948).

[11] T. G. Walsh and O. Piccioni, Phys. Rev. **80**, 619 (1950).

[12] O. Cocconi, Phys. Rev. **75**, 1074 (1949).

[13] K. Sitte, Phys. Rev. **78**, 714 (1950).

geometrical cross section of the respective nucleus. Thus, it appears that the ratio between measured and calculated collision lengths should vary from 1 with large nuclear masses to about 1.3 with the lighter nuclear masses. This assumes that this ratio does not vary strongly with the energy of the primary radiation and, as shown by Walker *et al.*,[4] that the collision lengths for non-ionizing and ionizing radiation are the same.

In order to bring the present results into agreement with those quoted above, one is led to assume that the hydrogen nuclei in water have a very small cross section for the production of penetrating showers by non-ionizing primaries. In fact, if one assumes that oxygen nuclei alone are responsible for the penetrating showers observed in this experiment, the calculated collision length becomes 77 g/cm^2, giving just the ratio of 1.3 between measured and calculated collision lengths. George and Jason[2] measured the collision length as $\sim$80 g/cm^2 for the ionizing primaries in paraffin. This result also indicates an extremely low cross section for hydrogen when compared with the result obtained by Walker[4] in carbon. Harding,[14] working with the production of π-mesons in ice, also concluded that π-mesons are produced only in the oxygen nuclei of ice.

It should be pointed out that the results obtained here are contrary to those of Meyer *et al.*,[3] who measured the collision length of the total (ionizing as well as non-ionizing) radiation producing penetrating showers in water as (54$\pm$19) g/cm^2. Pomeroy's[1] results in paraffin are also below those of George and Jason.[2]

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[14] J. B. Harding, Phil. Mag. 42, 621 (1951).

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Possibilities of Heavy Ion Bombardment in Nuclear Studies*

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Bombardment of nuclei by multiply charged ions of medium atomic weight such as C^{12} or O^{16} is considered as a possible means of studying nuclear structure. Estimates are made regarding the approximate magnitude of: (a) distortion effects in target nuclei produced by the incident particles, (b) consequences of the distortion such as effects on thresholds of reactions having their origin in Coulomb barriers, (c) stimulation to fission, (d) effects characteristic of the leakage of neutrons and protons out of the two colliding nuclei by wave-mechanical penetration of the regions of negative kinetic energy; an exploration of these effects should amount to a study of the halo of neutrons and protons surrounding the more compact nuclear interior and might be helpful in determining the number of nuclear particles at the nuclear surface having a given energy. The treatment is qualitative and the mathematical discussion involves many approximations. General design characteristics of a 60-inch cyclotron that should be capable of imparting the necessary energy to multiply charged ions are considered.

I. INTRODUCTION

IN the early development of nuclear physics it was important to bombard nuclei with charged particles under conditions which would insure the penetration of the Coulomb barrier. The limited energies available and technical difficulties with ion sources made it desirable, therefore, to choose relatively light particles as the bombarding projectiles, minimizing the loss of useful energy in recoil action and simplifying interpretation of the elementary processes involved.[1] Instrumentation for work along lines of "classical" nuclear physics has developed, therefore, along lines especially suitable for the acceleration of protons, deuterons, and alpha-particles. The interpretation of experiments performed by these means often involves a large amount of mathematical work on account of the necessity of taking into account the wave-mechanical nature of the initial collision process.

We have investigated the possibility of obtaining information regarding nuclear structure by bombarding nuclei with much heavier projectiles. In this case the wave-mechanical features of collision processes are considerably less important, and one may hope that the interpretation of most experiments could be made by considering the approach stage of the process by means of classical mechanics. Of course, quantum mechanics still will have to be used, but its application can be expected to be primarily concerned with questions of the structure of nuclei themselves rather than with the phenomena of the diffraction of waves representing the relative motion of the two colliding parts. The study of the possibilities of obtaining new information

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* Assisted by the joint program of the ONR and AEC.

[1] G. Breit, Phys. Rev. 34, 817 (1929).