On the photon component of cosmic radiation and its absorption coefficient

By L. Jánossy* and B. Rossi†

(*Communicated by P. M. S. Blackett, F.R.S.—Received* 17 *November* 1939)

1. Introduction

It has been established that the soft component of the cosmic radiation consists of electrons and photons. Much experimental data on the electrons forming the soft component are available and they are known to form a fraction of about 25–30 % of the whole beam of ionizing particles at sea level, excluding particles below 10^7 eV (e.g. Rossi 1933; Nielsen and Morgan 1938). The energy spectrum of the electrons is known roughly from the work of Blackett (1938), Wilson (1939) and others. The energy loss of electrons in metal plates has been investigated by Anderson and Neddermeyer (1934), Blackett and Wilson (1937), Williams (1939), Wilson (1938, 1939), showing that the experimental values of the energy loss are in agreement with the prediction of the quantum theory (Bethe and Heitler 1934).

Much less is known about the photon component of cosmic radiation, as comparatively few experiments have been carried out to investigate their properties. Further the results of the investigations available are partly contradictory.

The theory of the absorption of high energy photons has been worked out to the same extent as for electrons (Bethe and Heitler). Owing to the lack of experimental material, the theory could be tested only up to energies of about five million volts (McMillan 1934; Gentner 1935). The success of the theory of cascade showers due to Bhabha and Heitler (1937) and Carlson and Oppenheimer (1937), based on the Bethe-Heitler theory of electrons and photons, provides however an indirect test for the validity of the absorption formula for high energy photons.

The lack of experimental data on high energy photons is due to the difficulties in the method of observation; photons unlike electrons cannot be observed directly.

* John Harling Fellow in Physics at the University of Manchester.

† Fellow of the Society for the Protection of Science and Learning, now at the University of Chicago.

In the present paper a simple method for investigating cosmic-ray photons is described. Using this method, data about the number, energy distribution and absorption of cosmic-ray photons have been obtained.

2. The Experimental arrangement

The experimental arrangement is shown schematically in figure 1 and the dimensions of the counters and of the screens are given in table 1.

The counters were made of pyrex glass, with a copper foil 0·1 mm. thick as cathode and a 0·1 mm. tungsten wire as anode, and were filled with a mixture of argon and alcohol vapour.

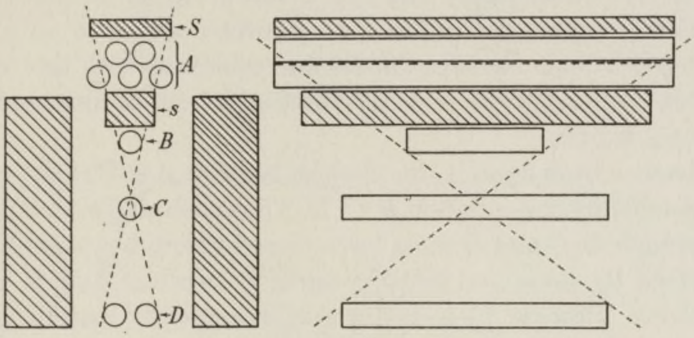

Figure 1. The experimental arrangement.

Table 1

Counters A: 60 cm. long, 3·0 cm. diameter.
Counter B: 20 cm. long, 3·0 cm. diameter.
Counters C and D: 40 cm. long, 3·0 cm. diameter.
Screen s: 60×7 sq. cm.
Screen S: 60×7 sq. cm.

Threefold coincidences between B, C, D, and fourfold coincidences between A, B, C, D, were recorded simultaneously as described in detail by one of us (Rossi 1930). Each of the counters or counter batteries A, B, C and D were coupled respectively to the valves a, b, c and d. The anodes of the valves b, c, d were connected in the usual way and received the anode potential through a common 200,000 Ω resistance R_1. The anode of the valve a was connected through an extra resistance R_2 of 70,000 Ω to the anodes of the other valves. The pulses occurring at that end of R_2 which was connected to R_1 were large whenever A, B, C and D discharged simultaneously, whilst a simultaneous discharge of B, C and D, not accompanied by a discharge of A, produced a smaller pulse at this point. By means of two thyratrons with different grid biases the large and the small pulses could easily be separated.

