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PHOTOPRODUCTION OF π^0 MESONS ON NUCLEI NEAR THRESHOLD

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Results are presented of a measurement of the differential π^0-meson photoproduction cross section on Be, Al, Cu, Cd, and Ta nuclei at 154 MeV mean primary photon energy. The π^0 mesons were detected by recording coincidences of the $\pi^0 \rightarrow \gamma + \gamma$ decay photons by means of two scintillation telescopes. An analysis of the results obtained shows that the main contribution to the cross section is due to the elastic coherent photoproduction.

1. INTRODUCTION

THE impulse and Born approximations are usually employed in analyzing the experiments on the photoproduction of π^0 mesons on nuclei. According to the impulse approximation, the matrix element of meson photoproduction on a nucleus with mass number A can be represented by the sum of the photoproduction matrix elements on separate nucleons:

$$T = \langle \psi_f \left| \sum_{j=1}^{A} T_j \right| \psi_i \rangle = A \langle \psi_f | T_j | \psi_i \rangle, \qquad (1)$$

where ψ_i and ψ_f are the wave functions of the initial and final state of the nucleus (we assume that the photoproduction amplitude is independent of the isotopic spin of the nucleon). The meson photoproduction amplitude on a single nucleon in the Born approximation is given by

$$T_j = \exp\,[i\,(\mathbf{k} - \mathbf{p})\,\mathbf{r}_j]\,(\mathbf{K}\sigma_j + L), \qquad (2)$$

where **k** and **p** are, respectively, the momentum of the photon and of the meson in the c.m.s., σ_j and $\mathbf{r}_j$ are the spin and coordinates of the j-th nucleon, **K** and L are, respectively, the spin-dependent and spin-independent part of the matrix element for the π^0-meson photoproduction on hydrogen. For nuclei with spin zero, the photoproduction is described by the operator L only.

In studying the photoproduction near the threshold it is assumed that the main contribution is due to the process of elastic coherent π^0-meson production ($\psi_i = \psi_f$). We then obtain easily from Eqs. (1) and (2) the relation between the differential cross section for photoproduction on a nucleus with spin zero and the spin-independent part of the differential photoproduction cross section on hydrogen:

$$(d\sigma/d\Omega)_A = A^2 F^2(q)\,(d\sigma/d\Omega)_H,$$
$$q = \hbar^{-1}\,(k^2 + p^2 - 2kp\cos\theta)^{1/2}, \qquad (3)$$

where q is the recoil nucleus momentum, θ is the angle of emission of the meson in the c.m.s., and F(q) is the nuclear form factor:

$$F(q) = \langle \psi_f | e^{i\mathbf{qr}} | \psi_f \rangle = \int_\tau \rho(\tau)\, e^{i\mathbf{qr}} d\tau. \qquad (4)$$

$\rho(\tau)$ represents the normalized nucleon density in the nuclear volume τ.

If in the matrix element of the photoproduction on a nucleon we consider only M_{1+}, i.e., the amplitude responsible for the (3/2, 3/2) resonance in the πN system, then we can correlate in the following way the quantity $(d\sigma/d\Omega)_H$ with the total photoproduction cross section of π^0 mesons on hydrogen (σ_t):

$$(d\sigma/d\Omega)_H = \sigma_t \sin^2\theta / 4\pi, \qquad (5)$$

so that

$$(d\sigma/d\Omega)_A = \sigma_t A^2 \sin^2\theta\, F^2(q) \,/\, 4\pi. \qquad (6)$$

For nuclei with spin different from zero, there is a contribution to the cross section from the spin-dependent photoproduction operator. However, the production of mesons in that case will be incoherent, and the contribution of this process to the cross section is A times smaller than that of the elastic coherent photoproduction. It should be noted that the photoproduction operators with spin flip give angular distributions of the $\cos^2\theta$ type.

