for smaller bursts with increasing lead, while the ratios for the larger bursts remain sensibly constant.

The variation of total burst frequency with thickness of lead at different altitudes is shown by the curves of Fig. 3. They are of the form of transition curves, and in general shape similar to those for showers as obtained with counters. The set of curves of Fig. 4 are for the different burst groups at Mt. Evans. While the maxima cannot be located exactly, they definitely shift to greater lead thicknesses for the larger sized groups. This is in agreement with the findings of Carmichael,[8] and also with those of Nie[9] who observes the maxima for large bursts to occur at 5 cm lead. Carlson and Oppenheimer[10] show on the theory of multiplicative showers that this shift is to be expected. Bhabha and Heitler[11] also predict a similar shift.

[8] H. Carmichael, Proc. Roy. Soc. **A154**, 223 (1936).
[9] H. Nie, Zeits. f. Physik **99**, 776 (1936).
[10] J. F. Carlson and J. R. Oppenheimer, Phys. Rev. **51**, 220 (1937).
[11] H. J. Bhabha and W. Heitler, Proc. Roy. Soc. **A159**, 432 (1937).

In Table III are given the ionizations contributed by all bursts greater than 10 rays to the total observed ionizations given in I.[1] No extrapolation can be made to smaller showers and hence no estimate can be made of the total contribution of the shower phenomena to the total ionization. Since the values of the tables are lower limits, the actual ionization produced by showers is an appreciable fraction of the total.

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Shower Production Under Thick Layers of Various Materials*

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Observations by G-M counters are reported on showers from lead and iron up to thicknesses of approximately 600 g/cm². As previously noted by others, the transition curves at large thicknesses have approximately the same slope as absorption curves obtained for the general cosmic radiation. Data are presented for the iron-lead and lead-iron transition curves beginning at a material thickness of 274 g/cm² in each case. For the iron-lead transition curve, the number of coincidences increases and attains a maximum in approximately 1 cm of lead, after which the counting rate decreases and finally falls on the air-lead transition curve. For the lead-iron transition curve, the number of coincidences decreases for the first increments of added iron, passes through a minimum and then increases to the air-iron transition curve. It is pointed out that the observations are consistent, in a qualitative way, with the multiplicative theory of the origin of cosmic-ray showers provided one assumes that additional shower producing radiation is generated in the lower layers of material.

THE application of the laws of radiation of high speed electrons and of the production of pairs by quanta has recently led to a fairly complete description of a portion of cosmic-ray shower phenomena. It has been shown[1, 2] that the multiplication theory is capable of accounting in a fairly satisfactory way for showers produced under relatively small thicknesses of material.

* A preliminary report on these experiments was presented at the Chapel Hill-Durham meeting of the American Physical Society, February 1937.

[1] J. F. Carlson and J. R. Oppenheimer, Phys. Rev. **51**, 220 (1937).
[2] H. J. Bhabha and W. Heitler, Proc. Roy. Soc. **159A**, 432 (1937).

The theory is, as yet, unable to account for showers produced under large thicknesses of material and no mechanism is provided for the transmission of the energy represented by such showers through the atmosphere and through large thicknesses of other absorbing material.

Evidence has recently[3, 4] been presented for the existence of a penetrating particle, the properties of which do not seem to be described by the usual properties of electrons in the same energy range. It is the purpose of the present paper to present data, which, while they give no information as to the mechanism by which the cosmic-ray energy is transmitted through large thicknesses of material, do indicate that there are no essential differences between the showers produced under large and small thicknesses of matter.

One of the essential tests of any theory of cosmic-ray showers is that it be capable of accounting for the transition curve. The iron-lead and lead-iron transition curves here presented afford additional evidence for the multiplication theory and indicate furthermore that showers produced under thick layers of producing material are generated in multiplication processes quite similar to those which are associated with the soft component.

The Air-Lead, Air-Iron, and Iron-Lead Transition Curves

Measurements on the frequency of showers were made by recording the number of four-fold coincident discharges in G-M counters arranged as shown in the inset of Fig. 1. With this arrangement the passage of a minimum of two particles through the counters is obviously necessary to cause a coincident discharge in all four counters. The separation of counters and their position with respect to the material is shown on the figure which has been drawn to scale. Sheets of material each 22 cm×30 cm were placed as indicated, the length being parallel to the axis of the counters.

