

ENERGY SPECTRUM OF PHOTONS FROM DECAY OF π^0 -MESONS GENERATED IN NUCLEAR INTERACTIONS AT THE ALTITUDE OF 3200 m ABOVE SEA LEVEL

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Apparatus of an area of 10 m² containing 6 layers of ionization chambers placed between lead and graphite absorbers was installed at mountain altitudes 3200 m above sea level. A layer of nuclear emulsion plates served for investigating the energy spectrum of photons from the decay of π^0 -mesons generated in the graphite absorber. The spectrum constructed on the base of 154 events in the energy interval $2 \times 10^{10} - 4 \times 10^{12}$ eV had an exponent $\gamma = 2.0 \pm 0.3$.

Introduction

In the Institute of Nuclear Physics of the Moscow University a large apparatus has been constructed for the investigation of high energy particles interactions. It is shown schematically in Fig. 1.

The apparatus has a horizontal area of 10 m² and contains six rows of ionization chambers separated by lead and graphite absorbers. Above the second row of ionization chambers, a layer of nuclear emulsions 50 μ thick was placed. Two layers of emulsions of the same thickness were also placed above the fourth row of chambers.

Experimental data obtained by means of ionization chambers allowed to work out the problem of the energy spectrum of nuclear-active particles generating π^0 -mesons in interactions with atomic nuclei of the absorbers. The π^0 -mesons initiated electron-photon cascades which were registered by ionization chambers. The results of these investigations have been published in various papers [2, 3, 8]. However, ionization chambers of a diameter of 10 cm are only able to register the total energy of the electron-photon component proceeding from a nuclear collision, it not being possible to construct on this base the energy spectrum of individual photons from π^0 -decays. Emulsion plates can be used perfectly well for this aim. Cascades detected in emulsion plates and initiated by single photons can be observed

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under the microscope and it is possible to estimate their energy even when they are some tens of microns apart.

After the energy spectrum of single photons from π^0 -decay has been obtained, it can be compared with the energy spectrum of nuclear-active particles and conclusions can be made as to the dependence of the nature of interaction on the energy of the colliding particle. In particular, if the exponent of the photon energy spectrum is equal to that of the nuclear-active particle spectrum, the conclusion to be drawn is that the meson generation spectrum and, probably, the energy spectrum of all particles generated in the collision is independent of the energy of the colliding particle; the nature of interaction is then independent on the energy of the interaction.

The problem of the photon energy spectrum has been worked out by the Japanese and Bristol groups. The Japanese group used a large emulsion chamber of an area of several m^2 , consisting of horizontal layers of thin emulsion separated by relatively thick (1.0 cm)

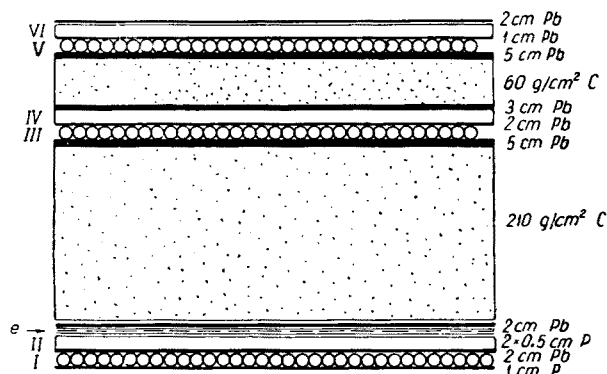


Fig. 1. Side view of apparatus. I—VI rows of ionization chambers, *e* — layer of emulsion plates analyzed by us.

