THE NATURE OF PENETRATING PARTICLES IN AIR SHOWERS

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Introduction

EXTENSIVE air showers consist mainly of electrons and photons, but contain in addition a small percentage of particles more penetrating than electrons.

The nature of these particles was recently discussed by Auger, Daudin, Fréon and Maze[1]; and independently by Broadbent and Jánossy[2]. Both groups came to the conclusion that the penetrating particles cannot be mesons of the ordinary type. Auger's group suggested that the penetrating particles are 'λ-mesons', that is, charged particles of elementary charge and mass about 3 m_e. Broadbent and Jánossy put forward the suggestion that the penetrating particles are 'heavy electrons', that is, electrons of mass about 10 m_e. The two suggestions are, of course, identical; both were, however, based on somewhat indirect arguments. Recent experiments, partly reported at the Bristol Symposium held last September, give additional support to the λ-meson or heavy electron hypothesis.

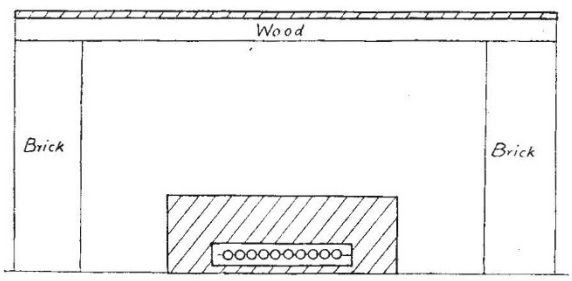
Recent Experimental Evidence

Miss Chowdhuri reported at the Bristol Symposium the following experiment. Air showers were recorded by means of fourfold coincidences. The set consisted of three unshielded counters in a horizontal plane and a tray of shielded counters near by; the tray was shielded by 15 cm. of lead. Fourfold coincidences were recorded both with and without a lead roof 1 cm. thick (supported by 1 cm. of iron) about 30 cm. above the top of the lead shield. The unshielded counters were placed at a sufficient distance from the shielded tray so as not to be affected by the roof. A considerable change of the rate of fourfold coincidences in the presence of the roof was noticed. The actual rates found are given in Table 1.

Table 1. Fourfold coincidences, rate per hour

With roof	0·263 ± 0·037
No roof	0·474 ± 0·053
Difference	0·211 ± 0·064

The above experiment was repeated and confirmed by us in Dublin. Threefold coincidences were recorded between two unshielded trays each of 750 cm.² area and a shielded tray of 1,500 cm.² area. The arrangement of the shielded tray and the roof are illustrated in the accompanying sketch. The roof was supported by 4 in. of wood resting on brick supports. The supports and the wood were left in position throughout the series. Measurements were carried out with various absorbers A placed on top of the wood. The results obtained are given in Table 2.



Shielded tray and roof

Table 2

Absorber A	No. of coincidences	Rate per hour
No absorber	325	3·32 ± 0·18
20 gm./cm.² brick	231	3·33 ± 0·20
1·7 cm. lead	380	2·53 ± 0·13

We see from Tables 1 and 2 that a thin lead roof reduces the number of penetrating extensive showers recorded, while a mass-equivalent brick roof shows no noticeable effect.

The above experiment can be interpreted, in our opinion, as follows:

(1) The penetrating particles in air showers are produced locally in the first few centimetres of lead.

(2) The penetrating particles are highly unstable and have a considerable chance of decay along the 50-cm. gap between roof and absorber. An apparent life of the order of 10^{-9} sec. is to be expected.

(3) While the thin lead roof shows a considerable effect, no noticeable effect is shown by a mass-equivalent brick roof. It must be concluded that the primaries of the penetrating particles are strongly absorbed in lead but not in the mass-equivalent of brick. This makes it virtually certain that the primaries of the penetrating particles are either electrons or photons or both.

(4) It may be added that this experimental evidence is incompatible with the view that the penetrating particles are produced by nucleons; nucleons would show similar effects in lead and brick roofs. Thus the present experiment further supports the view that the *local* penetrating showers which are produced by nucleons are qualitatively different from the extensive penetrating showers.

