Cosmic-Ray Shower Production and Absorption in Various Materials

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Measurements have been made of shower production in thin pieces of carbon, aluminum, copper, tin and lead. The results as shown by a study of three and twofold showers for thicknesses of 0.58 and 0.29 cm lead mass equivalent thickness and for several different experimental arrangements, indicate that the increase in counting rate associated with each atom in the producing material varies as the 2.0 ± 0.2 power of the atomic number of the element concerned. Our measurements indicate that the increase in counting rate for heavy elements such as lead increases faster than the first power of the thickness of producing material. The departure from linearity seems to be a function of atomic number, being greater for elements of large Z. Absorption measurements of showers from lead, in lead, tin, copper, aluminum and carbon show that the absorption per atom varies between the first and second powers of the atomic number. Rossi transition curves for lead, iron and aluminum are presented. In the case of iron and aluminum these measurements are extended to larger thicknesses than in previous investigations.

1. INTRODUCTION

DURING the past several years, a great deal of attention has been paid to the so-called cosmic-ray shower production.[1] Experiments of this kind are of importance not only because of the relation between showers and the general cosmic-radiation, but also because such studies give valuable information on the nature of the interaction between high energy particles and matter.

We have had in progress, during the past few years, a series of experiments concerned with the production and absorption of cosmic-ray shower particles in various materials. In this paper we present (1) our observations on shower production in small thicknesses of various materials as a function of atomic number; (2) shower production as a function of the thickness of producing material; (3) our measurements on the absorption of showers in various materials, and (4) measurements on the Rossi transition curve for lead, iron and aluminum.

2. EXPERIMENTAL ARRANGEMENTS

The apparatus used is a modification of the circuit of Johnson and Street[2] adapted for selective detection of double, triple, or quadruple coincidences of the Geiger-Müller counter discharges.

The counters were made by Mr. A. G. Nester, with the aid and supervision of Dr. G. L. Locher of the Bartol Research Foundation of the Franklin Institute. In most of the work we have used counters approximately 5 cm in diameter and 20 cm in effective length. In Section 6 and in the observations given in Fig. 7 of Section 4 we have also used counters $2\frac{1}{2}$ cm in diameter and 20 cm in effective length. In the latter case the counters are connected together in groups of three to each input channel.

Counts and time interval marks are recorded on a moving paper tape. This automatic recorder allows easy statistical analysis of count distribution over any desired interval from the permanent record.

Highly accurate voltage regulation is accomplished in the power pack by means of a constant current ballast tube, saturated core reactors, and a thermionic tetrode regulator of the type of Street and Johnson[3] for the direct counter voltage. Sufficient constancy is obtained so that all readings are repeatable, within normal statistical error, after several months elapsed time.

All apparatus is housed in a small cabin of very light construction in order to minimize the background shower count as much as possible. While we have never observed a definite change in sensitivity of our counters with temperature, we have, as a precaution, maintained the temperature within the cabin reasonably constant by thermostatic control.

The location of this experimental station is approximately 410′ above sea level.

[1] H. Geiger, Ergeb. d. Exakt. Naturwiss. **14**, 42 (1935).
[2] T. H. Johnson and J. C. Street, J. Frank. Inst. **215**, 239 (1933).
[3] J. C. Street and T. H. Johnson, J. Frank. Inst. **214**, 155 (1932).

TABLE I. *Shower production in various materials. In all cases the showers are produced in plates of same area and have a mass per unit area equivalent to 0.58 cm of lead.*

Element	Z	Total Count	Total Time (hr.)	Counts per hr.	A	$\Delta(0.58)$	$A\Delta(0.58)$
Background		14,139	2376.4	5.95±0.02			
Carbon	6	1,778	281.3	6.32± .12	12	0.37±0.12	4.5± 1.5
Aluminum	13	1,045	150.0	6.93± .11	26.97	0.98± .11	26.4± 3.1
Copper	29	1,290	160.0	7.91± .13	63.55	1.96± .13	124.5± 8.7
Tin	50	1,214	115.4	10.52± .18	118.7	4.57± .18	538. ±21
Lead	82	4,121	319.8	12.90± .17	207.2	6.95± .17	1440. ±35

