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212

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Multiple Electron Production in a High Energy Electron-Photon Shower

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An unusual electron-photon shower produced by an electron of $> 10^{11}$ ev initial energy has been detected in a stack of emulsion layers without backing, exposed in the stratosphere. Experimental data obtained on the basis of a study of this shower are presented which indicate the occurrence of three cases of simultaneous formation of four electrons (two electron-positron pairs).

THE INVESTIGATION of electron-photon showers by means of nuclear emulsions exposed in the stratosphere has considerable interest in view of the possibility of elucidating the details of high energy electromagnetic processes. Despite some contradictions in the existing experimental data on certain aspects of electron-photon showers, one can definitely say that anomalies exist with respect to accepted theoretical views. Among these one can mention problems such as the occurrence of multiphoton showers[1] and in connection with this, the question of the source of closely correlated gamma rays; the bremsstrahlung spectrum and its possible deviations from theoretical[2]. Indications[3] also exist that the cross section for electron-positron pair formation directly by the electron without intermediaries exceeds considerably the theoretical value at energies greater than 10^{10} ev. These conclusions cannot be considered final, however, because in certain other experiments similar effects have not been found[4]. The solutions to these problems have great significance, not only for quantum electrodynamics, but as noted by Heisenberg[5], for quantum field theory in general.

Examples of multiple formation of electrons detected in an electron-photon shower are described below. Information on similar cases, together with data on pair formation by electrons, will permit the evaluation of the role (at higher energies) of higher-order processes than pair formation by photons.

GENERAL CHARACTERISTICS OF SHOWERS. EXPERIMENTAL DATA ON CORRELATED PAIRS

During a systematic investigation of electron-photon showers, using stacked emulsions without backing exposed in the stratosphere, an unusual electron-photon shower was discovered.

The emulsion stack consisted of 150 layers of type R, having a thickness of 400 μ and a diameter of 10 cm. Irradiation took place at an altitude of 20–24 km for about 10 hours. Grain density in the minimum ionizing paths was 37 grains (or 31 conglomerates) per 100 μ.

The shower was initiated by a single electron entering the stack from outside. In each emulsion layer the electron travelled $\sim$ 0.5 cm, its total path in the emulsion was 8 cm. On the first two radiation lengths from its point of entry into the stack are registered 21 secondary electron-positron pairs, of which 12 had energies $E_i > 10^8$ ev. The most probable value of the primary electron's energy, determined from the cascade curve, turned out to be $E_0 = (0.6 - 2) \cdot 10^{12}$ ev.

The shower under consideration had the following peculiarity: six of the electron pairs formed were pairwise correlated. The appearance of two pairs in each case resembled, if one may so express oneself, a "quadrident": one heavy track beginning not far from the axis of the shower, gradually thickening and spreading out, and splitting into four separate tracks. The latter were in every case ascribed to electrons (positrons) because of the characteristic electromagnetic processes occurring along them. The following table gives the coordinates of the vertices of the quadridents (R—distance from the primary electron track in microns, t—distance from primary electron entrance point into stack, in millimeters) and the energies of the individual electrons, determined by the relative multiple scattering with an accuracy of 30–50%.

t, mm	R, μ	E_1, ev	E_2, ev	E_3, ev	E_4, ev
3.94	0.5	$2.1 \cdot 10^3$	$0.8 \cdot 10^9$	$1.7 \cdot 10^9$	$2.5 \cdot 10^9$
31.02	0.4	$2.0 \cdot 10^8$	$2.7 \cdot 10^8$	$3.2 \cdot 10^9$	$\sim 10^{10}$
40.51	2.0	$1.7 \cdot 10^8$	$1 \cdot 10^9$	$2.0 \cdot 10^9$	$3 \cdot 10^9$

Careful measurements of ionization were made along the quadrident tracks. Basically, a grain counting method was used. In the first two cases the total density of the primary and quadrident electron tracks was measured, since the distances between them were very small. In Fig. 1 – 3 the black dots indicate the results of measurements of ionization along the quadrident tracks, while the triangles denote the results of grain counting along the tracks of several relativistic electrons (evidently from the same shower). Because a diminution in grain density is observed near the emulsion surface, (sections $a'b'$ in Fig. 1 and $a''b''$ in Fig. 2) corrections have been introduced in the measurements (circles). The errors indicated are statistical.

