IL NUOVO CIMENTO Vol. VIII, N. 4 1 Aprile 1951

The Transition Effect of Extensive Air Showers.

D. D. Millar

Dublin Institute for Advanced Studies

(ricevuto il 12 Febbraio 1951)

Summary. — Measurements have been made of the transition effect of the extensive air showers of cosmic rays in absorbers of lead, iron, carbon and water. The results indicate that the photons of the showers are predominantly of lower energies than are the electrons, and forms of the energy spectra for the two components incident on the counter trays are deduced. The discrepancy between the absorption of the showers in air and in local absorbers of similar atomic weight, such as carbon and water, is briefly discussed.

Introduction.

Investigation of the absorption of the extensive air showers has been concerned mainly with the penetrating component of the showers, measurements of the intensity being made under absorbers of high atomic number and thicknesses of several cascade units. Daudin and Fréon [1] have, however, measured the increase in counting rate produced by the effects of pair production by incident photons in the absorber when their counters were shielded with 4 mm of lead. Similar observations of the transition effect of the extensive air showers have now been made using absorbers of lead, iron, carbon and water.

[1] J. Daudin and A. Fréon: *Compt. Rend.*, **214**, 662 (1942).

The Experimental Arrangement.

Coincidences were recorded between three trays of counters, each of area 750 cm², situated at the vertices of a triangle of side 4 metres. The counters of each tray were enclosed in a thin aluminium box, 1.5 mm thick, and immediately above each was a layer of wood, 9 mm thick resting on carbon which supported the absorber (fig. 1). This remained in position throughout the experiment. Measurements of the counting rates with the various absorbers in position were alternated with measurements of the rate without absorber, the consistency of the unshielded rate together with daily testing affording a check on the correct functioning of the apparatus.

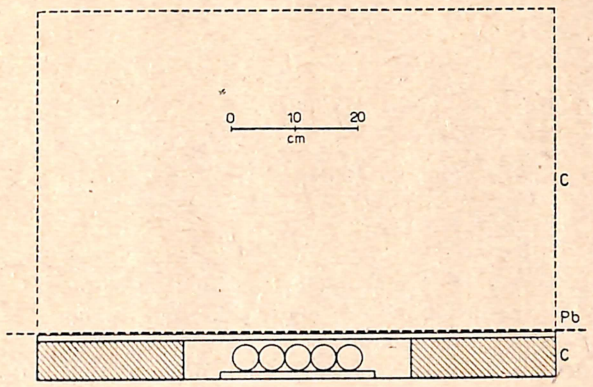

Fig. 1. – Counter tray with absorbers of full cascade unit of carbon, and of lead, in position.

In the case of water, the absorber was contained in open tanks of aluminium, 1.5 mm thick, and these were left in position above the trays while observations with and without water were being made. The unshielded rate with the additional aluminium of the tanks above the trays is given in Table I, from which it will be observed that the presence of the aluminium makes no significant difference to the unshielded rate. The unshielded rate with tanks in position was, however, used in the case of water in evaluating the function ρ occurring in the last line of the table. The carbon absorber was in the form of coal consisting of 80 % carbon, 7 % hydrogen and the residue presumably of atomic number comparable with that of silicon.

Geometry of the Arrangement.

In comparing the effects of the different absorbers on the counting rate equivalent thicknesses measured in cascade units were employed. Due to differences in the length of the cascade unit and in the densities of the various absorbers the geometry of the arrangement does not remain constant but alters from one absorber to another. In all cases, however, wide angle coverage was ensured by making the area covered by the absorber large compared

with that of the counter trays. This being so the effects of scattering in the absorber can be neglected and any dependence of the counting rate on the geometry of the arrangement may be attributed to the fact that a thick absorber will provide a larger effective collecting area than a thin one due to the spreading out of secondary showers originating in the absorber. The probability for such showers to be produced will be small in the thick absorbers of carbon and water, in which the critical energy is high, and since thicknesses not exceeding one cascade unit of these absorbers are used. With the absorbers of lead and iron, where production of secondary showers is more likely than with water and carbon, the absorbers are placed directly above the counters in order to minimise the effects of geometry, and are not spaced out above the trays to correspond to the spatial distribution of the carbon and water absorbers.

Barometer Correction.