3. Shower Production as a Function of Atomic Number

The dependence of shower production on the nature of various materials was investigated by means of the experimental arrangement shown in Fig. 1. The plate of material above the three counters was approximately 22 cm×30 cm with a mass per unit area equivalent to 0.58 cm of lead. These dimensions were kept constant for each of the elements investigated. Since only triple coincidences were recorded, inspection of the figure referred to above will show that any shower from the material must consist of at least three particles in order to be detected by the apparatus as a count. The series of elements carbon, aluminum, copper, tin and lead gave the data of Table I.

The large number of hours of operation with no producing material in position is due to the fact that this condition is used at frequent intervals to check the over-all efficiency of the apparatus. The differences $\Delta(0.58)$ between the number of observed coincidences when the material in question is placed above the counters and when it is removed is shown in column 7 for each of the elements investigated. In view of current theories of pair production we have also expressed these data in terms of the number of coincidences produced per hour per atom of material in the producing plate, by multiplying the above quantities by factors corresponding to their individual atomic weights. The results are given in column 8.

The curve A of Fig. 2, plotted from these data, represents the increase in counting rate per nucleus as a function of atomic number.

Using the same experimental arrangement, a similar set of data was obtained for a producing plate of 0.29 cm lead equivalent thickness. These results are plotted as curve B of Fig. 2. It will be apparent from an inspection of these curves that the observed increase in counting rate per atom increases rapidly with increase in atomic number. The log-log plot of these data

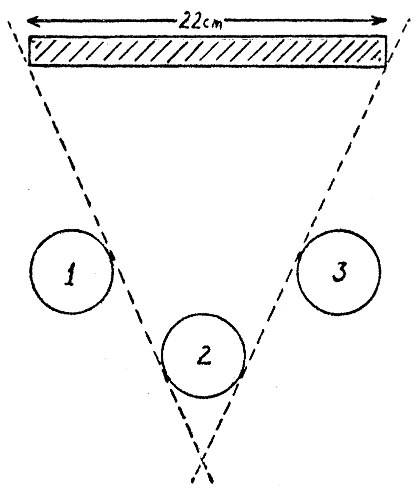

FIG. 1. Arrangement for investigation of shower production as a function of atomic number and thickness.

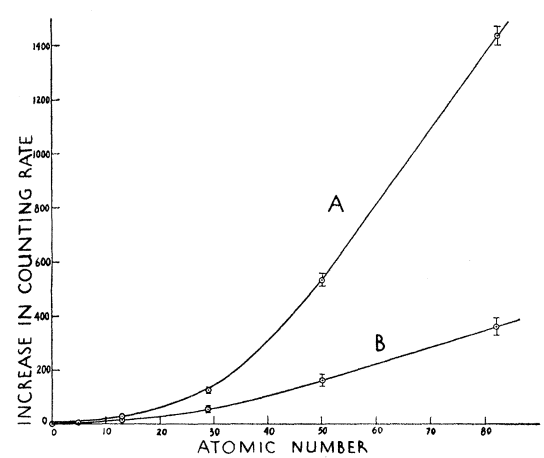

FIG. 2. Increase of counting rate, multiplied by atomic weight, as a function of atomic number.