The above conclusions, with the exception of (2), were put forward previously by Jánossy and Broadbent[2] as a result of a detailed analysis of shower data.

It should be noted that conclusion (1) stands independently of whether (2) is admitted or not. Though we think it likely that the actual decrease of the shower-rate is caused by decay, this interpretation is not essential for the arguments below; if the decrease were to be explained by any other mechanism (for example, scattering in the roof), it would still be necessary to maintain that the penetrating particles are produced by photons in a thin layer of lead.

Z Dependence of the Production of Penetrating Particles

In discussing the nature of the penetrating particles in air showers, we may recall the experiments carried out by Cocconi and Festa[3], Mura, Salvini and Tagliaferri[4], and Chowdhuri[5]. Extensive showers were recorded in these experiments by counter trays all except one of which were unshielded. The shielded tray was covered alternately with lead only and with lead under an iron shield. As was pointed out by

Ferretti, the number of penetrating events recorded should be proportional to

$$k = \Phi \text{ (prod)} / \Phi \text{ (abs)}, \quad (1)$$

where Φ (prod) is the cross-section for the production of penetrating particles in the top layer of the shield, and Φ (abs) is the cross-section for the absorption of the primaries giving rise to penetrating agents. As shown above, the penetrating agents are produced either by electrons or photons; thus

$$\Phi \text{ (abs)} \sim Z^2 \text{ per atom.}$$

The comparison of lead and iron absorbers has shown experimentally that Φ (prod) / Φ (abs) is independent of Z. Thus

$$\Phi \text{ (prod)} \sim Z^2. \quad (2)$$

Furthermore, it is found that $k \sim 1/50$, and therefore

$$\Phi \text{ (prod)} \sim \frac{\Phi \text{ (rad)}}{50}, \quad (3)$$

where Φ (rad) is the 'radiative cross-section'; that is, either the cross-section for *Bremstrahlung* or pair production.

Equations (2) and (3) are most remarkable. They show clearly that the penetrating radiation must be emitted in collisions in the Coulomb field of the nucleus; thus the conclusion can scarcely be escaped that the penetrating particles are either of the two following types:

(*a*) Particles somewhat heavier than electrons, created by photons by pair production.

(*b*) Neutral particles emitted by electrons as a kind of collision radiation.

If the latter hypothesis were assumed, it would be necessary to ascribe to the electron a charge which is the source of the neutral field. The neutral quantum could then be emitted by the electron accelerated in the Coulomb field. Hypothesis (*b*) is, however, rendered unlikely in view of the experiments of Broadbent and Jánossy, where penetrating agents are found to discharge frequently two covered trays (*m*) and (*b*) on top of each other.

We are therefore left with hypothesis (*a*) that penetrating particles in air showers are largely 'heavy electrons' or λ-mesons produced presumably by photons. We may add that the heavy electrons observed must have energies exceeding 200 MeV. as they are capable of penetrating 15 cm. of lead. If their rest energy is of the order of a few MeV., then the *proper life* is estimated to be of the order of $\tau \sim 10^{-11}$ sec.

This short life fully accounts for the absence of cloud chamber evidence (see, for example, Fretter[6]). A track which might possibly be a case of a decaying heavy electron is found in the left-hand bottom corner of a photograph of a penetrating air shower given by Jánossy, Rochester and Broadbent[7]. The particles penetrating a lead plate seen on the same photograph might very well be examples of heavy electrons.

The supposed short life of the heavy electrons throws more light on the analysis by Auger and co-workers[1]. This analysis shows that extensive showers when penetrating lead absorbers behave essentially differently from what is to be expected from cascades. On the other hand, the behaviour of extensive air showers in the atmosphere can be accounted for in terms of the cascade theory, as shown, for example, by Cocconi, Loverdo and Tongiorgi[8]. This discrepancy can be explained in terms of the instability of the heavy electron. The heavy electrons play an important part only in dense absorbers.