The counting rates were corrected for barometric fluctuations using a barometric coefficient of -11% per cm Hg ([2]). It will be seen from Fig. 2 where

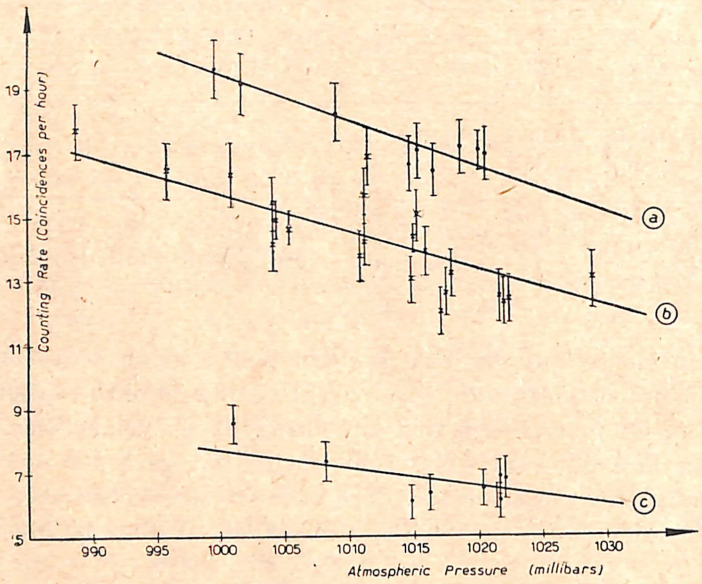

Fig. 2. – Counting rate as function of barometric pressure. The straight lines correspond to a barometer coefficient of -11% per cm Hg.
a) 1 cascade unit Lead; *b*) No Shielding; *c*) 1 cascade unit Carbon

([2]) D. D. MILLAR: *Proc. Roy. Ir. Acad.*, A **54**, 115 (1951).

the individual readings of the counting rates are plotted against barometric pressure for the cases with no absorber, and with a full cascade unit of lead, and of carbon, above the trays, that such a value is in good agreement with the observed barometer effect.

Results.

The counting rates obtained with the different absorbers above the trays, corrected to the mean atmospheric pressure over the whole series of readings, are given in Table I, together with the unshielded rate.

TABLE I.

Absorber	H_2O	C	C	Fe	Pb	Pb	Pb	Pb	Pb
Thickness g/cm²	22	26	52	14	3.0	6.0	12	18	24
Cascade units	.5	.5	1	1	.5	1	2	3	4
Shielded rate R_s (coincidences/hr)	9.37 ±.22	8.96 ±.22	6.88 ±.17	13.19 ±.27	16.91 ±.25	17.44 ±.27	16.52 ±.43	13.64 ±.46	12.31 ±.52
Unshielded rate R_0 (coincidences/hr)	14.02 ±.25	14.09 ± .20							
$\rho = \left(\frac{R_s}{R_0}\right)^{2/3}$	0.764 ±.015	0.740 ±.014	0.620 ±.012	0.957 ±.016	1.130 ±.016	1.153 ±.016	1.112 ±.022	.968 ±.024	.914 ±.027

The coincidence rate between a number of counter trays of area S is known to be proportional to S^γ, where γ is the exponent of the density spectrum and is ~ 1.5. It follows then that any change in the coincidence rate caused by shielding the counter trays may conveniently be regarded as due to a change in the effective areas of the trays. The ratio of the effective area in the presence of shielding to the area without shielding will then be given by

$$\rho = \left(\frac{R_s}{R_0}\right)^{1/\gamma} = \left(\frac{R_s}{R_0}\right)^{2/3},$$

where R_s and R_0 are the counting rates with and without absorber respectively. Values of ρ for the various absorbers are also given in Table I and are plotted as a function of absorber thickness in fig. 3.

The Transition Curves.