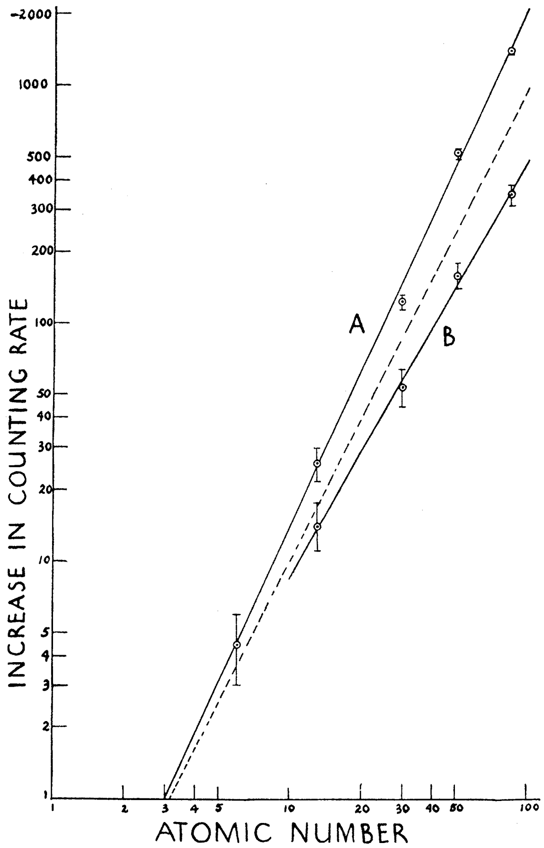

FIG. 3. Logarithmic plot of the data of Fig. 2. Dotted curve has a slope of 2.0.

shown in Fig. 3 indicates that this increase varies approximately as the second power of the atomic number. The data for a thickness of 0.29 cm indicate a power of Z of 1.85 while the data for the full thickness of 0.58 cm lead equivalent show a power of Z of 2.2. This difference is hardly outside the probable errors involved. In a later section we discuss some of our experiments on the absorption of cosmic-ray showers. At this point we wish only to point out that any detectable effects of absorption either of background or of the showers created in the producing material would lead one to expect a greater slope for the plot of observed data associated with the smaller thickness of producing material. This follows because of the greater coefficient of absorption, expressed in cm^2/g, for the elements of higher atomic number. That both sets of data give a dependence of shower production on Z in substantial agreement is a point of some interest.

We have also made measurements on the increase in counting rate for double coincidences produced in layers of materials of 0.58 cm lead equivalent. In this work we have recorded double coincidences between counters 1 and 3 of Fig. 1. These data are given as A of Fig. 4 in which log $A\ \Delta(0.58)$ is plotted as a function of log Z. The background count in this case was 47.18 counts per hour. The increase associated with 0.58 cm of lead was 31.1 counts per hour. The slope of the straight line drawn through the data points of A is 1.95.

In order to increase the importance of the producing material compared to the background we have also used the arrangement shown in Fig. 5. In this case the background count was 0.84 count per hour and the increase in counting rate with 0.58 cm of lead was 11.51 counts per hour. Measurements with copper and lead have been made and are plotted as B in Fig. 4, the slope of which is the same as that of A within the limits of error.

It would appear then that all of our measurements on shower production in different ma-

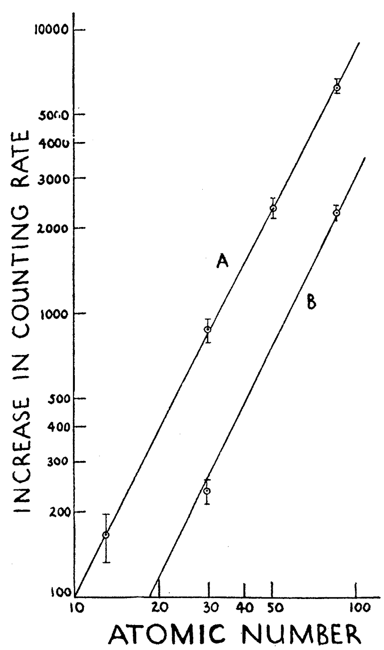

FIG. 4. Increase of counting rate, multiplied by atomic weight, for twofold coincidences. Data for curve A obtained with counters 1 and 3 of Fig. 1. Data for curve B obtained with arrangement of Fig. 5.

terials lead to the conclusion that the effectiveness of the various atoms in their contribution to the increase in counting rate varies quite closely as the 2.0 ± 0.2 power of the nuclear charge.

