Cross section of the photonuclear interaction at photon energies from 0.9 to 10 TeV

V. N. Bakatanov, R. V. Novosel'tseva, Yu. F. Novosel'tsev, A. M. Semenov, Yu. V. Sten'kin, and A. E. Chudakov
Institute of Nuclear Research, Academy of Sciences of the USSR

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An experiment to learn about the inelastic interaction of muons at the scintillation telescope of the Baksan Neutrino Observatory is discussed. Measurements of the cross section for the photonuclear interaction of photons with a nucleus, $\sigma_{\gamma A}$, over the photon energy range from 0.9 to 10 TeV are reported.

An experiment is being carried out at the Baksan underground scintillation telescope[1] to measure the cross section $d\sigma_{\mu A}(\nu,q^2)/d\nu$ for the inelastic scattering of cosmic-ray muons by nuclei of the telescope material, with an average atomic weight $\overline{A} = 26$ ($\nu = E - E'$), where E and E' are the muon energies before and after the interaction. If we know the cross section $d\sigma_{\mu A}(\nu,q^2)/d_\nu$ at small values of the square of the 4-momentum transfer, $q^2 = -Q^2$, we can obtain information about the cross section for the interaction of real photons with a nucleus, $\sigma_{\gamma A}(\nu)$, and the muon energy loss in the inelastic interaction.

In this experiment, four horizontal scintillation planes of the telescope along with overlaps between them are used as a calorimeter, which is used to detect electromagnetic and nuclear cascades generated by cosmic-ray muons in the soil above the apparatus ($\overline{A} = 25$) or in the aparatus itself ($\overline{A} = 27$) (Refs. 2 and 3). The average value of Q^2 in experiments of this type is[4] $Q^2 = 0.1$ GeV ($\hbar = c = 1$).

In the experiment we measured the ratio $R(\epsilon)$, i.e., the number of nuclear cascades $N_h(\epsilon)$ divided by the number of electromagnetic cascades $N_e(\epsilon)$, in identical intervals of the energy evolution in the apparatus, ϵ. Events of different natures are separated on the basis of the number of $\pi \to \mu \to e$ decays detected. The appearance of a delayed signal from a decay electron on an oscilloscope screen is accepted as evidence that a $\pi \to \mu \to e$ decay has been detected.[3]

The nuclear and electromagnetic cascades are separated in terms of the number of $\pi \to \mu \to e$ decays on the basis of the following principle in our experiment:

(1) The probability $P(m;\epsilon)$ of the detection of m decays and electromagnetic cascades which produce an energy evolution ϵ in the apparatus.

(2) The "separation criterion" $m_0(\epsilon)$, such that the probability χ for the detection of $m > m_0(\epsilon)$ decays in an electromagnetic cascade is $\lesssim 10^{-2}$, is determined:

$$\sum_{m=0}^{m_0} P(m;\epsilon) = 1 - \chi(m_0, \epsilon) \gtrsim 0.99. \tag{1}$$

(3) Cascades in which the number of $\pi \to \mu \to e$ decays is $m \leqslant m_0(\epsilon)$ are assumed to be electromagnetic.

The primary mechanism for the production of pions in an electromagnetic cascade is the photonuclear interaction of cascade γ rays with nuclei of the material:

$$\gamma + A \to x + n\pi^{\pm} .$$

The calculations of $P(m,\epsilon)$ used data on the interaction cross section and the multiplicity of the $\pi^{\pm}$ production from Refs. 5 and 6 for γ rays with energies $E_\gamma < 5$ GeV and from Ref. 7 for $E_\gamma > 5$ GeV. It is assumed that the number of $\pi \to \mu \to e$ decays detected is proportional to the energy evolution of the apparatus as the electromagnetic cascade passes. The calculations use the electromagnetic cascade curves generated by the Monte Carlo method for the actual structure of the apparatus. The muon spectrum at the position of the apparatus is taken in the form

$$N_\mu(> E) \sim (E + 200)^{-2.8} ,$$

where E is the muon energy, in units of gigaelectron volts. This is the shape of the spectrum found in this experiment.

The total number of electromagnetic events is found in accordance with expression (1):

$$N_e(\epsilon) = N(m \leqslant m_0, \epsilon)/[1 - \chi(m_0, \epsilon)]. \tag{2}$$

The other cascades detected are regarded as nuclear. One might ask whether it is possible that some nuclear cascades are not counted in the case in which nuclear cascades with a number $m < m_0$ of $\pi \to \mu \to e$ decays appear. Calculations show that the

TABLE I.