From Fig. 3 it will be observed that the transition curve for lead shows an initial increase in the value of ρ with increasing thickness up to a maximum

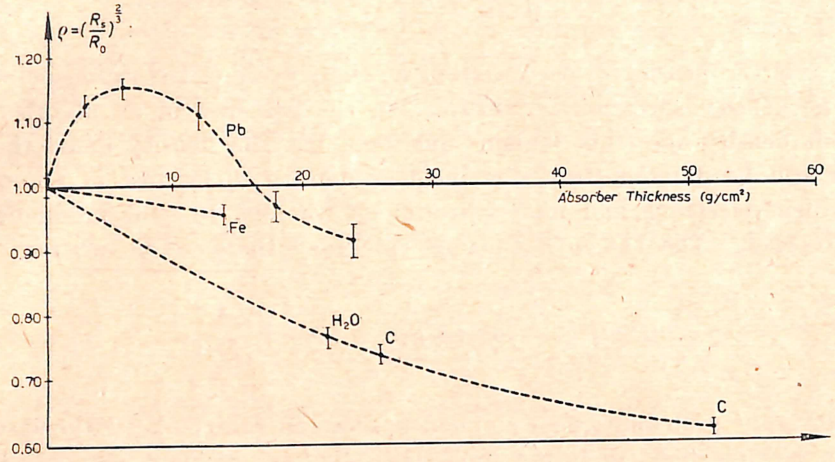

Fig. 3. – The Transition Curve.

in the region of one cascade unit, at which thickness the effect of such shielding on the counting rate is equivalent to an increase of 15% in the area of the unshielded trays. The other absorbers produce no such maximum and ρ decreases with increasing thickness. The absorption becomes stronger with decreasing atomic number of the absorber. Such an effect is readily explained in terms of incident photon-electron showers. The initial rise in the case of lead is due to the increase in probability with thickness for pair production by incident photons, and the increase in intensity due to this effect up to the maximum, corresponding to the mean free path for radiative collision by photons, outweighs the decrease in intensity due to absorption of incident electrons. Absorption of the incident and secondary electrons, the latter produced by photons, gives rise to the subsequent decrease. With the absorbers of iron, water and carbon, the decrease in intensity due to absorption of incident electrons is greater than the increase due to pair production by photons, and the contribution from the latter effect becomes smaller, as is to be expected, with decreasing atomic number.

Discussion.

It is well established that the coincidence rate for three counter trays of area S can be represented by

$$R_0\alpha \int_0^\infty (1 - \exp[-Sx])^3 \frac{dx}{x^{\gamma+1}},$$

where x is the density of the electrons at the trays and the exponent of the incident density spectrum is $\gamma \backsimeq 1.5$. In the presence of an absorber the incident density spectrum remains unaltered but the density under the absorber will be different from the incident density x, because of absorption of incident electrons and materialization of photons by pair production in the absorber. The threefold shielded rate may therefore be written

$$R_s\alpha \int_0^\infty [1 - \exp[-S(Q + rP')x]]^3 \frac{dx}{x^{\gamma+1}},$$

where Q is the probability that an incident electron will penetrate the absorber and so be detected. P is the probability that an incident photon will be detected by pair production in the absorber and r the ratio of photon density to electron density in the incident showers. It thus follows that

$$\rho = \left(\frac{R_s}{R_0}\right)^{2/3} = Q + rP,$$

which is the expression plotted in Fig. 3 as a function of absorber thickness. The quantities Q and rP in this expression will depend upon the forms of the energy spectra of the incident electrons and photons and it is possible to deduce expressions for these spectra from the observed values of ρ.

If it is assumed that the absorption of electrons in the different absorbers is due entirely to ionization loss, i.e. neglecting loss of energy by radiative collisions, and further, that pair production by incident photons in the absorbers of carbon and water is negligible, then the common absorption curve for carbon and water may be taken as giving the absorption per g/cm² of the incident electrons and applied to the case of iron and lead, since ionization loss, within the approximation here involved, may be taken as independent of atomic number. The difference between the curves for iron and for lead and the water — Carbon curve then gives the contribution due to the photons in the first two absorbers. The water-carbon curve can be represented by an exponential with absorption coefficient $-.012 \pm .001$ per g/cm², and subtracting the Q term in relation (3) as given by this exponential from the

observed values of ρ we obtain the following values of rP the contributio due to photons