4. Shower Production as a Function of Thickness

A comparison of the two curves shown in Fig. 2 at the abscissa corresponding to lead shows the surprising result that at $Z=82$ the ordinate of A has a value much more than twice that of B which corresponds to the smaller thickness. This fact has already been referred to in a previous note.[4] These data raise the question as to whether or not the contribution of a given thickness of material to the increase in counting rate is a function of the material above it. In this connection it is therefore of some interest to compare the increase in counting rate due to the second 0.29 cm lead equivalent of material placed above the counters with that due to the first 0.29 cm. To that end we give in Fig. 6 a plot of the ratio, R, which we define as the observed difference in counting rate $(\Delta(0.58)-\Delta(0.29))$ divided by the increase $\Delta(0.29)$, the contribution from the first increment in thickness. If the contributions measured in this way were equal, one would expect a constant ratio of unity. The points shown in Fig. 6 indicate, however, that this ratio increases with Z from a value of approximately unity for the elements of small Z to approximately three in the case of lead. While the probable error is necessarily large in such treatment of data the departure

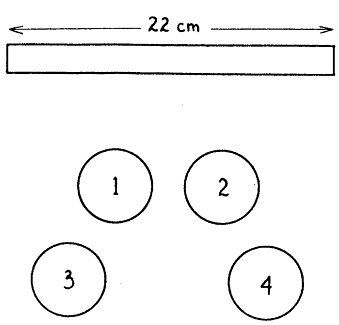

FIG. 5. Experimental arrangement for study of twofold coincidences.

[4] J. E. Morgan and W. M. Nielsen, Phys. Rev. **48**, 773 (1935).

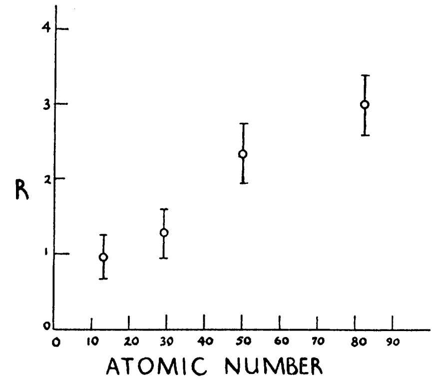

FIG. 6. Ratio R as a function of atomic number.

from unity for the heavy elements would seem to be quite definite.

While there is no doubt that the absorption of shower particles plays some part in the quantitative nature of the results obtained, it appears that it is not of sufficient importance to modify the conclusions arrived at from these data.

Our work on the absorption of shower particles will be discussed in detail in the next section. At this point we refer to the results of these experiments only insofar as they have a direct bearing on the conclusions of this section.

It is shown both in our own and in other work on the absorption of cosmic-ray shower particles that over the region of 0.0 to 0.5 cm the absorption is approximately exponential. Our work is also in agreement with that of others in showing that the coefficient of absorption per gram/cm^2 of the material in question is less for the lighter elements. Experiments also indicate that shower particles which have their origin in elements of smaller atomic number are more penetrating, that is, have a smaller value of the coefficient of absorption.

There are three possible ways in which the values of R may be affected by absorption. We propose to discuss them in order.

We first consider the absorption of shower particles in the material in which they are produced. It is quite obvious from geometrical considerations that any correction for such absorption must be of such a kind as to increase the ratio R. It is also clear from a consideration of the absorption coefficients given in the next

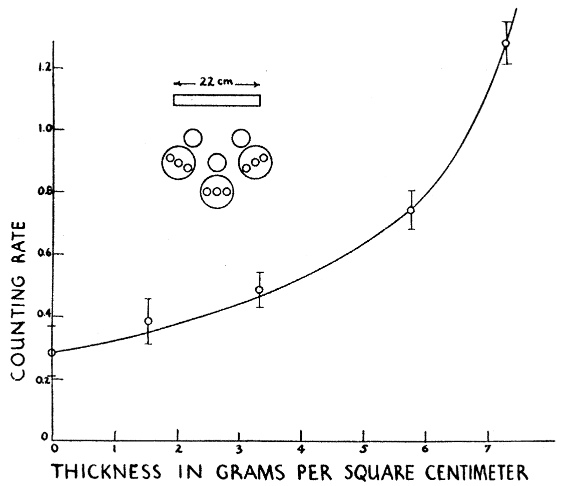

FIG. 7. Experimental arrangement and data for variation of the rate of occurrence of showers of at least three particles as a function of lead thickness.

section that such corrections will be larger for elements of higher atomic number.