As an additional check on the measurements, the graphic-photometric method [6] was used to measure track density (contours of the track grains, magnified 5500 times were traced on a fixed X-ray film and filled in with india ink, after which they were read with a photometer). The results obtained for the first quadrident are shown in Fig. 4. As can be seen from Figs. 1 and 4, the results of both methods are in complete agreement. In all three cases one observes the following pattern of change in ionization by the quadrident electrons: a jump to double (or somewhat greater) the value, a gradual increase, and a transition to a fourfold ionization $4I_0$. Figure 5 is a microphotograph of the third quadrident (composite).

INTERPRETATION

Two different interpretations of the appearance of the quadridents are possible: 1) the pairs were formed sequentially at small distances from each other; 2) four electrons were formed simultaneously. From a detailed examination of the structure of the tracks and of the ionization curves, it follows that the distance between the points of sequential formation of the pairs could not exceed 300–500 μ. From this one can estimate the probability w_1 of sequential pair formation (first possibility). From the number of pairs with energy $> 10^8$ ev discovered in the shower within a radius $R \lesssim 2\ \mu$, and assuming in first approximation that they are formed with equal probability volume-wise, one can obtain a value $w_1' \sim 10^{-7}$. (It was considered that in the plane perpendicular to the shower axis the coordinates of the pair formation points could not differ by more than 0.2–0.5 μ.) If one assumes the second pair to be formed by the bremsstrahlung from the first pair, then taking into account the conversion and radiation lengths in emulsion, the probability becomes $w_1 \sim 10^{-9}$. One must observe that consideration of all the electron-photon showers registered in the emulsion (in agreement with published data) cannot lead to a value $w_1 > 10^{-4}$. Furthermore, with sequential pair formation one ought to observe stepwise changes in ionization along the quadrident tracks.

The quadridents are therefore difficult to explain as sequentially formed pairs. This leaves the second possibility – the multiple process or simultaneous formation of four electrons. In this case the gradual increase in ionization can be primarily attributed to mutual shielding of the electrons and positrons at close distances[2,7], an effect discovered earlier in electron-positron pairs of energy

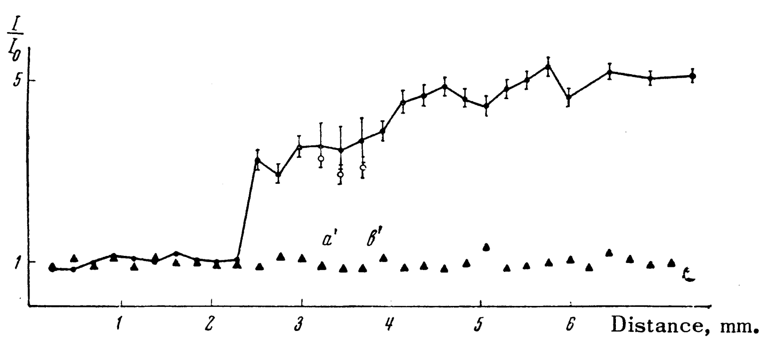

FIG. 1.