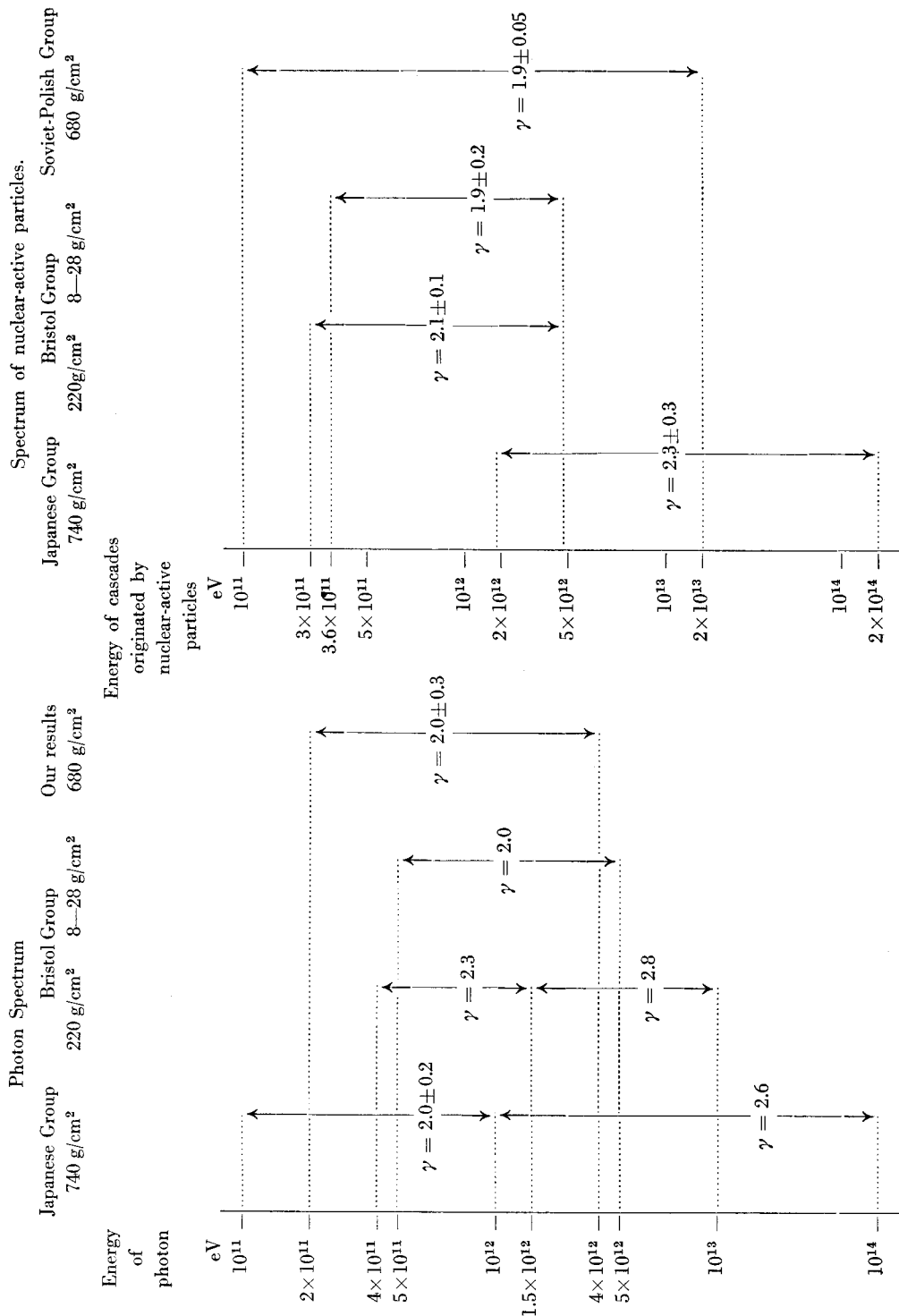
lead plates. This chamber was exposed at an altitude of 2740 m above sea level. The Bristol group used small blocks of vertical thick emulsion plates separated by thin layers of heavy absorbers (Pb, W, Cu), exposed in an airplane at a depth of 220 g/cm^2 in the atmosphere or in balloon flights at a depth of 8–28 g/cm^2 .

The results published by either group [1, 3, 5, 6, 7, 8] are presented in Table I, which contains the values of the integral energy spectrum exponents.

