ON THE PRODUCTION OF THE ELECTRON-PHOTON COMPONENT IN THE INTERACTION OF COSMIC-RAY PARTICLES OF ENERGIES GREATER THAN 10^{11} EV WITH BERYLLIUM NUCLEI

L. T. BARADZEI, V. I. RUBTSOV, IU. A. SMORODIN, M. V. SOLOV'EV, B. V. TOLKACHEV, and Z. I. TULINOVA

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editor February 6, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 17-20 (July, 1957)

Four events of electron-nuclear showers produced by cosmic-ray particles of energy exceeding 10^{11} ev interacting with beryllium nuclei in a cloud chamber are discussed. The energy transferred to π^0-mesons in the interactions is determined. Large fluctuations in the π^0-meson energy were observed. One of the photographs is an example of an interaction in which π^0-mesons are apparently not generated.

RESULTS of experiments carried out with a Wilson cloud chamber in a magnetic field[1] are described in this article. The chamber operated for 52 hours at an altitude of 9000 m. A block of beryllium of thickness 26.5 g/cm^2 was placed above the chamber. Inside was a lead plate of thickness 17.5 g/cm^2 (3.3 radiation lengths). Photographs were taken upon generation of electron-nuclear showers in the absorbers.

In all, 1490 photographs were obtained. On 86 of these electron-nuclear showers from the beryllium block were registered. Among these, 5 cases were found of electron-nuclear showers in which the observed number of particles was greater than 10. The plate shows photographs of four interactions, in which the position in the chamber made it possible to draw definite conclusions about the character of the interaction.

Row		Number of shower			
		8550	1403	3183	3402
1.	Number of particles above the lead plate	12	15	16	17
2.	Number of electrons among them	1	1	0	2
3.	Number of penetrating particles in the shower	9—11	10—18	15—16	7—15
4.	Range of the secondary particles in g/cm^2 in matter above the chamber	11	2	3	13
5.	Magnitude of the angle $\theta_{1/2}$	3.5°	4°	4.5°	6°
6.	Energy of the primary particles, in nucleon masses	450±120	340±70	300±60	230±50
7.	Total energy of the secondary particles in Bev	>30	>52	>29	>25
8.	Number of electrons of energy greater than 6 Mev	62—68	21	13	68—74
9.	Number of electrons of energy greater than 30 Mev	30	15	3	35
10.	Energy definitely belonging to electrons, in Bev	>7	3.8	0.3	>7
11.	Energy of the electron-photon component, in Bev	14—40	7.6—15	0.7—1	14—50
12.	Ratio of the energy of the electron-photon component to the energy of the incident particle, in %	4.4—12	2—6	0.2—0.5	5—29
13.	Number of secondary interactions in the lead block	1	1—2	0—1	2

The main data characterizing the showers considered are given in the table. Row 1 of the table gives the number of particles observed above the lead plate. The position of the particle tracks in the chamber was such that the proportion of ionizing particles not registered on the photographs constituted several per cent. A certain number of electrons coming from conversion in beryllium of photons from π^0-decays could have been among particles observed above the plate. In row 2 the number of particles identified as electrons is given.

In row 3 the first number indicates the number of particles going through the lead plate without cascade multiplication and which are therefore not electrons. Part of the tracks could not, because of their unfavorable position, be observed under the lead plate, and the question as to whether these tracks belonged to penetrating particles could not be directly answered. The second number in row 3, does include the tracks not traced, and gives therefore the maximum number of penetrating particles in the interaction. However, if among the tracks not traced the proportion of electrons is the same as among those traced, the main part of the tracks not seen should belong to penetrating particles. Thus, the true number of penetrating particles should be close to the maximum, given in row 3. The place at which the shower has been produced is indicated in row 4.

The angular distribution of the secondary particles can be characterized by the value of the angle $\theta_{1/2}$, inside of which half the particles are emitted. The magnitude of the angle $\theta_{1/2}$, given in row 5, was determined for both the particles known to be penetrating and for the maximum number of penetrating particles, given in row 3. In all cases the difference did not exceed 0.5°.

The angles of the emitted particles were measured from the axis of the shower, the direction of which was determined such that in two mutually perpendicular projections there were the same number of particles on both sides of the axis. The error in the determination of the axis constituted, on the average, 1°. However, because the angular distribution of the penetrating particles was strongly peaked forward, the error in the determination of $\theta_{1/2}$ connected with the inaccuracy in the determination of the axis of the shower was about 0.5°.

Assuming that the observed interactions are nucleon-nucleon ones, the energy of the incident nucleon can be determined by the angular distribution of particles in the shower. In row 6 values are given for γ_0, calculated according to the formula of Dilworth et al.[2]

$$N_s/2\Gamma^2 = \sum_{i=1}^{N_s} 1/(\Gamma^2 + \cot\theta_i),$$

where $\Gamma^2 = (\gamma_0 + 1)/2$. The errors given take into account a possible asymmetry in the emission of the particles in the center-of-mass system by the technique, proposed in the same article, for the upper limit of the number of particles in the shower.