Since the resolving power of the arrangement was about 10^{-5} sec., the number of threefold or fourfold chance coincidences was less than 1 in 10 hr. and was therefore negligible. The efficiency of the counter battery A, as shown by control experiments, was at least 99 %.

3. The experimental method

The principle of the experiment was to detect the electrons generated by photons in a metal plate. The experiments will be discussed assuming that no non-ionizing agent other than photons occurs to an appreciable extent. It will be seen that the results are consistent with this assumption although the existence of a small fraction of other non-ionizing rays cannot be excluded.

As can be seen from figure 1, the counter battery A covers the whole solid angle subtended by the counters B, C, D. Thus each single ionizing particle passing through B, C and D must have passed through A as well unless (a) it is produced by some non-ionizing agent between A and B, or (b) it is scattered by s. Process (b) seems in our arrangement not to be of great importance. In the present experiments we are therefore mainly concerned with threefold coincidences B, C, D which were not accompanied by a fourfold coincidence A, B, C, D. For brevity threefold coincidences not accompanied by fourfold coincidences are to be termed "anti-coincidences". In an experiment of this kind it is essential to count simultaneously the number N_3 of threefold coincidences and the number N_4 of fourfold coincidences, since the average fluctuation of the small difference $N_3 - N_4$ is $\sqrt{(N_3 - N_4)}$ for the case of simultaneous recording, whereas it is $\sqrt{(N_3 + N_4)}$ when N_3 and N_4 are measured by separate observations. The disturbing effect due to variations of the cosmic-ray intensity is also greatly reduced by simultaneous recording.

4. The transition curve for the showers produced by photons

(a) *The experimental results*

Measurements were carried out with no absorber above the counters A and an absorber of variable thickness between A and B in position s. The various thicknesses of absorber s were placed so that the upper surface was always as close as possible to A.

The experimental results are collected in table 2 and the observed rates of anti-coincidences together with the statistical fluctuations are plotted against the thickness of the absorber s in figure 2. A zero rate of 11·4 anti-coincidences per hour has been subtracted from each value (see § 5a).

TABLE 2. TRANSITION CURVE OF PHOTON INITIATED SHOWERS

s	Threefold coincidences		Anti-coincidences	
cm. Pb	Total	Rate per hour	Total	Rate per hour
0·1	10665	441 ± 4	443	$6·9 \pm 0·9$
0·45	10616	444 ± 4	1064	$33·1 \pm 1·0$
0·8	11369	451 ± 4	1334	$41·6 \pm 1·5$
1·1	20344	446 ± 3	2394	$41·0 \pm 1·1$
1·45	20915	441 ± 3	2218	$35·4 \pm 1·0$
2·15	12405	414 ± 3	1143	$26·9 \pm 1·1$
2·8	19045	418 ± 3	1411	$18·4 \pm 0·8$
5·1	16703	366 ± 3	770	$5·4 \pm 0·6$

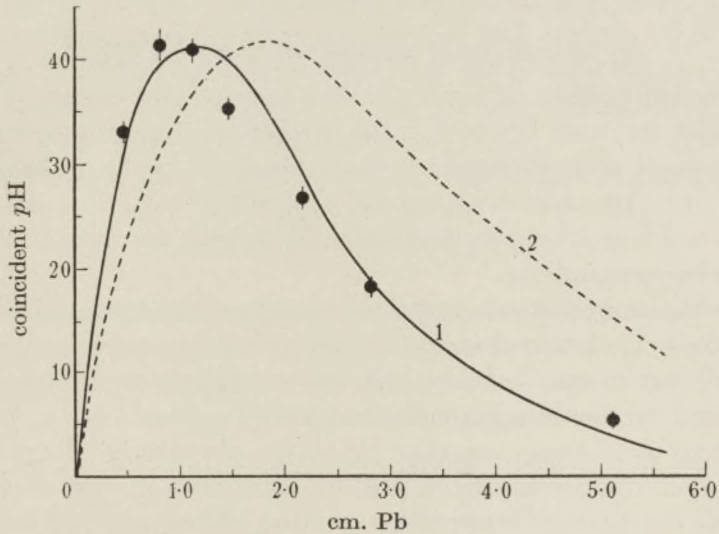

FIGURE 2. The transition effect for showers initiated by photons. ● observed. ---- calculated for E_c/E^2 spectrum. — calculated for E_c^2/E^3 spectrum ($E > E_c$); $1/E$ spectrum ($E < E_c$).