We turn next to the absorption of the so-called background. If one assigns a coefficient μ per cm of material to the absorption of shower particles effective in the discharge of the counters it can be shown that the corrected value of R takes on the form

$$\frac{\Delta(0.58)-\Delta(0.29)+N_0(e^{-0.29\mu}-e^{-0.58\mu})}{\Delta(0.29)+N_0(1-e^{-0.29\mu})}$$

where N_0 represents the background count. Rossi[5] using an arrangement (Arrangement II of his paper) essentially the same as that shown in our Fig. 8*b* was unable to determine any absorption. In fact, for some thicknesses his results indicate an increased counting rate, presumably because of the presence in the background of particles which are capable of causing new showers.

Arguments will be presented in the next section which indicate that arrangements such as shown in Fig. 8*b* give values of the coefficient of absorption which are too high. For the present, it is of interest to take a value of 1.2 per centimeter of lead, suggested by the results of Zeiller with arrangement *b* of Fig. 8 without the "Trennwand." We have multiplied the value of 0.8 per cm of lead as obtained by Zeiller by 3/2 in an attempt to correct for the difference between 3- and 2-fold shower coincidences. There is evidence[6] that showers originating in light material are more penetrating, so there is the possibility that we are here using too large a value for the coefficient of absorption. Substituting the values of 6.95, 1.74 and 5.95 for $\Delta(0.58)$, $\Delta(0.29)$ and N_0 in the above corrected expression for R we obtain a value of about 1.9.

To test still further this departure from linearity in the shower contribution from different layers of producing material of high atomic number we have also measured triple coincidences using the arrangement shown in Fig. 7, in which at least three particles from the lead are necessary to give a count. The experimental data obtained with this arrangement are plotted in the curve of Fig. 7. One of the important features of this curve is that the increase due to the lead is much larger compared to the background than in the former arrangement. The increase in counting rate for the two thicknesses, 7.6 g/cm^2 and 3.35 g/cm^2 are 1.0 and 0.21 counts per hour, respectively. The ratio R as previously defined has then a value of approximately four while the ratio of the two thicknesses is approximately 2.3. If we take the same value of μ as used previously the corrected value of R has the value 2.9. If we make the extreme and unlikely assumption that all of the background is absorbed in the first 3.35 g/cm^2 of lead the ratio would be 1.6. It is quite apparent that if the absorption of the background were a critical factor in our qualitative estimates of the ratio R, one would expect a marked dependence on the magnitude of the so-called background.[7] This fact, together with other considerations previously noted, points to the definite conclusion that the increase in counting rate associated with a given thickness of producing material is for small thicknesses of lead very definitely a function of the thickness of lead above it. From Fig. 6 one would infer that this increased contribution to the counting rate from the second

[5] B. Rossi, Zeits. f. Physik **82**, 151 (1933).

[6] J. A. Priebsch. Zeits. f. Physik **95**, 102 (1935).

[7] It is clear from an inspection of Fig. 1 and Fig. 7 that the absorption of the background is of greater importance in the latter case. This follows because in the former arrangement some of the background counts are very probably caused by particles which do not pass through the region occupied by the producing material. We would therefore not expect the corrected values of R obtained in the two experiments to agree with each other but only regard the departure from unity as of significance.

increment of material decreases with decrease in atomic number.

Finally, it is necessary to say a word about the absorption of the so-called shower producing radiation. It is customary in discussing the Rossi transition curve to postulate such a producing radiation and to assign absorption coefficients to it. In any case, the intensity of such producing radiation would normally be expected to decrease with depth beneath the top of the slab of material. On such a view one would therefore expect a decreased contribution from the second or lower layers of material. The point involved here would seem to be whether or not there is a unique cosmic-ray shower producing radiation. Our results would indicate that any such shower producing radiation must undergo modifications, either in quality or in intensity, of such a kind as to increase the recorded coincidences from the second increment of thickness.