The assumption that the incident nucleon interacts with several nucleons leads to an increase in the value of the energy of the incident particle. The detection of four showers in the conditions of the experiment described corresponds to a current of shower-producing particles $(1.7 \pm 0.8)\times 10^{-5}$ particles per cm^2 per sec per sterad, if the interaction cross section in beryllium is geometrical. Assuming, according to the data of Refs. 3 and 4, that the absorption of particles in the atmosphere takes place with a range of 120 $g\text{-}cm^{-2}$, one obtains a value of the current at the limit of the atmosphere equal to $(2 \pm 1)\times 10^{-4}$ particles per cm^2 per sec per sterad. According to the data given in the review of Fradkin,[5] this quantity corresponds to a beam of particles with energy in excess of 250 Bev.

The presence of a magnetic field in the chamber makes it possible to evaluate the energy of the shower particles. Because more than half the shower particles have momenta larger than that measurable, which is 3 Bev/c, the quantity given in row 7 is the lower limit of the total energy of the penetrating particles.

The number of electrons below the lead plate with energies in excess of 6 and 30 Mev are given, respectively, in rows 8 and 9. Row 10 gives the total electron energy obtained by measuring the electron momenta under the plate. In showers 8550 and 3402, these measurements gave the lower limit of the total electron energy because, the electron momenta could not be measured if they did not exceed 500 Mev/c, owing to the high electron density. The quantities given made it possible to determine the energy of the electron-photon component generated in the interaction (row 11). The lower limit of the energy of the electron-photon component was obtained from the data in row 10 on the assumption that the photon component of the shower has the same energy as the electron component. An upper limit on the energy can be obtained from the number of electrons under the lead plate on the assumption that they are produced in one cascade shower caused by the photon. The calculation was carred out with the formula of cascade theory in approximation A of Ref. 6 for the number of electrons with energy greater than 30 Mev.

The ratio of the energy of the electron-photon component to the energy of the incident particle is given in row 12. The two quantities in the row give, respectively, the minimum possible proportion of the energy in the electron-photon component, calculated as the ratio of the minimum possible value of the energy of the electron-photon component to the maximum value of the energy of the incident particle, and the maximum value obtained under the opposite assumptions. The data given indicate the existence of large fluctuations in the proportion of the energy transferred to the electron-photon component in the interaction.

Shower No. 3183, where the proportion of energy in the electron-photon component does not exceed several tenths of a percent, is of particular interest. In this case the existence of processes other than the decay of π^0-mesons leading to production of an electron-photon component should be considered, such as δ-electrons, bremsstrahlung of mesons in the lead plate, and radiation of photons in the accleration of charges in the nuclear interaction process. Besides these, low-energy π^0-mesons can be generated in secondary interactions in the beryllium block.

Estimates show that the contribution of the first two processes does not exceed 10% of the measured energy. The radiation of photons in the acceleration of charges in nuclear interactions, according to an estimate from formulae given by Feinberg[7] and Schiff,[8] gives a contribution of several hundred Mev to the energy of the electron-photon component if the generating particles are π-mesons. If, together with π-mesons, mesons of spin 1 are generated, then the photon energy increases.

If a Poisson law is taken for the fluctuations in the number of particles, the mean value of the ratio $N_{\pi^0}/N_{\pi^\pm}$ is 0.5, and the energy distribution of the π^0-mesons is taken to coincide with the energy distribution of charged π-mesons, then the probability of production of one π^0-meson of energy less than 10^8 ev is 7×10^{-4}. The production of more π^0-mesons is still less probable. Consequently, it is improbable that the electron-photon component observed in this shower was brought about by π^0-mesons.

In shower No. 1403 one cascade pencil of electrons was observed, which means that the number of generating π^0-mesons was small. At the same time, the number of electron pencils in shower No. 8550 was not less than 4, and in shower No. 3402 it was not less than 10.