Without any lead at s, 18·3 anti-coincidences per hour were recorded. The lead screen s increased the number of anti-coincidences considerably. This increase was obviously due to photons generating Compton or pair electrons in the screen s and so starting showers hitting the three counters underneath. The points given in figure 2 represent therefore the transition effect of showers generated by photons.

The anti-coincidences observed with no lead do not represent the "true zero effect" because some amount of matter was always present between the counters A and B (the walls of the counters themselves plus 6 mm. wood and 0·5 mm. iron of the framework of the apparatus). We estimated this amount of matter to be roughly equivalent to 0·1 cm. Pb and added, therefore, in the first column of table 2, 0·1 cm. to the actual thickness of the lead screen s. The assumed zero rate of 11·4 anti-coincidences per hour will be justified by experiments to be described later. The zero rate was due mainly to showers coming from the side, i.e. to air showers not completely cut off by the lead walls (see figure 1) and to knock-on showers generated in the lead itself by penetrating particles. As already mentioned the lack of efficiency of the counters could not account for more than 1 % of the anti-coincidences, i.e. four anti-coincidences per hour.

As it is unlikely that the zero effect can be altered appreciably by varying the lead screen s, it can be regarded as a constant background of the transition curve.

(*b*) *Discussion of the observed transition effect*

The transition curve obtained with the arrangement described above is very suitable for comparison with the theoretical transition curve. This is so, since a fairly accurate estimate can be obtained for the probability that a shower of a given size emerging out of s will give rise to a coincidence. The expected transition curve was calculated from the cascade theory on the following assumptions:

(1) The showers recorded are due to *single* photons hitting the absorber s. Photons accompanied by electrons do not give rise to anti-coincidences and the probability of two or more photons coming together without being accompanied by electrons is small (see § 5 (*b*)).

(2) Electrons of energy less than 10^7 eV (i.e. the critical energy for lead) are neglected. This assumption is justified since most of these electrons are stopped by the material between the counters and the counter walls (total quantity 2 g./cm.^{2}).

We will work out the probability that a photon of energy E hitting s will produce an anti-coincidence. For simplicity we assume that the average angular spread of a shower produced by a photon in s is Ω and that the shower particles are distributed at random inside Ω. The solid angle covered by the counters D as seen from a point inside B we call ω and we suppose $\omega \ll \Omega$. The probability that a photon of a given direction produces an anti-coincidence is, according to the above assumptions,

$$p = (1 - e^{-\omega/\Omega\,\overline{N}(E_1 x)})$$
$$\approx \omega/\Omega\,\overline{N}(E_1 x) \quad \text{for } \omega/\Omega\overline{N} \ll 1.$$

The number of showers per unit time is therefore

$$J_s = J\Omega F p,$$

where F is the average effective area of the absorber from which particles crossing the counters B, C and D may arise and J is the number of photons per unit time, unit area and unit solid angle. It is useful to compare J_s with the number $J_p = J\omega F$ of photons travelling along lines crossing the counters B, C, D. We find

$$J_s/J_p \equiv P(E,x) = \Omega/\omega(1 - e^{-\omega/\Omega\,\bar{N}(E,x)}), \tag{1}$$

$$\approx \bar{N}(E,x) \quad \text{for } \bar{N}\omega/\Omega \ll 1. \tag{2}$$

We see from (2) that for small showers $P(E,x)$ is independent of the value of Ω. For large showers we can put, as a rough approximation, $\Omega = 2\pi$. Showers containing many particles however are produced by very energetic photons only and are very rare. Our results therefore cannot be affected appreciably by the above assumptions concerning big showers. The effect of big showers is especially small for the first part of the transition curve. Putting $\omega/2\pi = 0{\cdot}035$ (obtained from the dimensions of the counters arrangement) we have $\omega/2\pi\bar{N} < 0{\cdot}1$ up to light quanta of 4×10^9 eV, according to the numerical values given by Arley.