5. The Absorption of Shower Particles

Our experiments on absorption of shower particles have extended over a number of different geometrical arrangements and cover most of the elements under investigation in this paper.

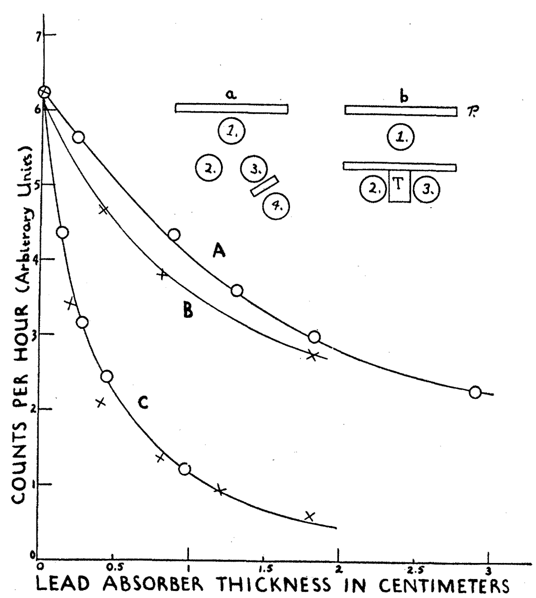

Fig. 8. Arrangements for and data of absorption measurements. Curve A represents our data using arrangement a. Curve B represents plot of Zeiller's data using arrangement b without "Trennwand." Crosses and circles on curve C represent Zeiller's and our observations, respectively, using arrangement b with "Trennwand."

We give at a in Fig. 8 the arrangement used in our earlier attempts. The results obtained with this arrangement are shown in the curve A of Fig. 8. A semi-log plot of these data indicates that the absorption in the first 5 mm is approximately exponential, the coefficient of absorption being 0.47 per centimeter of lead. It is of interest to compare this curve with some work of Zeiller[8] the arrangement and data of which are shown in Fig. 8 at b and B, respectively. From data obtained from his plotted curve without Trennwand T (curve B of Fig. 8) we have computed an absorption coefficient of 0.8 per centimeter of lead. The difference between this value and that given by our own data is about what one might expect from Zeiller's results on the absorption of two and threefold showers. In our case only one counter is shielded by absorbing lead, whereas, in the case of Zeiller both lower counters are shielded. Zeiller has also presented an absorption curve obtained with the Trennwand T in place as indicated. We have multiplied his data by a constant factor and plotted it on curve C of Fig. 8. Our data obtained by the use of an identical arrangement are also plotted on this curve. Both sets of data are in very good agreement. Our results lead to a coefficient of absorption of approximately 3.2 per centimeter of lead. The marked difference between the absorption coefficients obtained with and without the Trennwand in place is interpreted by Zeiller[8] and Geiger[1] as indicating that radiation from the plate P ejects secondary radiation (D radiation in the nomenclature of Geiger) from the absorbing plate as it passes from counter 1 towards counter 2 or counter 3. The presence of the Trennwand then results in a reduction of the number of coincidences which can occur when it is not placed between the lower counters. Zeiller has also plotted the difference between the curves obtained without and with the Trennwand in position. This curve shows a saturation value at a thickness of about 0.5 cm as do the so-called backward scattering curves.[1] It is of some importance that using an arrangement as in a of Fig. 8 we have obtained results which are of the same general character as those obtained by Zeiller without the Trennwand for, if it be true that the differences between curves

[8] O. Zeiller, Zeits. f. Physik **96**, 121 (1935).