Estimate of the Mass of the Heavy Electron

The experiments described above, together with those reported earlier[1,2], seem to show conclusively that at least an appreciable fraction of the penetrating particles in air showers are different in nature from particles observed hitherto. The conclusion that these new particles are, in fact, heavy electrons must be taken only as a conjecture, supported by general theoretical arguments. It seems, however, worth while to show that the assumption of a heavy electron of suitable mass does not lead to contradictions.

In particular, it follows from general arguments that the ratio between the cross-section for production of heavy pairs and the cross-section for collision radiation of a heavy electron must be very nearly the same as the ratio of the corresponding cross-sections for ordinary electrons; we show in the following that the observed effects are compatible with this general assumption.

The cross-section Φ (prod) of equation (1) is the average cross-section for the production of a heavy pair per incident electron. We derive the actual probability for the production of a heavy pair in the following way.

An electron or photon of energy E incident on the absorber gives rise to cascades, and the total photon path-length of photons with energy exceeding E' is

$$t\,(E, E') = 0{\cdot}572\, E/E' \text{ cascade units.}$$

Assuming that the number of photons is 1·5 times the number of electrons in the shower, we have for the total photon path associated with one electron

$$2{\cdot}5\, t\,(E, E') = 1{\cdot}43\, E/E'.$$

The energy spectrum of the air shower can be represented by

$$dS\,(E) \sim \frac{E_c\, dE}{(E + E_c)^2} \quad E_c = 100 \text{ MeV.} \quad (4)$$

(Mitra and Rosser, in the press; reported at the Bristol Symposium).

Thus the total path-length per incident electron in cascade units is

$$T\,(E') = \frac{1{\cdot}43}{E'} \int_{E'}^{E_1} \frac{E\, E_c\, dE}{(E + E_c)^2} = \frac{1{\cdot}43\, E_c}{E'} \left\{ \log \frac{E_1 + E_c}{E' + E_c} - \frac{E_c\,(E_1 - E')}{E_1 + E_c} \right\} \quad (5)$$

(E_1 is the upper limit of the validity of (4)).

The mean free path of a photon for giving rise to an ordinary pair is 1·35 cascade units; thus the probability P of a heavy pair being produced is about $0{\cdot}76\, T\,(E')\, K$, where $K \sim (m_e/m_h)^2$.

We have to consider the probability that a heavy electron discharges one of the shielded counters. The ionization loss in 15 cm. of lead (30 cascade units) is 200 MeV.; thus only heavy electrons with $E' >$ 200 MeV. need be considered. The probability of a heavy electron $E' > 200$ MeV. traversing the absorber of 30 cascade units is of the order of $\exp\,(-30\, K\, \alpha\,(E'))$, 30 K being the thickness of the absorber in cascade units of the heavy electron; $\alpha\,(E')$ is a function derived from cascade theory, which has values somewhat less than unity for small energies and is decreasing for larger energies.

We have thus for the fraction k of penetrating particles

$$k = 0{\cdot}76\, T\,(200 \text{ MeV.})\, K \exp\,(-30\, K\, \alpha\,(E')).$$

Now putting $k = 1/50$ (equ. 3), $K = 1/30$, $\alpha = 1$, the equation requires $T'(E') \sim 2{\cdot}0$. This value is reasonable; it is obtained from (5) by putting $E_1 \sim$ 6,000 MeV. Thus the experimental findings are roughly in accord with $K = 1/30$; that is, $m_h \sim 6m_e$. The above consideration is very rough; but it seems to show that the heavy electron hypothesis is not incapable of accounting for the experimental findings.

We are greatly indebted to Prof. W. Heitler for detailed discussions, and we are also indebted to Dr. T. Nevin for help during the experiments.

Note added in proof. After submitting this communication a photograph purporting to be that of a particle of mass $10\,m_e$ has been reported by Cowan (*Science*, November 12, 1948).