From (1) we get for the number of anti-coincidences at the thickness

$$T(x) = \int_{10^7\,\mathrm{eV}}^{\infty} \rho(E)\,P(E,x)\,dE. \tag{3}$$

The function $\bar{N}(E,x)$ for photons has been recently calculated by Arley.* Therefore P can be regarded as a known function of E. Theoretical considerations seem to indicate that the differential spectrum of photons is roughly of the following form (see Heitler 1937, Nordheim 1939)

$$\left.\begin{aligned} &\rho(E) \sim E_c^{\alpha}/E^{\alpha+1}, \quad E > E_c \quad (a)\\ &\rho(E) \sim 1/E, \qquad\quad\;\; E < E_c \quad (b)\end{aligned}\right\}. \tag{4}$$

We evaluated (3) by numerical integration, using the spectrum given in (4) and taking $E_c = 1{\cdot}5 \times 10^8$ eV. The values obtained for $T(x)$ are plotted in figure 2. The full line corresponds to the spectrum with $\alpha = 2$, while the broken line corresponds to the spectrum with $\alpha = 1$.

The intensity factors have been chosen so as to give the observed intensities for the maximum, i.e. 41·5 anti-coincidences per hour.

The agreement of the calculated curve for the spectrum given in (3) for $\alpha = 2$ is as good as it can be expected. Hence it is concluded that both the

* We are indebted to Dr N. Arley for having kindly communicated the unpublished numerical results.

assumptions about the shape of the energy spectrum and the results deduced by Arley from the Bethe-Heitler theory are a good approximation to the facts. On the other hand, the transition curve calculated for the $1/E^2$ spectrum (i.e. for $\alpha = 1$) differs markedly from the observations.

(c) *The total intensity of photons*

The total number of incoming photons can be estimated from our observations. The initial rise of the transition curve is only slightly affected by the shape of the energy spectrum, since, for small values of x, $\bar{N}$ varies very slowly with E. Thus the factor required to fit the first slope of the calculated transition curve to the observations gives the total photon flux. According to equations (1) and (3) the average number of anti-coincidences recorded per photon with an energy greater than 10^7 eV is given by

$$t(x) = T(x) \Big/ \int_{10^7\,\mathrm{eV}}^{\infty} \rho(E)\,dE.$$

Assuming the spectrum has the form given in (4) and $\alpha = 2$, one finds for $x = 0{\cdot}8$ cm. Pb

$$t(0{\cdot}8) = 0{\cdot}89.$$

Since from table 2 the observed number of anti-coincidences per hour is

$$T(0{\cdot}8) = 41{\cdot}6,$$

we find
$$\int_{10^7\,\mathrm{eV}}^{\infty} \rho(E)\,dE = \frac{T(0{\cdot}8)}{t(0{\cdot}8)} = 47 \text{ per hour.}$$

This is the number of photons with energy greater than 10^7 eV travelling along straight lines passing through the counters B, C and D. The corresponding number of ionizing particles is 450 per hour (table 2). Thus the number of photons with energy greater than 10^7 eV is $47/450 = 10{\cdot}5\,\%$ of the number of single particles. Using the spectrum (4), $\alpha = 2$, we get table 3.

TABLE 3

Energy interval in eV	$1\text{–}5 \times 10^7$	$5\text{–}15 \times 10^7$	$> 15 \times 10^7$	$> 10^7$
No. of photons per 100 ionizing particles	5·3	3·6	1·6	10·5

The above estimate represents a lower limit for the actual number of photons for it does not include those photons which are accompanied by at least one electron within an area of 600 cm.^{2}, i.e. photons occurring in the denser parts of the extensive air showers. Moreover, some photons are certainly missed because of shower particles scattered back from the lead screen s, towards the counters A.

5. The absorption of high-energy photons

(*a*) *Experimental results*

In order to determine the absorption curve of cosmic-ray photons, measurements were made with a constant amount of lead in position s (figure 1) and different screens above the counters A (position S). The measurements were carried out with 0·35 and 2·0 cm. of lead at s.

A photon hitting the screen S can (*a*) traverse the screen unabsorbed, (*b*) produce a Compton electron or an electron pair. Case (*a*) is exactly the same as if the absorber S had not been there at all, and the chance of recording the photon as an anti-coincidence is the same as it was without the absorber S. In case (*b*), however, a shower is started in the screen S. This shower may or may not emerge from S, but if it does it is very improbable that the counters B, C, D are discharged without one of the counters A being discharged as well. Thus the decrease of the number of anti-coincidences due to S is a direct measure of the probability that a photon is removed by pair production or Compton scattering.