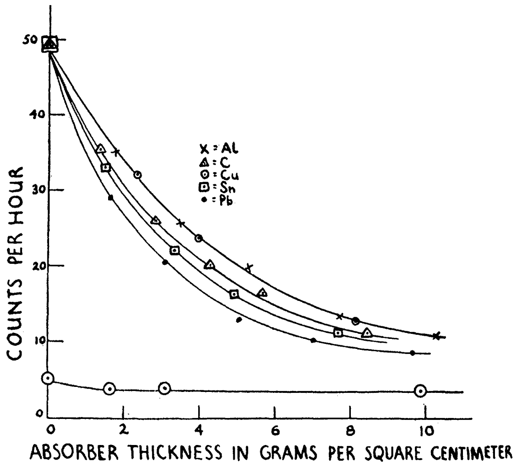

FIG. 9. Absorption in various elements of showers produced in lead. The lower curve corresponds to the absorption of the background. (Symbols for carbon and copper data should be interchanged.)

A and *C* are due to a secondary radiation (*D* radiation) then it seems reasonable to assume that this same radiation is also effective in the discharge of our counters. From the geometry of our arrangement this implies that a part of this *D* radiation is scattered in the backward direction.[1] It would also seem that if one were to correct in a detailed manner the data presented in previous sections of this paper for shower absorption such corrections would have to be made using coefficients of absorption obtained by the use of arrangements in which such secondary *D* or other radiation contributes to the counting rate as in the actual experiment.

We have already referred to our measurements of the absorption coefficient of lead showers in lead using an arrangement similar to that of Zeiller.[8] Using the same arrangement we have also measured the absorption coefficient of copper showers in copper and aluminum showers in aluminum with the results indicated in Table II. We have also made similar measurements on the absorption of lead showers in carbon,

TABLE II. *Coefficients of absorption of showers generated in various materials. In all cases the coefficients refer to absorption in the same element as producing material.*

Producing and Absorbing Material	μ (cm^{-1})	μ (cm^2/g)
Lead	3.2	0.28
Copper	2.4	.27
Aluminum	.54	.20

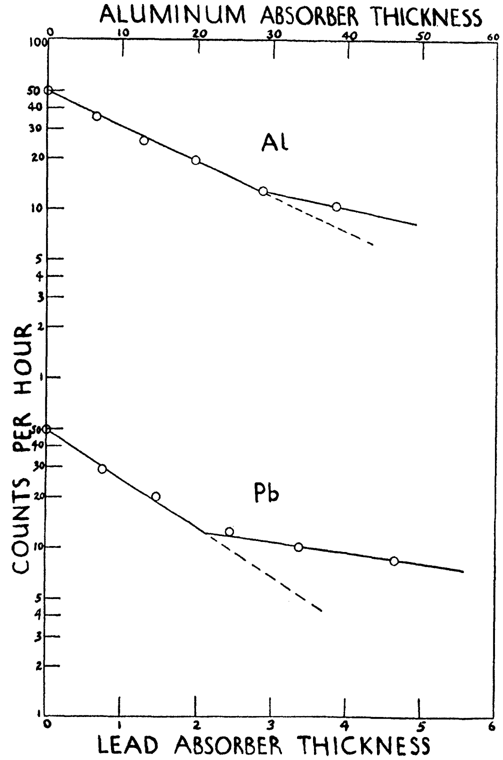

FIG. 10. Logarithmic plot of lead and aluminum data of Fig. 9. The abscissae are proportional to the absorber thickness in g/cm² divided by the atomic weight of the element concerned.

aluminum, copper, tin and lead. The absorption data are plotted in Fig. 9. A semi-log plot of the data for lead and aluminum is shown in Fig. 10. The abscissae here are proportional to the number of atoms in question per unit area of absorbing material. As previously noted by others[8] such plots indicate a more penetrating type of radiation in addition to the softer radiation represented by the initial approximately linear decrease.

In Fig. 11 we have plotted the absorption coefficients of the less penetrating showers as a function of atomic number. Our results indicate that the absorption coefficient of such shower particles varies with a power of *Z* between the first and second. A similar conclusion follows from a less extensive series of measurements of Woodward.[9] The straight line drawn in Fig. 11 has a slope corresponding to the 1.4th power of *Z*. The point for carbon indicates, however, that for

[9] R. H. Woodward, Phys. Rev. **49**, 711 (1936).