Second-order effects in the interaction of mesons with nuclei proportional to A^2 were predicted by Feĭnberg[1] already in 1941. The theory of coherent photoproduction of π^0 mesons was developed by a number of authors.[2-4] Experimentally, second order effects in the photoproduction of π^0 mesons on complex nuclei were first observed in 1957.[5] In these experiments the π^0-meson photoproduction cross sections were found to depend on A stronger than linearly at all angles, for elements from carbon to copper, at 180 and 200 MeV maximum energy of the bremsstrahlung spectrum. The elastic photoproduction of π mesons on nuclei was later investigated in a number of experiments.[6-11] We should like to mention especially the experiments [7] and [10] in which the process of coherent elastic photoproduction was used to obtain information on the intranuclear distribution of matter. From these experiments it follows also that the main contribution to meson photoproduction at primary photon energies up to 200 MeV is due to the elastic coherent production.

In the present article we describe a measurement of the angular distribution of π^0 mesons in the photoproduction on Be, Al, Cu, Cd, and Ta nuclei by photons with 154 MeV mean energy. For the first time the differential cross sections were measured so close to the photoproduction threshold (135 MeV). In the c.m.s. the energy of the produced mesons amounted to ~ 17 MeV. At this energy, the mean free path of mesons in nuclear matter is equal to ~ 25 F, so that the effects of multiple scattering should be small even for very heavy nuclei. Inelastic production for 150 MeV photons should also be small because of the Pauli principle. Consequently, we can expect that the experimental results will be well described by Eq. (6) and will yield information on the form factor of the nuclei investigated.

2. EXPERIMENTAL ARRANGEMENT

The experiment was carried out using the synchrotron of the Physics Institute of the Academy of Sciences. The investigated targets, ~ 0.1 radiation length thick, were place in the collimated bremsstrahlung photon beam with maximum energy of 180 MeV (Fig. 1). The π^0 mesons produced in the targets were detected by recording the coincidences of the $\pi^0 \rightarrow \gamma + \gamma$ decay photons in two scintillator telescopes. The maximum angle of emission of the decay photons $\psi_{\max}$ reaching the telescopes is related to the lower limit of the π^0 meson energy by the equation $E_{\min} = M_\pi c^2/\sin(\psi_{\max}/2)$, where M_π is the meson mass (in our experiment $E_{\min} = 140$ MeV). The upper limit of the π^0 meson energy was determined by the maximum energy of the bremsstrahlung spectrum from the synchrotron (180 MeV). The angle θ_T (Fig. 1) determined the mean value of the angle of emission of the π^0 mesons. Since the rest energy of the investigated nuclei is much greater than the energy of the primary photons, then the energy spectrum of detected π^0 mesons is almost independent of θ_T for a given angle ψ between the telescopes and of the mass of the nucleus. The angle ψ therefore varied little in the measurements, amounting on the average to 133.7°.

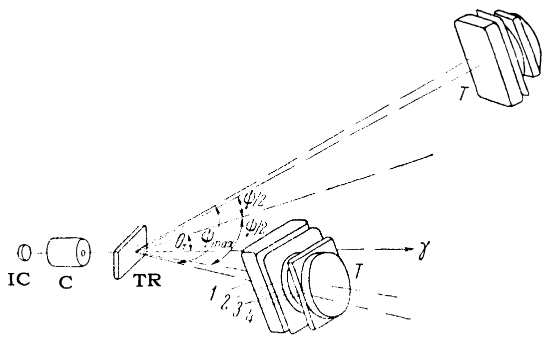

FIG. 1. Geometry of the experiment (IC – ionization chamber, C – collimator, TR – target, T – telescopes 1 – absorber, 2 – converter, 3 – scintillator, 4 – aluminum absorber).

The telescopes used in the experiment consisted of a plastic absorber 3 cm thick, a lead converter 5 mm thick, and two scintillation counters with an aluminum absorber between them (the two absorbers shielded the telescope from background electrons and low-energy γ rays). The pulses from the scintillation counters were fed, after shaping, to a diode fourfold coincidence circuit whose output was connected through a wide-band amplifier and discriminator to a mechanical register. The coincidence system worked with 100% efficiency for a resolving time of 5×10^{-9} sec.