As the probability of a photon traversing 5 cm. of lead with no encounter is extremely small, the frequency of the anti-coincidences observed with 5 cm. of lead in S is to be considered as the zero effect due to showers coming from the side and similar disturbing effects. The zero effects amount to 10·3 coincidences per hour for the observations with 0·34 cm. Pb at s and to 12·0 for the measurements with 2·0 cm. Pb at s. The difference of the two zero effects is not outside the statistical fluctuations. Nevertheless, since the possibility of a systematic difference cannot be excluded, the individual values for the two sets of measurements were preferred. The zero effect used in the discussion of the transition curve was the mean of the two values.

The results of the two sets of measurements are given in tables 4 and 5. The results of the absorption measurements in lead are given graphically in figures 3 and 4, where the logarithms of the observed quantities (after the subtraction of the zero effect) are plotted against the thickness of S in cm. of lead. The full lines represent straight lines fitted with the method of the least squares to the observations. The broken lines give the slopes expected according to the theory of Bethe and Heitler. Observations were also made with 1·0 cm. Fe and 6·3 cm. Al to compare the effect of different elements.

Table 4. Absorption curve for $s = 0{\cdot}35$ cm. Pb

		Threefold coincidences		Anti-coincidences	
X cm.	Material	Total	Rate per hour	Total	Rate per hour
0·00	Pb	13297	437 ± 4	1341	$44{\cdot}2 \pm 1{\cdot}2$
0·35	Pb	10620	442 ± 5	826	$34{\cdot}4 \pm 1{\cdot}2$
0·70	Pb	10737	446 ± 5	715	$29{\cdot}6 \pm 1{\cdot}1$
1·40	Pb	9161	417 ± 4	456	$20{\cdot}7 \pm 1{\cdot}0$
5·0	Pb	8972	374 ± 4	248	$10{\cdot}3 \pm 0{\cdot}6$

Table 5. Absorption curve for $s = 2{\cdot}0$ cm. Pb

		Threefold coincidences		Anti-coincidences	
X cm.	Material	Total	Rate per hour	Total	Rate per hour
0·00	Pb	21858	430 ± 3	1932	$37{\cdot}9 \pm 0{\cdot}9$
0·35	Pb	19801	417 ± 3	1326	$28{\cdot}0 \pm 0{\cdot}8$
0·70	Pb	19389	410 ± 3	1118	$23{\cdot}6 \pm 0{\cdot}7$
1·40	Pb	17119	402 ± 3	768	$18{\cdot}1 \pm 0{\cdot}7$
5·0	Pb	16938	372 ± 3	547	$12{\cdot}0 \pm 0{\cdot}5$
1·0	Fe	16504	408 ± 3	1089	$27{\cdot}0 \pm 0{\cdot}8$
6·3	Al	16097	409 ± 3	1056	$16{\cdot}9 \pm 0{\cdot}8$

(*b*) *Discussion of the results*

The interpretation of the above results is affected by two possible sources of error namely:

(1) *Multiple photons striking S.* Let us suppose the absorption coefficient of a single photon to be μ. When n photons hit S simultaneously the variation of the number of anti-coincidences with S corresponds to an absorption coefficient $n\mu$. This is due to the fact that anyone of the photons has independently a certain chance of producing an electron which can pass through A and prevent the anti-coincidences. An estimate of the density of air showers however suggests that this effect cannot give rise to an appreciable correction to our result. This can easily be understood since photons accompanied by electrons cannot give rise to anti-coincidences. Thus the denser parts of air showers where there are more than one photon in an area comparable with the surface of S will also contain electrons and so will not be recorded.

The following experimental test showed too that the effect of multiple rays could not be appreciable. A lead absorber of 1·4 cm. thickness covering only *half* the area of S was brought above the counters A. In case of single photons such an absorber ought to reduce the intensity by a factor

$$\tfrac{1}{2}(e^{-\mu \times 1{\cdot}4} + 1) = 0{\cdot}63,$$

where μ is the observed absorption coefficient. Since the observed reduction was (64 ± 5) % the photons must be nearly all single. If multiple photons were present the observed reduction would be larger.