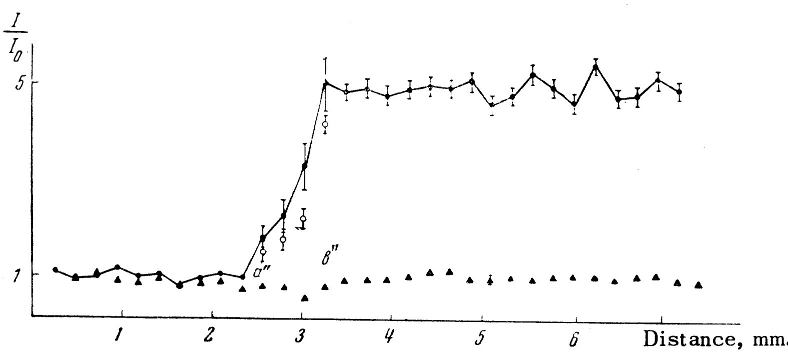

FIG. 2

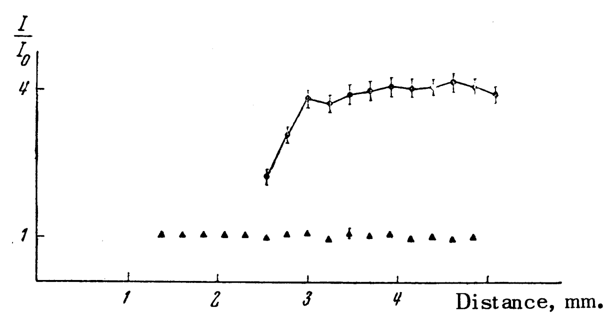

FIG. 3.

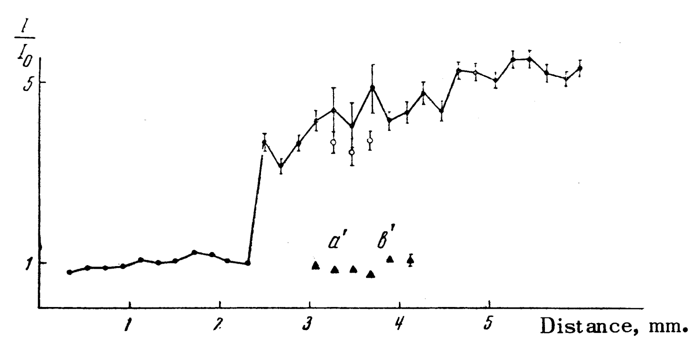

FIG. 4.