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[6] Fretter, *Phys. Rev.*, **73**, 41 (1941).
[7] Jánossy, Rochester and Broadbent, *Nature*, **155**, 142 (1945).
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SIMULTANEOUS MEASUREMENT OF THE OPTICAL CONSTANTS OF METALS OVER A WIDE WAVE-LENGTH RANGE

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THE optical constants of metals can be calculated from a knowledge of the ellipse of vibration which results from the reflexion of plane polarized light usually at an azimuth of 45° by a plane metallic surface. In the present method, this ellipse is determined by finding the ratio of the major and minor axes and the orientation of the major axis to the plane of incidence. It differs, however, from other methods using this principle in that the data from which the ellipse is obtained are produced on a photographic plate in the form of a thin vertical strip of variable intensity for each wave-length. A continuous source and a dispersing prism enable a record to be obtained simultaneously for the whole of the spectrum-range required.

The essentials of the optical system are shown in Fig. 1. The reflected elliptically polarized light passes through the rotator T, which consists of two prisms of right- and left-handed quartz in optical contact. Above the central plane the ellipse will be rotated clockwise; below, counter-clockwise. Fig. 2 indicates the relative orientations of the ellipse in the light emerging from the rotator. If the analysing

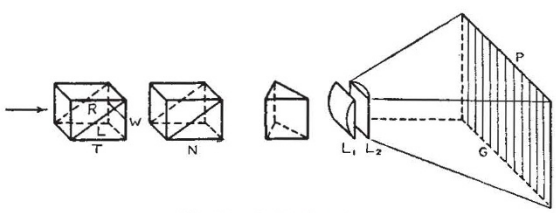
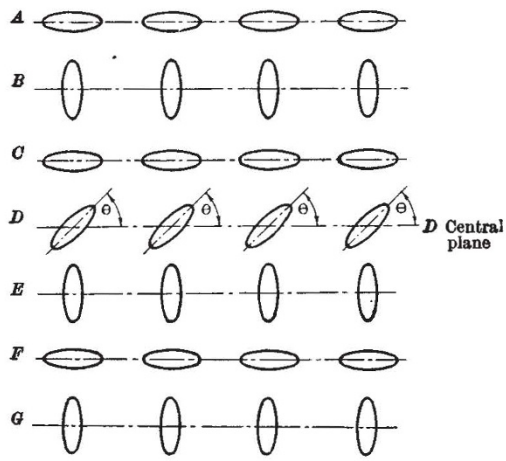


Fig. 1. Optical system



A, C, F, minima; *B, E, G*, maxima; $BC = AC$
Fig. 2. Relative orientations of the ellipse

nicol N is adjusted for plane polarized light, the vibration direction of which is vertical, then in the positions ACF the intensity will be a minimum, and in positions BEG a maximum. The square root of the ratio of these intensities gives the ratio of the axes. DD is the central plane, so that the orientation of the ellipse is given by

$$\theta = \frac{CD}{CF} \times 180°.$$

A fiducial line consisting of a very fine wire W is placed immediately after the rotator and adjusted to be in the central plane. A plano-cylindrical lens L_1 produces at its conjugate focus P an image of the pattern of Fig. 2, modified by the analyser, and of the fiducial line, magnified in the vertical plane only. A second plano-cylindrical lens L_2 converges the light horizontally into a vertical strip of variable intensity in its focal plane P. Using white light and a prism, a spectrum crossed by a system of dark and bright bands together with the horizontal fiducial line is obtained on a photographic plate placed at P. By removing the rotator and analyser, which are mounted together, and placing in position a triangular aperture with base horizontal and its plane coincident with the fiducial line W, an exposure of graded intensity is obtained. In front of the photographic plate P, which can be moved horizontally in its own plane, a grid G is placed, consisting of alternate opaque and transparent strips. This enables the crossed spectrum and the comparison spectrum of graded intensity to be obtained, adjacent strips being of the same wave-length.

Fig. 3 shows the pattern obtained with aluminium, the exposure time for each spectrum, taken consecutively, being 40 sec. Microphotometric comparison of the maxima and minima against the adjacent graded intensity enables the ratio of the axes to be determined, while the distance between the fiducial line and the various maxima and minima gives the orientation of the ellipse. Since the time involved in obtaining the data for a wide wave-length region is so short, the method is clearly advantageous in that deterioration or change of the surface while observations are being made is avoided. So far as we are aware, all existing methods of measuring the optical constants of metals require the use of monochromatic light, making the determination of a dispersion curve a lengthy process.