(2) *A single electron is stopped in S by the emission of an energetic light quantum*. This light quantum may escape out of S without producing a secondary effect and so may give rise to an anti-coincidence by absorption in s. It seems very difficult to evaluate theoretically the correction due to this effect, but it is unlikely to be important for the absorption curve with 2·0 cm. of lead at s although it may have some effect on the absorption curve with 0·35 cm. Pb at s. We intend to carry out at a later date an experiment to investigate the correction arising from this effect.

(c) *Comparison of the observed absorption curve with the theory*

The absorption curve is given theoretically by the following expression

$$A(X) = \int \rho(E)\, P(E_1 x)\, e^{-\mu(E) X}\, dE,$$

the functions $P(E_1 x)$ and $\rho(E)$ having been defined in the previous section (x is the thickness of the lead screen where the showers are produced and X

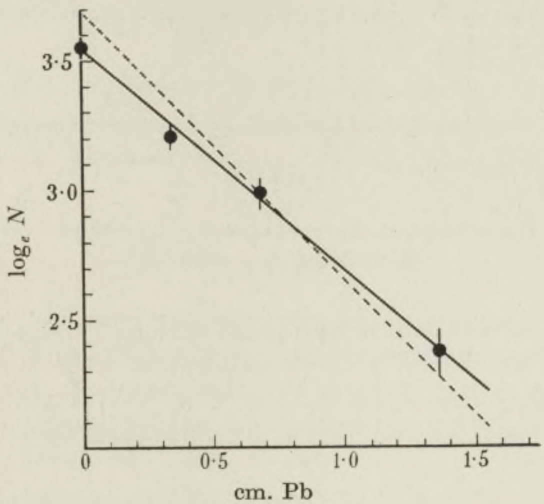

FIGURE 3. The absorption curve of cosmic-ray photons. $s = 0{\cdot}35$ cm. Pb. ● observed, ---- calculated.

the thickness of the absorbing screen S). We have evaluated the expression (5) numerically for $x = 0{\cdot}35$ cm. Pb and $x = 2{\cdot}0$ cm. Pb using the values for $\rho(E)$ given by Bethe and Heitler (see Heitler 1936). The results for lead are represented graphically in figures 3 and 4 by the dotted curves.

It appears from the calculations that the theoretical absorption curve $A(x)$ is almost exactly exponential. The reasons for this are that the absorption coefficient of photons in the high-energy region varies only very slowly with the energy and that most of the observed anti-coincidences arise from a rather narrow band of the photon spectrum. As it can be seen from figures 3 and 4 the observed absorption curves are also closely exponential in form. The theoretical and experimental absorption coefficients are compared in table 5.

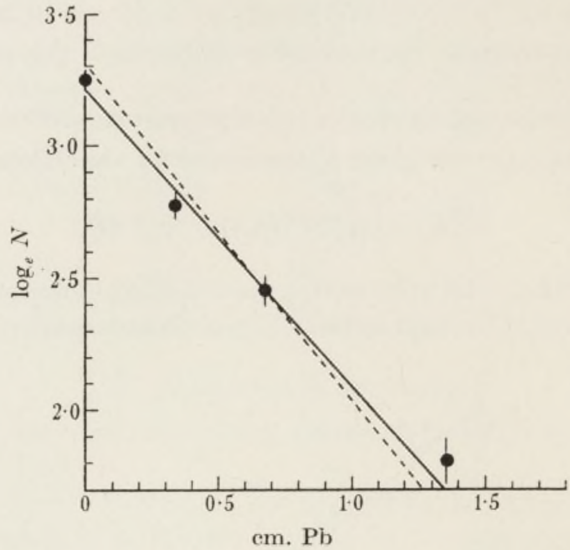

FIGURE 4. The absorption curve of cosmic-ray photons. $s = 2·0$ cm. Pb. ● observed, ---- calculated.

The absorption coefficient in lead found with $s = 2·0$ cm. of lead is in good agreement with the theory, while the absorption coefficient with $s = 0·35$ is rather smaller than the calculated one. This deviation may be partly due to the effect of electrons stopping in S as discussed above.