Comparing the values of the exponent for the photon spectrum and nuclear-active particle spectrum both from the Japanese and Bristol papers one could conclude that for photon energies $\sim 10^{12}$ eV a change in character of the interaction appears, because the exponent of the photon spectrum changes above the energy 10^{12} eV, while the exponent of the nuclear-active particle spectrum remains unchanged. This fact is also pointed to directly by the meson generation spectrum constructed by the Japanese group. This spectrum, although not confirmed by a good statistics, shows a change of exponent for energies of the interacting particle larger than 10^{13} eV.

On the base of experimental data provided by ionization chambers of the above-mentioned large apparatus at 3200 m above sea level, the spectrum of electron cascades

TABLE I



originated by nuclear-active particles was obtained with the exponent $\gamma = 1.90 \pm 0.05$ for the energy interval $(10^{11} - 2 \times 10^{13})$ eV [8]. In the present paper we shall concern ourselves with the photon spectrum using emulsion data from the apparatus presented in Fig. 1.

Detection of cascades

Emulsion data for the present investigation were obtained owing to our collaboration with the group of Professor Grigorov of Moscow University.

The apparatus in which the emulsions were exposed is situated in the high-mountain station on Mount Aragac in Armenia at an altitude of 3200 m above sea level. The emulsion plates analyzed in this publication had been placed above the second row of ionization chambers. They are denoted in Fig. 1 with the letter "e". The emulsion plates of dimensions 13×18 cm² were of *NIKFI* production.

From the indications of the ionization chambers (the first and the second rows of chambers were crossed) it was possible to determine the point at which the electron-photon cascade passed through the plates, with an accuracy of ~ 10 cm. For each event indicated by the chambers, one or two plates were taken out and scanned under a microscope. It follows from our experiments that ionization chambers are a good indicator of events of energy larger than 5×10^{11} eV. Events of such energies which would not be indicated by the chambers are practically not found in emulsions. Consequently, the large amount of work required for scanning the plates not indicated by the chambers is spared. The cascades found in the emulsions were initiated by photons from decays of π^0 -mesons generated in nuclear interactions in the graphite above the plates or in the air surrounding the apparatus (see, Fig. 1). Cascades produced by photons which arose above the apparatus or in the upper layer of graphite will not be detectable in emulsions, because they pass to the lower part of graphite through lead of a thickness of 20 cascade units or more. After passing through such a thickness of lead, electrons and photons of a cascade have an energy near the critical value for lead (7.6 MeV). When passing through graphite, whose critical energy is large (80 MeV), electrons are absorbed on a path shorter than one cascade unit because of ionization losses.

Elaboration of cascades

In the plates indicated by the ionization chambers during the 450 hours of work of the apparatus, 166 cascades were found. Of these, 69 cascades were in groups of two or more separated by distances of some tens or hundreds of microns. These cascades could as well have been initiated by photons as by electrons of pairs. The divergence angle between electrons in a pair is, according to the formula of Borsellino [4], about 100 times less than that between photons (from π^0 -decay) of the same energy; we were therefore able, knowing the distance between two cascade cores and their approximate energies, to distinguish between cascades from electron pairs and cascades from two photons of π^0 -decay.

In this way it was decided that 26 cascades proceeded from electrons of pairs and the others from photons. Moreover, 12 cascades were excluded from our considerations as initiated by μ -mesons, on the base of the large inclination of their axes in comparison with

that of the others and, simultaneously, their large energy. Finally, 141 cascades initiated by single photons were dealt with as follows:

All cascades were reproduced in drawing by means of a special arrangement for drawing microscope pictures. The number of electron tracks were then counted in circles with radii: 40, 100 and 160 μ in a plane perpendicular to the axis of the cascade. The numbers of electrons thus obtained are incorrect if the cascades are near to one another, because in this case tracks belonging to two or more cascades become mixed. A correction for this mutual influence of cascades was taken into account if it was of the order of some per cent or more, practically in cases in which the distance between two cores was less than 1000 μ .