In order to find the absolute value of the cross section it is necessary to know the photon detection efficiency of the telescopes. A new method was developed for this purpose, based on the detection of a bremsstrahlung photon in coincidence with the electron which emitted it. The energy of the electron before and after emission was measured by magnetic spectrometers. The energy difference determines the energy of the detected photon, and the ratio of the number of the γe coincidences to the number of electrons detected during the same period of time gives the value of the counter efficiency for photon detection. A description of the experiments on the determination of the telescope efficiency can be found in [12].

The measurements were carried simultaneously at three angles by three identical telescope pairs. A cyclical permutation of the pairs enabled us to check the performance of the system (the yield of the particles at each angle was determined from the count of all telescope pairs). All telescope pairs gave the same results within the limits of statistical accuracy. In addition, a count from a carbon target was taken for a given position of the telescopes to check the stability of the apparatus.

In addition to the coincidence count, control experiments were carried out to find out the nature of the events recorded. In one of such experiments, we have measured the ratio of counts with the converter placed respectively between and before the scintillation counters of the telescopes. This ratio was found to equal 0.06 and to be independent of the telescope angle with respect to the bremsstrahlung beam from the synchrotron. This shows that in the experiment we recorded photons and not charged pairs (the small residual count can be explained by the conversion of photons in the plastic absorbers, in the steel walls of the telescope, and in the first scintillator). In the second control experiment, we have measured the variation of the coincidence counting rate with the maximum energy of the bremsstrahlung spectrum.[11] The fast decrease in the counting rate when the spectrum limit approached the photoproduction threshold testified that π^0 mesons were detected, and that the contributions of chance coincidences and of charged pairs were small.

Chance coincidences amounted to less than 1% of the effect at all angles and for all targets. To decrease the number of chance coincidences, the pulse duration was stretched to 1000 μsec. This corresponds to a change of the maximum bremsstrahlung energy from 175 to 180 MeV. The count without the target, negligibly small for Be and Al, rose to a considerable fraction for Cu, Cd, and especially Ta for large values of θ_T, and was subtracted from the count with the target.

For the relative measurements of the bremsstrahlung beam intensity we used a thin-wall ionization chamber. Absolute measurements were carried out by activating graphite detectors in the reaction $C^{12}(\gamma, n)C^{11}$. We compared the activation method results with the quantometer measurements. The latter gave an intensity by 6% greater than the graphite detectors. This may serve as an estimate of the accuracy of the absolute measurements.

3. CALCULATION OF THE CROSS SECTIONS FROM THE YIELDS BY THE MONTE CARLO METHOD

The quantity obtained directly in the experiment was the yield, i.e., the number of coincidences for a given telescope position relative to the intensity of the primary photon beam. As is well known, the yield of a reaction N is related to the differential cross section dσ/dΩ by the equation

$$N = n\int_E\int_\Omega \frac{d\sigma}{d\Omega}(E, \Omega)\,\eta(E)\,\varepsilon(E, \Omega)\,dE\,d\Omega, \qquad (7)$$

where n is the number of target nuclei per cm^2, $\eta(E)$ is the primary particle flux, $\epsilon(E, \Omega)$ is the detection probability of the process investigated by the apparatus employed, E is the primary particle energy, and Ω are the angular coordinates of the direction of emission of the reaction products. In addition to the absolute value of the cross section, the energy and angular resolution curves of the apparatus are of interest:

$$R(E) = \int_\Omega \eta(E)\,\varepsilon(E, \Omega)\,d\Omega, \qquad (8)$$

$$R(\Omega) = \int_E \eta(E)\,\varepsilon(E, \Omega)\,dE. \qquad (9)$$

From Eqs. (7)—(9) it follows that in the reduction of data it is necessary to know the function $\epsilon(E, \Omega)$ which is determined by the kinematics of the process, the geometry of the setup, and instrumental parameters. Because of the complicated kinematics of the photoproduction process, involving the detection of the π^0 mesons through the two decay photons, and the geometry of the experiment, an exact analytical calculation of $\epsilon(E, \Omega)$ is impossible. We used therefore the Monte Carlo method to determine the detection probability in the present experiment. This could be done since the processes studied in the experiment, beginning with the interaction event, and ending with the activation of the mechanical register, can be represented as a sequence of random events occurring with a given probability. The application of this method consists in making a model of this chain of events by means of a corresponding probability scheme and carrying out, using this scheme, of a large number of trials. If l out of k independent trials for fixed values of E_0 and Ω_0 result in the detection of the event, then as an estimate of $\epsilon(E_0, \Omega_0)$ we can take the ratio l/k (the variance of this estimate for $k \gg l \gg 1$ equals l/k^2). By varying E_0 and Ω_0 we find $\epsilon(E, \Omega)$.