TABLE 6. ABSORPTION COEFFICIENTS OF COSMIC-RAY PHOTONS

		μ cm.$^{-1}$	
Material	x cm.	Calc.	Obs.
Pb	0·35	1·12	0·85 ± 0·07
Pb	2·00	1·19	1·02 ± 0·07
Fe	2·00	0·35	0·54 ± 0·07
Al	2·00	0·068	0·085 ± 0·010

The observed absorption coefficients in Fe and Al seem to be both somewhat larger than calculated. On the whole, however, the agreement of observed and calculated values is satisfactory.

6. Conclusion

The cross-section for pair production by high energy photons has been measured and was found to be in agreement with that predicted by the theory of Bethe and Heitler for energies of about $1\cdot5\times10^8$ eV. The dependence of the absorption coefficient on the atomic number was found to be in fair agreement with theory for lead iron and aluminium absorbers.

The shower transition curve has been obtained for photon-initiated showers in lead. The result indicates a photon spectrum as given in equation (4), and confirms the conclusions of the cascade theory as extended by Arley.

The present experiments do not suggest the existence of non-ionizing particles other than photons. We estimate that if such non-ionizing particles occur at all in the cosmic-ray beam they did not produce more than about 10 % of the anti-coincidences at the maximum of the transition curve.

One of us (B. R.) has pleasure in expressing his thanks to the Society for the Protection of Science and Learning for financial support and to Professor P. M. S. Blackett for his hospitality in the laboratory at Manchester.

Summary

Photons unlike ionizing particles cannot be observed directly with counters. Owing to this difficulty very few investigations dealing with the photon component of cosmic radiation have been carried out. In the present paper a simple method is described which is suitable for the observations of cosmic-ray photons. The transition effect of photon-initiated showers in lead has been measured. The result is in agreement with the prediction of the cascade theory of Bhabha and Heitler as extended by Arley. The absorption coefficients of cosmic-ray photons have been measured in lead, iron and aluminium, and they agree with the theoretical values as given by Bethe and Heitler. The lower limit for the total flux of cosmic-ray photons above 10^7 eV has been found to be 10 % of the ionizing component of the cosmic-ray beam.

References

Anderson, C. D. and Neddermeyer, J. H. 1934 *Phys. Rev.* **46**, 325.
Bethe, H. and Heitler, W. 1934 *Proc. Roy. Soc.* A, **146**, 83.
Bhabha, H. J. and Heitler, W. 1937 *Proc. Roy. Soc.* A, **159**, 432.
Blackett, P. M. S. 1938 *Proc. Roy. Soc.* A, **165**, 11.
Blackett, P. M. S. and Wilson, J. G. 1937 *Proc. Roy. Soc.* A, **160**, 304.
Carlson, J. F. and Oppenheimer, J. H. 1937 *Phys. Rev.* **51**, 220.
Gentner, W. 1935 *J. Phys. Radium*, **6**, 274, 340.
Heitler W. 1936 *Quantum theory of radiation*. Oxford.
— 1937 *Proc. Roy. Soc.* A, **161**, 261.
McMillan, E. 1934 *Phys. Rev.* **46**, 325.
Nielsen, W. M. and Morgan, K. Z. 1938 *Phys. Rev.* **53**, 915.
Nordheim, L. W. and Hebb, M. H. 1939 *Phys. Rev.* **56**, 494.
Rossi, B. 1930 *R.C. Accad. Lincei*, **11**, 831.
— 1933 *Z. Phys.* **82**, 151.
Williams, E. J. 1939 *Proc. Roy. Soc.* A, **172**, 194.
Wilson, J. G. 1938 *Proc. Roy. Soc.* A, **166**, 482.
— 1939 *Proc. Roy. Soc.* A, **174**, 72.

Crystal boundaries in tin

By Bruce Chalmers, Ph.D.

(*Communicated by E. N. da C. Andrade, F.R.S.—Received* 2 *December* 1939)

Introduction

When an ingot of tin is melted, it can be seen that the crystals break off as if the material forming the crystal boundaries melts at a lower temperature than the crystals themselves. It is impossible, however, to draw any quantitative conclusions from observations of this kind, although such results would yield much wanted evidence as to the nature of the crystal boundary. In particular, it would be of interest to evaluate the temperature difference referred to, and to determine to what extent it varies with the amount of impurities present and with the angle between the crystallographic axes of the two crystals between which the boundary occurs. The present paper describes a series of experiments in which specimens consisting of two crystals with a single boundary between them were examined from this point of view.