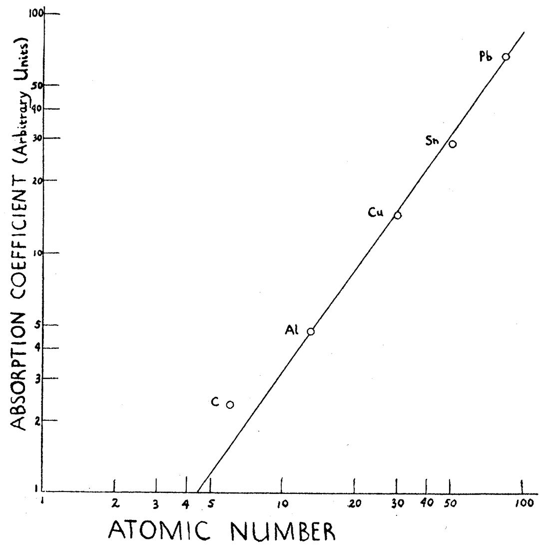

FIG. 11. Absorption coefficient as a function of atomic number of absorber.

elements of low atomic number the dependence upon Z is not as high as this.

6. Rossi Transition Curves in Lead, Iron and Aluminum

The Rossi transition curves of lead, iron and aluminum have been the subject of several investigations. Our measurements on iron and aluminum have apparently been carried to larger thicknesses than heretofore. The curves shown in Fig. 12 were obtained with an arrangement shown in the inset. In the case of lead and aluminum the producing blocks were 660 square centimeters in area while the results for iron are for a producing block of 22.9 cm×38 cm area. In adding successive layers, the position of the lower layers remained fixed in all cases. The positions of the first maxima for lead and iron are in agreement with the results of previous investigations. Our results for aluminum show a broad maximum at a thickness of approximately 75 g/cm^2. This is considerably greater than observed by Fünfer, presumably because of the presence of extraneous scattering material in his experiments.[10] The relative positions and magnitudes of the maxima in the cases of lead and aluminum are apparently in fair agreement with the theoretical calculations of Oppenheimer.[11]

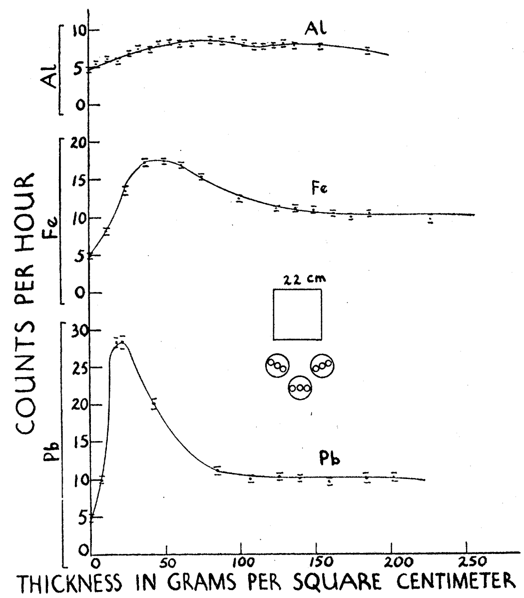

FIG. 12. Rossi transition curves for lead, iron and aluminum.

The transition curve for iron at the larger thicknesses does not decrease as rapidly as it does near the thickness of maximum counting rate. The interpretation of similar observations with lead has been associated with the presence of a second maximum in the transition curve.[12] This feature of the Rossi transition curve will be discussed in a future contribution from this laboratory.

We wish to thank Mr. Roy A. Hunt of the Aluminum Company of America for providing the necessary aluminum in this investigation. We are also indebted to the Research Council of Duke University for providing funds with which to carry out this work.

[10] E. Fünfer, Zeits. f. Physik **83**, 92 (1933).
[11] J. R. Oppenheimer, Phys. Rev. **50**, 389 (1936).
[12] M. Ackermann, Zeits. f. Physik **94**, 303 (1935); J. N. Hummel, Naturwiss. **22**, 170 (1934); H. Kulenkampff, Physik. Zeits. **22**, 785 (1935); R. H. Woodward, reference 9.