1/2	cascade unit	lead	$.166 \pm .016$
1	»	» lead	$.224 \pm .017$
1	»	» iron	$.114 \pm .020$

where thicknesses of absorber up to one cascade unit only are considered. This being so, an incident photon will make on average not more than one radiative collision. If this is at the mid point of the absorber the resulting electrons of average energy half that of the parent photon must have energy sufficiently great to survive ionization loss in the remaining thickness of absorber. Thus the cut-off energy is given by βt where t is the thickness in cascade units and β the ionization loss per cascade unit. Assuming the contribution by photons to be proportional to the absorber thickness t, and to the number of incident photons of energy greater than this cut-off energy we then have

$$\begin{aligned} N(E > 3.5 \text{ MeV}) &\alpha .332 \pm .032 \\ N(E > 7 \text{ MeV}) &\alpha .224 \pm .017 \\ N(E > 25 \text{ MeV}) &\alpha .114 \pm .020 \end{aligned}$$

which can be expressed in terms of a photon spectrum

$$N(>E)\alpha E^{-.55 \pm .12}.$$

Similarly the absorption curve for water and carbon can be accounted for in terms of an incident electron spectrum

$$N(>E)\alpha(E + E_c)^{-.64 \pm .06},$$

with $E_c = 114$ MeV the critical energy in air, on the assumption that only electrons above 55 MeV will be recorded under the half cascade unit of water, and above 70 MeV and 140 MeV respectively under the half cascade unit and full cascade unit of carbon.

A more detailed calculation taking into account radiation loss by electrons and using the values of ionization loss as given by HALPERN and HALL [3] results in a spectrum for the electrons with exponent $\gamma = .62$ instead of the above value .64. In the case of the photon spectrum the largest source of error in the above simple derivation arises from the assumption that all photons above the cut-off energy have an equal probability for pair production per cascade unit. Taking into account the logarithmic decrease of this probability with decreasing energy due to the effects of screening [4] and considering only the two cases of the full cascade unit of Lead and

---

[3] O. HALPERN and H. HALL: *Phys. Rev.*, **73**, 477 (1948).
[4] B. ROSSI and K. GREISEN: *Rev. Mod. Phys.*, **13**, 240 (1941).

of iron so that absorption by Compton effect may be neglected above the cut-off energy the exponent of the photon spectrum becomes $\sim .8$ instead of .55 as above.

The theory of electron-photon cascades according to BHABHA and CHAKRABARTY [5] predicts that a primary spectrum of form $N(>E)\alpha E^{-\gamma}$ will result in an electron spectrum $N(>E)\alpha(E+E_c)^{-\gamma}$ at large depths. It appears that the best agreement between cascade theory and observation is obtained if $\gamma \backsimeq 1.5$ [6]. The discrepancy between this value and the value of $\sim .6$ derived above may be attributed to the fact that any counter arrangement such as used here will respond only to particle densities greater than a certain minimum imposed by the finite size of the counter trays. In this case the cut-off density lies between 13 particles per m^2 and 1.3 particles per m^2, i.e. $1/S$ and $1/10S$ [7]. The incident energy spectrum upon the unshielded trays will therefore be biassed against the low energies which occur at the outer fringes of the shower and at the tail end of showers which have become dissipated before reaching the apparatus, where in both cases the density will be low. The above forms of the incident energy spectra cannot therefore be compared directly with the predictions of cascade theory. The same limitation has been noted by MITRA and ROSSER [8] in measuring the energy spectrum of the electrons of the extensive air showers by magnetic deflection of cloud chamber tracks. The energy distribution which they obtain conforms to a spectrum of the above form with exponent $\gamma = 1.1 \pm .3$.

It follows further from the present observations that the density of high energy photons incident on the apparatus is less than that of the electrons of the same energy. This fact is already assumed in the above derivation of the spectra, where pair production in the absorbers of carbon and water was neglected. Reference to the deduced spectra cannot therefore be made, to show that this is in fact the case. If however it is assumed that the ratio of the density of photons to electrons above an energy of 140 MeV, the cut-off energy for the full cascade unit of carbon, is, say, 1 : 4, then the observed value of ϱ in this case ($= .62$) will arise from 52 % of the incident electrons plus a contribution by photons $\sim .13 \cdot 7/9$, since the asymptotic value of the probability per cascade unit for pair production may be assumed. Such an electron contribution will correspond to a spectrum $(E_c/E+E_c)^{\gamma}$ with $\gamma = .81$. The contribution to ϱ by electrons under one cascade unit of lead and of iron can then be deduced from this spectrum and the difference between the observed ϱ

---

(5) H. J. BHABHA and S. K. CHAKRABARTY: *Proc. Roy. Soc.*, A **181**, 267 (1943).