For the π^0 meson photoproduction the sequence of events which essentially contribute to the detection probability is as follows: A π^0 meson is produced within volume dV with probability $\eta(V)dV$. Since the lifetime of a π^0 meson is very short ($\tau \sim 2 \times 10^{-16}$ sec), we can consider the decay to occur in the same volume element. The function $\eta(V)$ thus serves to select the point of π^0-meson decay. The function $\eta(V)$ can easily be determined if the intensity profile of the bremsstrahlung beam and its absorption in the target are known.[13] The direction of the photon emission in the π^0 meson decay was first determined in the rest system of the meson where the distribution is isotropic and then calculated in the laboratory system (l.s.) using relativistic transformation formulae. If one of the decay photons was not absorbed in the target (the probability of such an event is κ_{12}) and two photons reached the telescopes and were detected (with efficiency ξ), then the trial resulted in the detection of a photoproduction event. A detailed description of the method and its execution using fast computers can be found in[13].

The calculated energy resolution of the system is shown in Fig. 2. The resolution was found to be identical for all angles θ_T (because of the weak dependence of the angle ψ between the telescopes on θ_T). The mean value of the primary photon energy was equal to 154 ± 8 MeV. As can be seen from Fig. 2, an error of several MeV in the value of the maximum energy of the bremsstrahlung spectrum does not cause a large error in the detection efficiency and, consequently, does not influence the absolute value of the cross section.

The angular resolution for various θ_T shown in Fig. 3 is practically independent of the atomic number of the target nucleus since the rest mass of all nuclei used as targets is much greater than the energy of the primary photons.

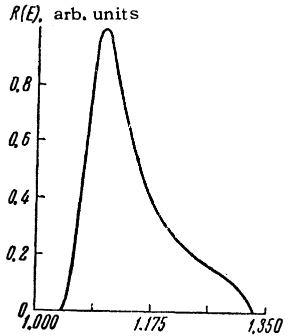

FIG. 2. Energy resolution of the system (energy expressed in rest-mass units of the π^0 meson).

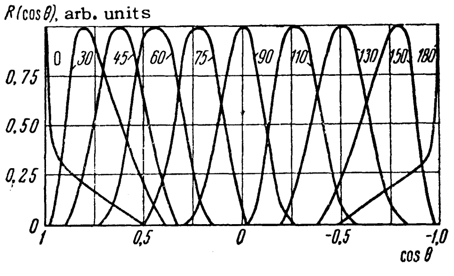

FIG. 3. Angular resolution for different positions of the telescope. The numbers at the curves give θ_T in degrees.

The data of the present experiment were processed using the electronic computer of the Physics Institute of the Academy of Sciences.

4. RESULTS

The results for Be are compared in Fig. 4 with the cross section of coherent π^0 meson photoproduction calculated according to Eq. (6) using a modified exponential distribution of nucleon density in the nucleus. The experiments on high-energy electron scattering[14] gave for this distribution a mean-root square nuclear radius of 3.04 ± 0.07 F for Be, while calculations based on the shell model gave 2.3 ± 0.2 F. As can be seen from Fig. 4, our results are well described by the model of coherent photoproduction with a root-mean-square ra-