ϵ GeV	$\overline{E}_e$ GeV	$\overline{E}_h$ GeV	m_0	$N_e(\epsilon)$	m						x %	$\overline{m}_e$	$\overline{m}_h$
					0	1	2	3	3				
111–133	906	1150	2	630	470	134	19	7	60	e			
					477	126	20	4	3	t	1.1	0,308	8.4
160–230	1400	1780	3	425	273	113	28	7	44	e			
					277	113	25.4	5.5	3.8	t	0,88	0.478	11.5

fraction of such events does not exceed 3–4%; this figure is well below the statistical error in the number of nuclear cascades detected.

Table I shows experimental (e) distributions in m of all events, in comparison with the theoretical (t) distributions for electromagnetic events in two intervals of the energy evolution ϵ. The theoretical distributions have been normalized to the total number of electromagnetic events, $N_e(\epsilon)$, found from expression (2). Here $\overline{E}_e, \overline{E}_h$ are the average energies of the electromagnetic and nuclear cascades which are responsible for the given energy-evolution interval, and $\overline{m}_e \overline{m}_h$ are the average theoretical multiplicities of $\pi \to \mu \to e$ decays detected for the electromagnetic and nuclear cascades. The calculations of $\overline{E}_h$ and m_h made use of the data of Ref. 7 and of nuclear cascade curves found by the Monte Carlo method.

It can be seen from Table I that the experimental and theoretical distributions agree well at $m \leqslant m_0$; a good agreement is also observed for other ϵ intervals. Figure 1 shows the results of measurements of the quantity $R(\epsilon)$: the ratio of the number of nuclear cascades to the number of electromagnetic cascades detected in identical intervals of the energy evolution ϵ. Plotted along the abscissa here is the average energy $\overline{E}_h$ of the nuclear cascades which are responsible for the interval of energy evolutions e. The curve is theoretical, based on the cross sections from Refs. 8–10 for the various

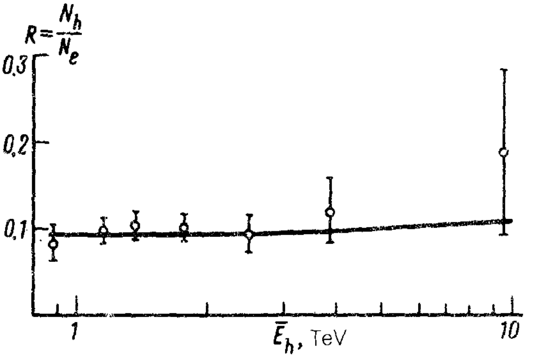

FIG. 1. The ratio (R) of the number of nuclear cascades, N_h, to the number of electromagnetic cascades, N_e, in identical energy-evolution intervals. Here $\overline{E}_h$ is the average energy of the nuclear cascades which are responsible for the given interval of energy evolutions. The line is theoretical.[10]

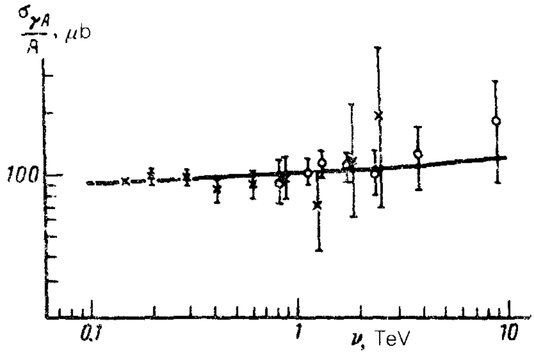

FIG. 2. Cross section for the photonuclear interaction of a photon with an $A = 26$ nucleus as a function of the photon energy. x—Ref. 11; o—results of the present study; line—theoretical.[10]

processes which lead to the production of cascades. Using the results in Fig. 1, and assuming that the cross sections for the production of electromagnetic cascades are well know, we can determine the cross section for the photonuclear interaction of real photons: $\sigma_{\gamma A/A}$. In Fig. 2, our results on $\sigma_{\gamma A}/A$ for $A = 26$ are compard with results found in Ref. 11 in a nearby interval of the energy transfer $\nu = \overline{E}_h$. The results found here agree with calculations based on the data of Ref. 10. There is some increase at the cross section at $\nu > 3$ TeV, but it is not statistically significant.

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