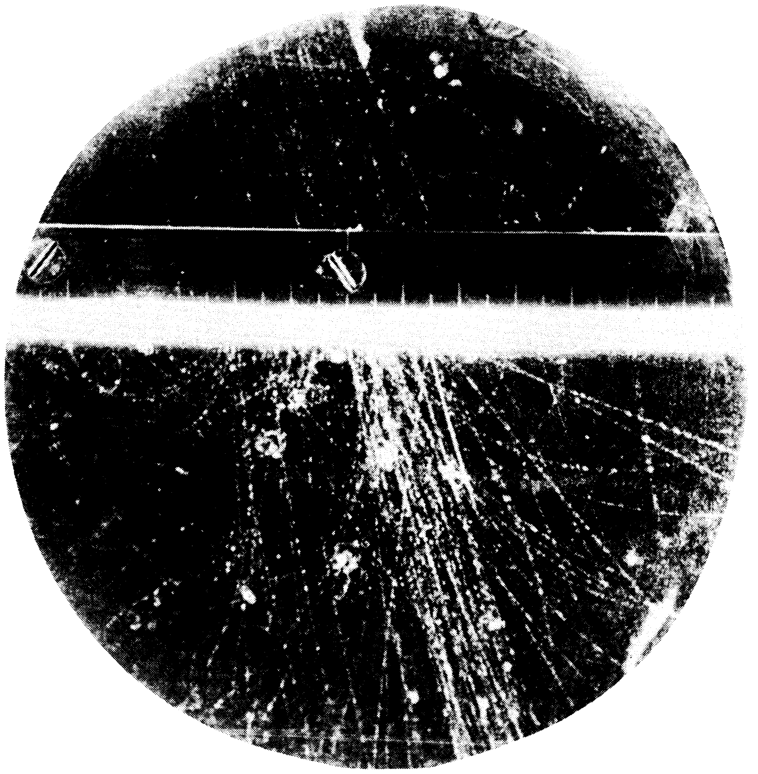
It should be noted that penetrating particles generated in the showers interact with lead nuclei with a cross section equal to the geometrical one. Row 13 of the table indicates the number of secondary interactions observed in the lead plate. Their total number is 4 — 6, which coincides with the expected number of secondary interactions if the interaction cross section in lead is geometrical.

Thus, the data given indicate that in the interaction of charged cosmic-ray particles of energy $10^{11} - 10^{12}$ ev with light nuclei, the proportion of energy transferred to the electron-photon component is subject to considerable fluctuations and can drop to several tenths of a per cent. Shower No. 3183 is, apparently, an example of such interactions in which π^0-mesons are not generated, whereas the number of charged particles generated in the shower is about 15.

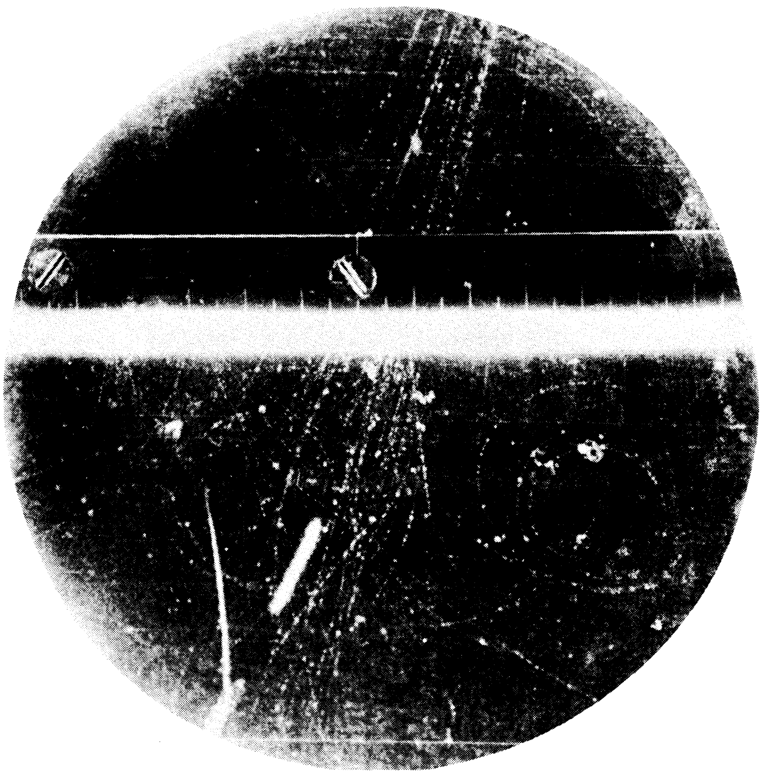
In conclusion, the authors use this opportunity to express deep gratitude to Professor

1403

8550



3402



3183

Photographs of electron-nuclear showers, produced by 10^{11}-ev cosmic-ray protons interacting with beryllium. The shower number is printed below the photograph

S. N. Vernov for discussion of the results given here.

[1] Baradzei, Rubtsov, Smorodin, Solov'ev, Tolkachev, and Tulinova, Dokl. Akad. Nauk SSSR **115**, 685 (1957).

[2] Dilworth, Goldsack, Hoang, and Scarsi, Nuovo cimento **10**, 1261 (1953).

[3] K. P. Ryzhkova and L. I. Sarycheva, J. Exptl. Theoret. Phys. (U.S.S.R.) **28**, 618 (1955), Soviet Phys. JETP **1**, 572 (1955).

[4] Kaplan, Klose, Ritson, and Walker, Phys. Rev. **91**, 1573 (1953).

[5] M. I. Fradkin, Usp. Fiz. Nauk **53**, 304 (1954).

[6] B. Rossi and K. Greizen, The Interaction of Cosmic Rays with Matter (Moscow) 1948 (Russian translation).

[7] E. L. Feinberg, J. Exptl. Theoret. Phys. (U.S.S.R.) **19**, 1098 (1949).

[8] L. I. Schiff, Phys. Rev. **76**, 89 (1949).

Translated by G. E. Brown
3