Method of cascade energy determination

The cascades found in the emulsion were initiated by photons from the decay of π^0 -mesons generated in lower part of graphite absorber. These cascades after passing of graphite have a few electrons in a circle with radius of 100 μ . These electrons together with a comparable number of photons carry nearly the total energy of the cascade (~ 80 per cent). These particles create in lead separate cascades which can be distinguished in emulsion if the distances between them are not too small. But usually these secondary cascades join into one cascade with slight groupings of tracks.

For determining the cascade energy, the theory of Nishimura and Kamata [9] was used. On the base of this theory Nishimura and Kidd [11] calculated for G5 emulsion the curves of the dependence of the number of electrons in a circle of radius r (μ) traced about the cascade axis on the product (Er) (GeV μ), where E is the energy of a primary photon. The thickness t (in cascade units) of an absorber in which the cascade develops is the parameter of the family of curves. The same authors also calculated analogous curves for a primary electron pair.

We applied these curves for a primary photon and primary electron pair recalculating the values of the product (Er) to the corresponding values for lead. Fig. 2 represents the curves of Nishimura and Kidd on recalculation.

The energy of cascades was read from these curves for the number of electron tracks in circles with a radius of 100 μ . For cascades initiated by photons, we applied the curves for a primary photon. In this way the energy of the primary photons was obtained. For cascades initiated by electron pairs we applied the curves for a primary electron pair. The energy of the electron pair obtained is equal to the energy of the primary photon producing the pair. As thickness of the absorber, we took the total thickness of the layers of lead under the lower graphite absorber. This thickness varied according to the inclination of the cascade axis. The extension of a cascade in the air break between the layers of lead absorber was also taken into account.

The curves of Nishimura and Kidd had been calculated for a single primary photon or electron pair, whereas in our case cascades in lead were created as a combination of several cascades initiated by photons and electrons coming from graphite to lead. Since the curves of Nishimura and Kidd can be approximated by straight lines with a slope of $\sim 45^\circ$ for the intervals of (Er) and thicknesses of the absorber interesting us, the treatment of compound

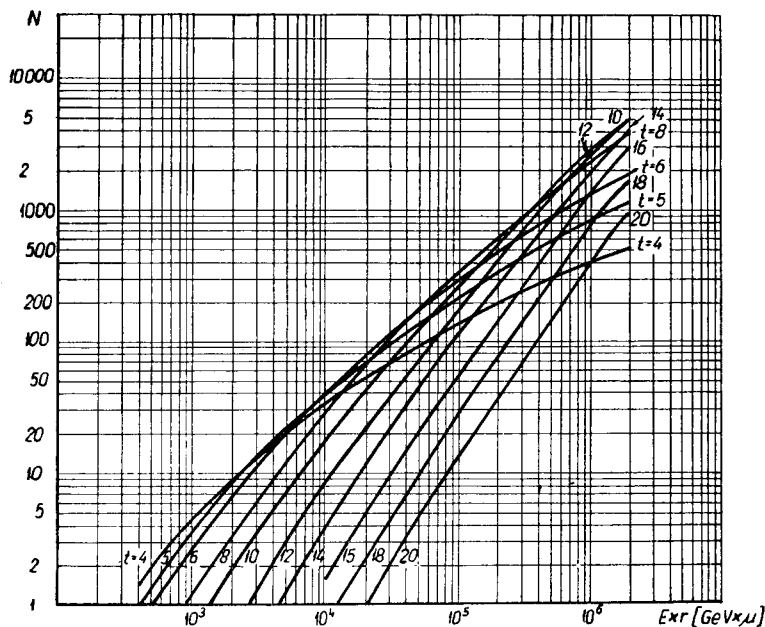


Fig. 2. Curves of Nishimura and Kidd for a primary photon after recalculation for lead. N denotes the number of electrons in circle of radius r (μ) for a cascade initiated by a photon of energy E (GeV). t denotes the thickness of the lead layer, in cascade units, penetrated by the cascade.

cascades as single cascades from a primary photon or an electron pair gave rise to error not exceeding 20 per cent in the energy estimation. The total error in the primary photon energy estimation, in our opinion, amounts to about 40 per cent.