(6) L. JANOSSY: *Cosmic Rays* (Oxford, 1950), Chapt. VIII.

(7) G. COCCONI, V. COCCONI TONGIORGI and K. GREISEN: *Phys. Rev.*, **76**, 1020 (1949).

(8) S. M. MITRA and W. G. V. ROSSER: *Proc. Phys. Soc.*, A **62**, 364 (1949).

and this deduced electron contribution will give the contribution by photons. The values of the photon contribution are then .200 and .104 for lead and iron repectively. But from the assumed density of high energy incident photons alone one expects a photon contribution $.13 \cdot 7/9 = .10$ in both cases. Thus the contribution in the case of iron can be explained entirely by the effects of such high energy photons, while it is clear, comparing the contribution by photons in lead and in iron that an appreciable part of that contribution in lead arises from photons in the range 7 MeV to 25 MeV, the cut-off energies in lead and iron, consequently it is reasonable to assume that in both cases photons of energy lower than 140 MeV must be effective. It can therefore be concluded that the ratio of photon density to electron density above an energy of 140 MeV is certainly less than .25 (and hence that the exponent of the electron spectrum must be less than .8). This is in qualitative agreement with what is to be expected if in general the cascade showers are being detected at a distance of several metres from the shower core ([9]). The electrons detected have been ejected from the core by Coulomb scattering, and since there is no equivalent mechanism for removing photons from the core those which are detected will be secondary to higher energy scattered electrons.

Comparison with Absorption in Air.

The decrease in counting rate obtained on shielding the counter trays with carbon and water can be represented by an exponential coefficient of $-0.018 \pm .001$ per g/cm^2. On the other hand from the altitude measurements of HILBERRY ([10]), and MAZE, FRÉON and AUGER ([11]) and from the observed barometer coefficient of -11% per cm Hg one obtains an absorption coefficient in the atmosphere of ~ -0.008 per g/cm^2. The absorption in carbon and water is therefore much stronger than in air although the atomic numbers and hence the critical energies of these absorbers are all of the same order of magnitude. The explanation lies in the fact that in a local absorber such as here, the absorption is measured of the electrons which have been scattered out of the shower core and these are absorbed by ionization loss. In the case of air on the other hand, the absorption evidenced by altitude and barometer dependence is rather that of the cascade-sustaining core itself from which the outer regions of the shower, the regions which are in general detected, are being continuously replenished, and absorption of this high energy core is determined by the mechanism of the cascade process rather than by ionization loss.

([9]) J. ISE and W. B. FRETTER: *Phys. Rev.*, **76**, 933 (1949).
([10]) N. HILBERRY: *Phys. Rev.*, **60**, 1 (1941).
([11]) R. MAZE, A. FRÉON and P. AUGER: *Phys. Rev.*, **73**, 418 (1948).

A further point in connection with the barometer and altitude dependence of the intensity of the extensive air showers, is the fact that this is due not only to absorption of the showers in air, but also to the effect which change of pressure has on the lateral spread of the showers caused by changes in the length of the cascade unit with density of the air, and this will tend to counteract the effects of absorption.

Acknowledgements.

The author is grateful to Professors L. JANOSSY and C. B. A. MCCUSKER for valuable discussion and criticism and to Dr. D. M. RITSON and Dr. T. E. NEVIN for assistance. He is also indebted to the Sir JAMES CAIRD TRUST for the provision of a scholarship.

RIASSUNTO (*)

Sono state eseguite misure dell'effetto di transizione degli sciami estesi dell'aria in assorbitori di Piombo, Ferro, Carbonio e acqua. I risultati indicano che i fotoni degli sciami sono prevalentemente di energie inferiori a quelle degli elettroni e se ne deducono forme degli spettri di energia delle due componenti incidenti sui telescopi di contatori. Si discute brevemente la discrepanza tra l'assorbimento degli sciami nell'aria e negli assorbitori locali di peso atomico analogo come il Carbonio e l'acqua.

(*) *Traduzione a cura della Redazione.*