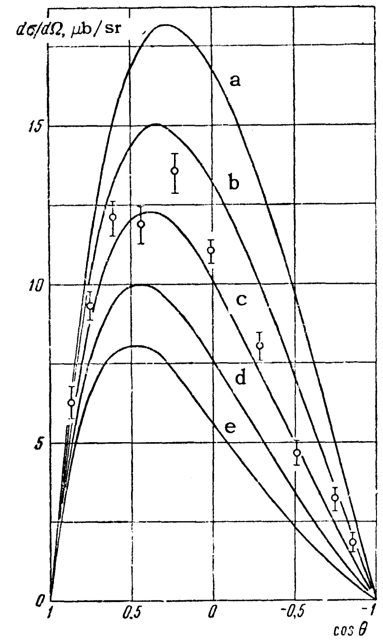

FIG. 4. Differential cross section for π^0 meson photoproduction on Be. The curve represents the elastic coherent photoproduction cross section for the modified exponential model and the following values of the root-mean-square radius: a – 1.84, b – 2.14, c – 2.44, d – 2.74, and e – 3.04 F.

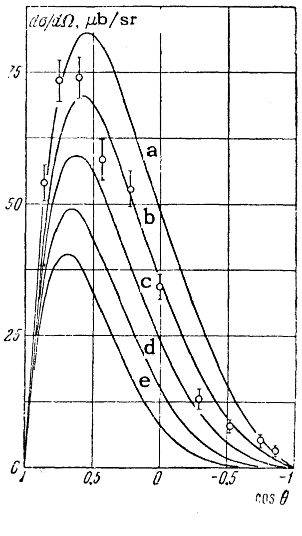

FIG. 5. Differential π^0 meson photoproduction cross section on Al. The curve represents the elastic coherent photoproduction cross section for the Fermi model with t = 2.5 F and different values of c: a – 2.57, b – 2.89, c – 3.21, d – 3.53, and e – 3.85 F.

dius of ~ 2.4 F, which is in agreement with the theoretical prediction.

In Figs. 5—8 are given the experimental data and the calculated results on the coherent photoproduction of mesons on Al, Cu, Cd, and Ta, assuming a nucleon density distribution according to the Fermi model. The parameters of the Fermi model: c (the distance at which the density decreases by a factor of two as compared with the density in the center of the nucleus) and t (the thickness of the surface layer) were varied around the values obtained for medium and heavy nuclei in electron scattering experiments ($c = 1.07\ A^{1/3}$ F, $t = 2.5$ F [14,15]). From Figs. 5—8 it follows that near the first maximum the experiment is in agreement with the calculation, while in the region of the second maximum there is a discrepancy.

In calculating the differential cross section from Eq. (6), we used for σ_t the values obtained in [16] from the dispersion relations for π^0 meson photoproduction on protons. In the energy range of interest, these values coincide with the earlier experimental results. [17]

The values of the cross section in Figs. 4—8 are given in the l.s. For Al, Cu, Cd, and Ta the c.m.s. system practically coincides with the l.s. The corrections are much smaller than the statistical errors. For Be the correction due to the transformation to the c.m.s. amounts to 6%.

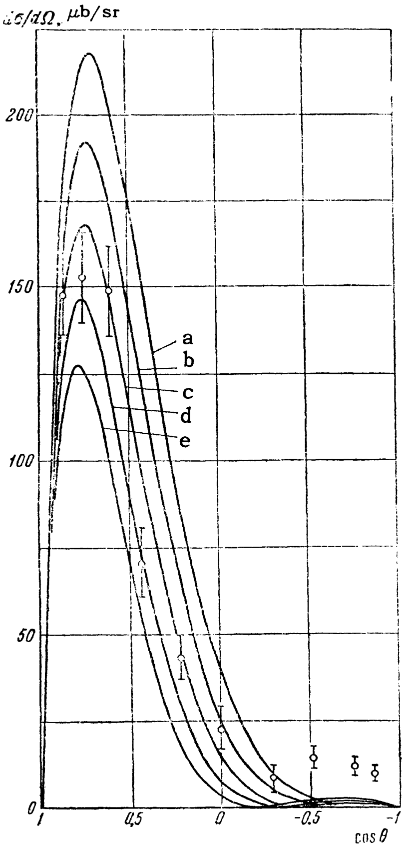

FIG. 6. Differential π^0 meson photoproduction cross section on Cu. The curve represents the elastic coherent photoproduction cross section for the Fermi model with t = 2.5 F and different values of c: a – 3.87, b – 4.07, c – 4.27, d – 4.47, and e – 4.67 F.

