Direct measurement of inelastic photoproduction of π^0 mesons at light nuclei

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Measurements of the yields of the photoproduction of π^0 mesons at the ^{6}Li nucleus, with excitation of the 0^+1 level of the nucleus (3.56 MeV), and at the ^{12}C nucleus, with excitation of the 2^+0 level (4.44 MeV), are reported.

Only neutral mesons can be produced both incoherently and coherently at all nucleons of a nucleus. In incoherent (or inelastic) photoproduction of neutral pions, partial reactions are of considerable interest.[1–4] When quantum states of the final nucleus are selected experimentally in such reactions, it becomes possible to obtain more-detailed information about the one-nucleon amplitudes for the photoproduction of pions, on the behavior of Δ isobar in a nucleus,[2] and on the transitional nuclear densities. In particular, only the isoscalar parts of the one-nucleon amplitude contribute to the amplitude for the partial reaction[1]

$$\gamma + {}^6\mathrm{Li}(1^+0, 0\ \mathrm{MeV}) \to \pi^0 + {}^6\mathrm{Li}^*(0^+1, 3.56\ \mathrm{MeV}). \qquad (1)$$
$$\hookrightarrow {}^6\mathrm{Li} + \gamma'$$

The values of the isoscalar multipoles which have been determined from $\gamma N \to \pi N$ experiments are extremely unreliable, since their contribution to the cross sections for the elementary processes is small.[2] In this situation, measurements of the cross section for reaction (1) will add substantially to our knowledge of the values of the basic isoscalar multipoles.

In the resonance region of the energies of the incident γ rays, many experiments have measured only the inclusive yields of π^0 mesons at nuclei. In recent experiments, attempts have been made to distinguish a coherent photoproduction of pions or other reaction channels.[5–8] The method of an "active" target,[5] the detection of other particles,[6] and other methods which have been used do not lead to a reliable discrimination of reaction channels. It is possibly for this reason that it has not been found possible to completely explain the results of these experiments on the basis of the theoretical models which have been tried.[5,7]

In this letter we report preliminary measurements of the yields of the inelastic production of π^0 mesons at lithium and carbon nuclei. Photons from the decay of a neutral pion and photons from a radiative transition of an excited nucleus were detected in coincidence. The use of this method runs into difficulties associated with the discrimination of rare two-step processes and in achieving a high energy resolution for spectrometers under the working conditions at today's accelerators, with their small duty factor.[8,9] An experiment has been carried out in the bremsstrahlung beam of the Sirius synchrotron, with a filling factor of 10%. Bremsstrahlung with a maximum

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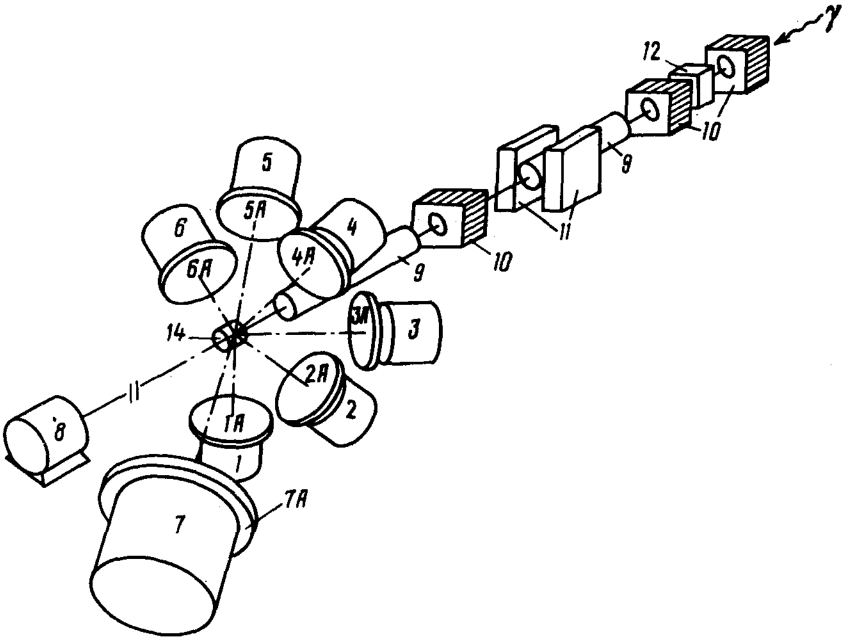

FIG. 1. Experimental layout. 1–6—Scintillation spectrometers; 1A–7A—anticoincidence counters; 7—Cerenkov spectrometer; 8—quantometer; 9—vacuum chambers; 10—collimators; 11—purifying electromagnet; 12—"spectrum hardener."