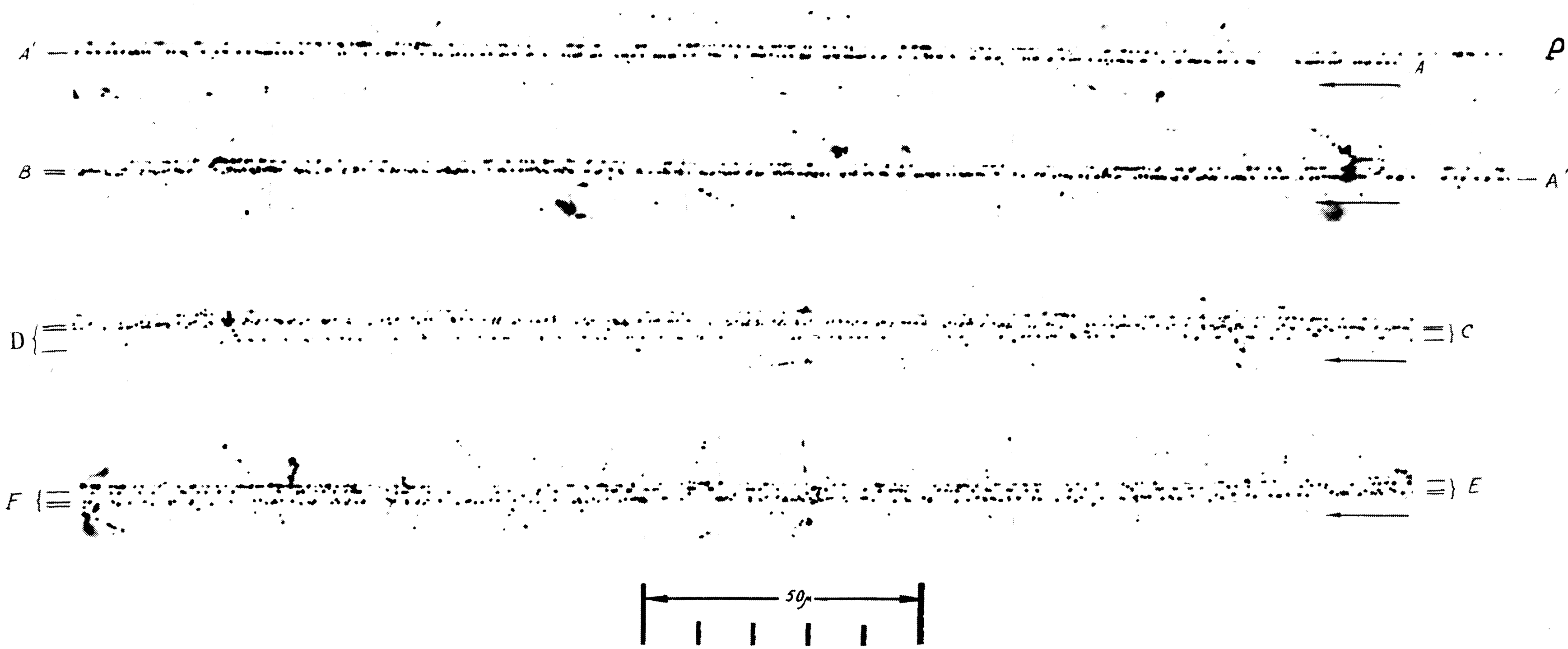

FIG. 5. Microphotograph of the tracks of two electron-positron pairs formed at a distance $t = 40.51$ mm and $R = 2\mu$ (third quadrident). AB – initial segment of the quadrident; the splitting into two separate tracks may be seen. CD – segment at a distance 3.2 – 4.1 mm from the point of formation of the pairs; the quadrident track consists of three separate tracks, of which the lower one deviates from the track axis. EF – segment at a distance 6.7 – 7.6 mm; the body of the quadrident track consists of three separate electron tracks; on this segment the fourth electron had deviated and is not seen on the photograph. The track of the primary electron P is seen alongside the quadrident tracks.

$10^{10} - 10^{11}$ ev.[8] In the second and third quadrident the track sections along which the ionization increases are approximately the same as those of the pairs, and in the first quadrident considerably longer.

DISCUSSION

If one notes that up to the present time about 150 electron-photon showers have been examined, and that on the average some 15 – 20 pairs have been noted in each, then the appearance of the three quadridents corresponds to the evaluation of the relative probability of simultaneous two-pair production performed by Hooper and King[9] on the basis of two quadridents found by them among ~ 1400 pairs. Yet the fact that all three quadridents were formed in a single shower, with energy $E_0 > 10^{11}$ ev, and that in each case the total energy of the quadrident electrons exceeded $5 \cdot 10^9$ ev, is remarkable. Moreover, the energy estimates are only lower limits to the actual values. The question presents itself whether quadridents are not formed by gammas with relatively greater cross section at higher energies?

According to Heitler's calculation[10], simultaneous formation of two pairs is ~ 137 or even 137π times less frequent than ordinary pair formation.* If this relationship is correct, one would expect three quadridents approximately for every $(137/10)^3 \approx 2500$ showers with energy $E_0 \gtrsim 10^{11}$ ev. But up till now, according to published data, the detailed structure of the first two radiation lengths has been examined in not more than ~ 50 showers with energy $E_0 \gtrsim 10^{11}$ ev. In addition, in a number of showers (notably at higher energy) the tracks of pairs were situated close to the shower axis, forming a continuous dense track and obscuring the possible occurrence of multiple electron production.

Hence the appearance of three quadridents in a single shower is something of an indication that multiple electromagnetic processes play an increasing role at higher energies. Of course the data from this shower are insufficient for any kind of quantitative deduction. But roughly speaking, the simplest explanation of this event is that the multiple process is 2 – 3 times more probable than theory predicts.

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*More accurate calculations lead to a value of the relative probability $(1/137)^2 \log (K/mc^2)$, where K is the gamma energy, mc^2 the electron rest energy.

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213