The data shown in Fig. 1 were obtained about a year ago in a light wooden frame structure near the top of Beech Mountain at an altitude of approximately 4500 ft. The air-lead transition curve which is represented by the filled circles shows a maximum at approximately 20 g/cm² of lead. The air-iron transition curve which is represented by the open circles shows a maximum

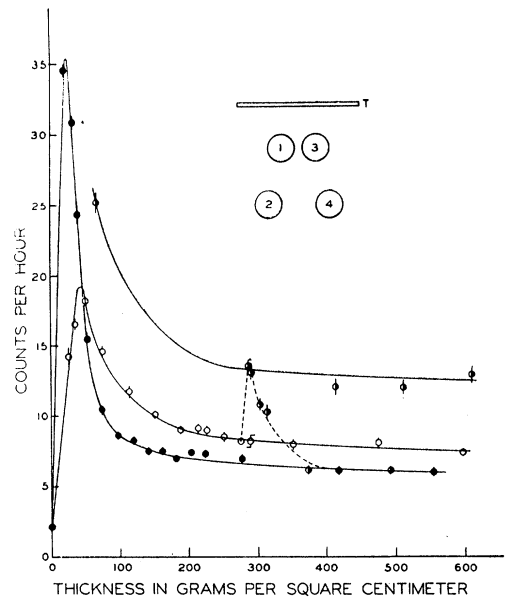

Fig. 1. The frequency of coincidences as a function of material thickness. The data shown by filled circles are for lead, those shown by unfilled circles are for iron. The dashed curve represents the iron-lead transition under 274 g/cm² of iron. The upper curve, shown with half-filled circles, represents the data for various iron thicknesses with a constant lead thickness of 13.12 g/cm² underneath the iron.

at approximately 47 g/cm² of iron. In all cases where the probable errors are larger than the diameters of the circles, they are represented by vertical lines. The relatively small decrease in counting rate in both curves for the larger thicknesses of material has been noted before by a number of investigators[5–8] and is associated with a more penetrating component of cosmic radiation.

While the interpretation of showers on the multiplication theory does not treat the phenomena in such a way that one can assign absorption coefficients to the right-hand side of the transition curve, it is nevertheless of interest to compare the shape of this portion of our curves with the data of Auger and his co-

[3] J. C. Street and E. C. Stevenson, Phys. Rev. **51**, 1005 (1937).
[4] Seth H. Neddermeyer and Carl D. Anderson, Phys. Rev. **51**, 884 (1937).
[5] M. Ackermann, Zeits. f. Physik **94**, 303 (1935).
[6] J. N. Hummel, Naturwiss. **22**, 170 (1934).
[7] H. Kulenkampff, Physik. Zeits. **36**, 785 (1935).
[8] R. H. Woodward, Phys. Rev. **49**, 711 (1936).

workers[9] on the absorption of the general cosmic-radiation as measured by three G-M counters placed in a vertical line. In such a comparison we find it convenient to compute the slopes of the data on semi-logarithmic plots which roughly fall on portions of two straight lines. The calculated slopes are for lead 0.0302 cm^2/g and 0.0006 cm^2/g. The corresponding values for iron are 0.0072 cm^2/g and 0.00044 cm^2/g. The coefficients for the data at large thicknesses indicate, as is obvious from inspection of the curves, that the shapes of the transition curves of lead and iron are quite similar for large thicknesses of producing material.[10] It is of some interest to point out that the coefficients for lead, found in this way, are quite closely the same as those observed by Auger and his co-workers. The corresponding coefficients obtained by them in the work referred to above are 0.030 cm^2/g and 0.0007 cm^2/g. The close correspondence between the shape of the transition curve and the absorption of the general cosmic-radiation has also been noted by Clay.[11]

The dashed curve of Fig. 1 connecting the half-filled circles represents the transition from iron to lead. It is important to observe that this transition begins at an iron thickness equivalent to 274 g/cm^2 of iron, a thickness of material which is usually regarded as being sufficient to remove a large percentage of the soft component of the shower producing radiation. The full line connecting some of the half-filled circles represents the counting rate for various thicknesses of iron with a constant thickness of 13.12 g/cm^2 of lead underneath. One would infer from this curve that the iron-lead transition curve at 274 g/cm^2 would be duplicated in its essential features for other iron thicknesses out to a thickness of 600 g/cm^2, the maximum iron thickness employed. The data for the point with wings were obtained by placing 13.12 g/cm^2 of lead above the 274 g/cm^2 of iron instead of below it.

[9] P. Auger, L. LePrince-Ringuet and P. Ehrenfest, Jr., J. de phys. **7**, 58 (1936).

[10] The coefficients when expressed in terms of the number of electrons per cm^3 indicate a variation with the first power of Z. The accuracy of such determinations is not high and it is therefore necessary to regard this as a rough approximation.

[11] J. Clay, A. Van Gemert and J. T. Wiersma, Physica **7**, 627 (1936).

The success of the multiplication theory in accounting for the phenomena at small thicknesses of producing material makes it desirable to examine the observed transition curve in the light of that theory even though it is unable to account for the penetration of the particles considered in that theory through large thicknesses of matter.

According to the multiplication theory of cosmic-ray showers initiated by particles of electronic mass or by quanta, the number of particles in a shower increases by successive radiation of quanta and pair production. This process continues until the probability of energy loss by electrons through ionization becomes comparable to the probability of energy loss by radiation. The maxima in the transition curves are to be associated in a rough way with the energy for which the probabilities of these two methods of energy dissipation are of comparable magnitudes.