Results

After the energy of the cascades found in the emulsion plates had been estimated, we introduced into the number of cascades the correction for the efficiency of scanning. This efficiency was determined by the method of double scanning used for part of our material. The method is described in the paper by Lim *et al.* [10]. The curve of the dependence of the scanning efficiency on the cascade energy is shown in Fig. 3.

In the above manner, the correct number of cascades and that of primary photons was obtained. In turn, the integral energy spectrum of photons was constructed, as shown in Fig. 4. The exponent of this spectrum in the energy interval of $(2 \times 10^{11} - 4 \times 10^{12})$ eV is $\gamma = 2.0 \pm 0.3$.

Our result is in agreement with that obtained by the Japanese group for energies $\leq 10^{12}$ eV (see, Table I). Our energy interval reaches a little above the energy 10^{12} eV, where both the Japanese and Bristol groups obtained a larger value of γ . Unfortunately, our material was too scarce for confirming the change in photon energy spectrum exponent or for contradicting such a change.

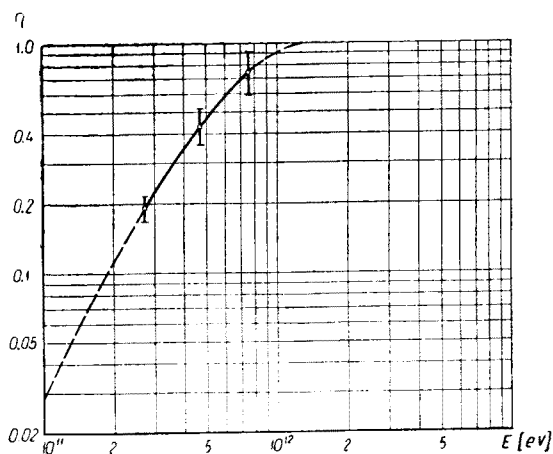


Fig. 3. Scanning efficiency of emulsion plates, E — energy of the cascade

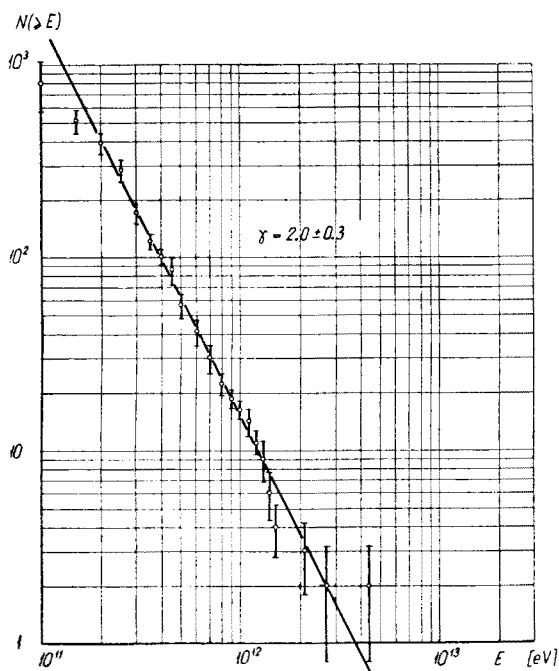


Fig. 4. Integral energy spectrum of photons from the decay of π^0 -mesons generated in the lower layer of graphite in the apparatus

Measurements carried out with ionization chambers belonging to the same apparatus yielded a value of the integral energy spectrum exponent $\gamma = 1.90 \pm 0.05$ for electron cascades caused by nuclear-active particles up to the energy 2×10^{13} eV [5]. According to our results, both nuclear-active particle and photon energy spectra have the same exponent γ in the

energy interval ($10^{11} - 4 \times 10^{12}$) eV. Thus, the character of the nuclear interaction does not change in this energy interval *i.e.* neither the mean inelasticity coefficient nor the exponent of the π^0 -meson generation spectrum varies.

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