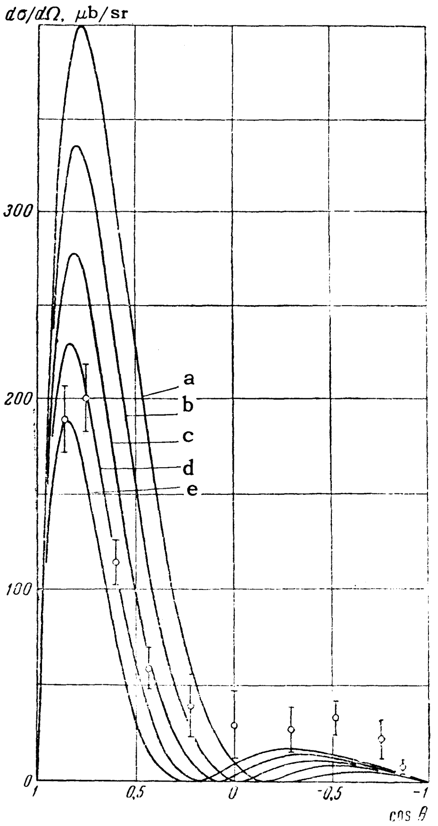

FIG. 7. Differential π^0 meson photoproduction cross section on Cd. The curve represents the elastic coherent photoproduction cross section for the Fermi model with t = 2.5 F and different values of c: a – 4.63, b – 4.88, c – 5.13, d – 5.38, and e – 5.63 F.

Thus, a preliminary analysis of the results shows that the main contribution to the π^0 meson photoproduction cross section near the first maximum at 154 MeV primary photon energy is due to the elastic coherent photoproduction of the mesons on all nucleons, independently of the isotopic spin and position in the nucleus. The discrepancy between the experiment and the theory in the range of the second maximum, using the data on the form of the nucleus from electron scattering experiments indicates either an inaccuracy in the assumptions underlying Eq. (6) or the necessity of using in the calculation a nucleon density distribution in nuclei different from that obtained in the experiments of Hofstadter et al. [14] A more detailed analysis of the experimental results will be given in a following article.

In conclusion, the authors express their gratitude to Prof. P. A. Cerenkov for his interest in the experiment, to A. M. Baldin and A. I. Lebedev for discussion of the theoretical problems, and to the accelerator team for assuring good operation of the synchrotron. We are also greatly obliged to

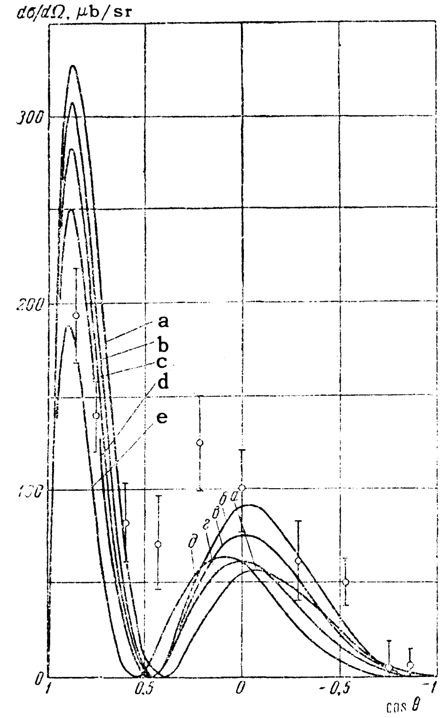

FIG. 8. Differential π^0 meson photoproduction cross section on Ta. The curve represents the elastic coherent photoproduction cross section for the Fermi model for different values of the parameters c and t (in Fermis): a – c = 6.15, t = 2.5; b – c = 6.45, t = 1.5; c – c = 6.45, t = 2.0; d – c = 6.45, t = 2.5; e – c = 6.75, t = 2.5.

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