According to Bethe and Heitler[12] the ratio of the energy loss by radiation to that by ionization is given approximately by the ratio

$$EZ/1600\ mc^2,$$

where E denotes the energy of the electron or positron, Z represents the atomic number of the element considered, and the other symbols have their usual meaning. This implies that the multiplication of a shower will continue to a lower energy in lead than in iron.

The increase in the counting rate for the first increments of lead in the iron-lead transition curve are, on this theory, to be associated with the fact that the shower particles which come from the iron are more effective in producing new showers in lead than they would be if they were to penetrate additional iron. We would also expect on this theory that the maximum in the iron-lead transition curve would come at a smaller value of lead thickness than in the air-lead transition curve. Our data indicate that the former occurs at a lead thickness of approximately 1 cm and as already noted the latter occurs at a thickness of about 2 cm of lead. These results are then in qualitative agreement with the multiplication theory.

[12] H. Bethe and W. Heitler, Proc. Roy. Soc. **146A**, 83 (1934).

THE LEAD-IRON TRANSITION CURVE

Observations on the lead-iron transition curve were made at Hickory, North Carolina, at an altitude of approximately 1200 feet. The data shown in Fig. 2 were obtained by counting coincidences with the same apparatus, counter, and material arrangements as shown in the inset of Fig. 1. We have also indicated the air-lead and air-iron transition curves observed at this elevation. The dashed curve of Fig. 2 represents the transition from lead to iron beginning with a thickness of approximately 274 g/cm^2 of lead. The important features of this curve are the initial decrease in the counting rate for the first increments of added iron, followed by the later rise and complete recovery to the air-iron transition curve.[13]

It is of interest to discuss this curve also in the light of the multiplication theory. As in the former case, we must assume that the particles which are responsible for the penetration of cosmic radiation through large thicknesses of matter generate high energy particles of electronic mass or photons[14] and that such secondary particles generate showers by the usual multiplicative processes. The decrease in the observed number of coincidences for small layers of iron (0–15 g/cm^2 approximately) beneath the lead is interpreted to mean that the showers from the lower layers of lead decrease in size when they pass into iron.[1] One would expect that the energy of such showers would more likely be dissipated by ionization processes in the iron. The increase in the observed number of coincidences for material thicknesses greater than approximately 290 g/cm^2 must be due to the production of shower producing radiation in the added layers of iron. Two important factors very probably associated with this increase are the rate at which such secondary particles are generated, and the thickness of matter traversed before their energy is dissipated in a shower. It would seem plausible to assume[10] that the

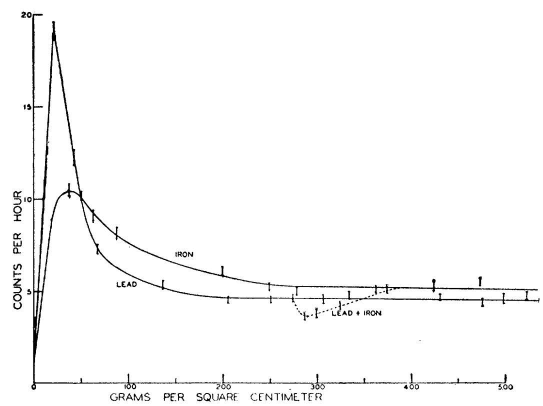

FIG. 2. The frequency of coincidence as a function of material thickness. The dashed curve represents the lead-iron transition under 274 g/cm^2 of lead.

number of such shower producing particles generated in the same atomic thickness by the penetrating component varies approximately as Z. On the other hand, showers multiply much faster in lead than in iron. It is probable that the longer mean free paths of shower electrons in elements of smaller atomic number more than compensate for the difference in the number of shower producing particles generated in the same atomic thickness. In this way, the intensity of the shower producing radiation increases, and, as the data show, the frequency of coincidences increases with increase in iron thickness to a point characteristic of the air-iron transition curve.

It would appear that all of the results here presented can be interpreted in a qualitative way on the multiplication theory of cosmic-ray showers provided one assumes that particles which are capable of producing showers are generated at large depths of material by the penetrating component of the cosmic radiation.

We are indebted to the Research Council of Duke University for a grant which has made this work possible.

[13] This curve is similar to ionization curves observed by H. Schindler, Zeits. f. Physik **72**, 625 (1931). The fact that such a curve is observed for showers is a point of considerable interest.

[14] The present experiments give no information on certain specific properties of the penetrating component. Thus for example, the data are not inconsistent with the assumption of a decrease in the probability of radiation loss by particles of electronic mass at very high energies although other considerations [L. W. Nordheim, Phys. Rev. **51**, 1110 (1937)] suggest that the radiation theory for electrons and quanta may be valid at high energies.