energy $E_0 = 500$ MeV was formed by collimators, purified, and sent through the target to a quantometer (Fig. 1). The high-energy photons from the decay of the pions were detected by a total-absorption Cerenkov spectrometer, which was positioned in a horizontal plane, monitored a solid angle of 50 msr, and had an energy resolution of 30%, a time resolution of 2 ns, and a sensitivity of 80 MeV. The nuclear photons and the hard photons from the pion decay were detected by six large-volume spectrometers positioned at azimuthal angles $\gtrsim 130°$ in various planes. The spectrometers were surrounded by very effective lead-concrete shielding. The common "trigger" of the apparatus operated upon the detection of fast coincidences of pulses from the Cerenkov spectrometer and from one or several of the scintillation spectrometers. The trigger pulse initiated the operation of several pieces of apparatus, which performed the following actions: conversion of the analog and temporal data coming from the detectors into digital form, sorting, and sampling data. The following were then written in the computer memory: the "trigger configuration," the charges, and the temporal position of the spectrometer signals. Controllable light-emitting diodes were used to automatically monitor the gain of the spectrometer as the statistical base was being built up.

The measurement procedure consisted of the determination of the yield of nuclear γ rays as a function of the average emission angle of the π^0 mesons. Figure 2 shows low-energy fragments of the γ spectra found for scintillation spectrometer 3 at an average pion emission angle of 40°. In the γ energy spectra which were constructed

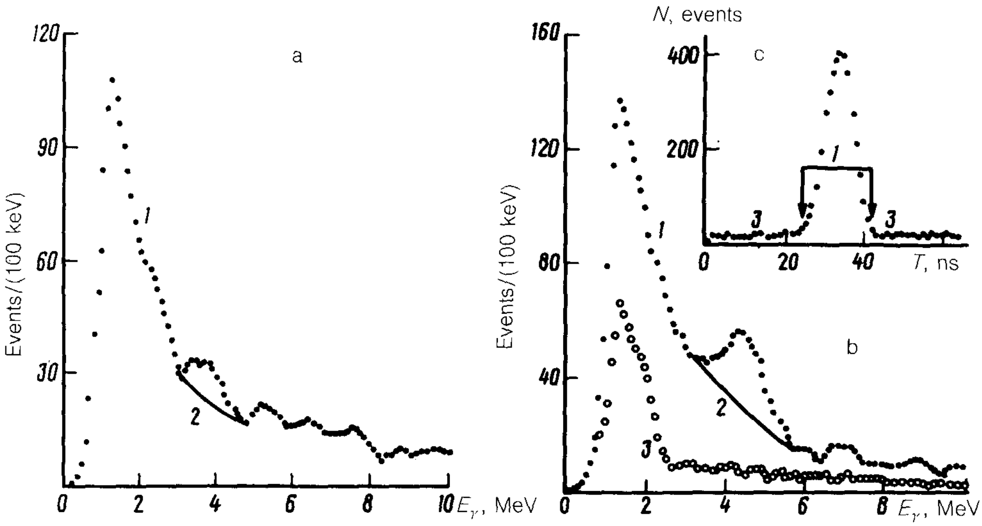

FIG. 2. Fragments of the energy spectra of photons detected by spectrometer 3, connected in coincidence with the Cerenkov spectrometer. a: Spectra of photons for the ^{6}Li nucleus. 1—Spectrum of photons for time-correlated events; 2—approximation of the continuous distribution in spectrum 1. b: Spectra of photons for the ^{12}C nucleus. 1,2—The same as in part a; 3—spectrum for time-correlated events.

from the events which fell within the temporal correlation peak [Fig. 2(c)] we can clearly see the following peaks: at the ^{6}Li nucleus, a peak for $E_\gamma = 3.6$ MeV, which corresponds to a radiative transition of the nucleus from an excited 0^+ level (3.56 MeV) to the ground level; at the ^{12}C nucleus, a peak for $E_\gamma = 4.4$ MeV, which corresponds to a transition of the nucleus from the 2^+ level (4.44 MeV) to the ground level. In these spectra we determined the areas under the peaks, from which we then determined the differential yield of the partial reaction, from the following formula (under the condition that the emission accompanying the nuclear transition is isotropic):

$$Y_e(\theta_C) = \sum_i \frac{4\pi N^i_\gamma}{n\epsilon_i\eta_i\Omega_C\Omega^i_\gamma}, \tag{2}$$

where N^i_γ is the area under the peak in the spectrum for spectrometer i, n is the number of nuclei in the target, ϵ_i is the photoefficiency of the spectrometer, η_i are corrections for the absorption of photons in the target and in the material along the path to the spectrometer, Ω_C and Ω^i_γ are the solid angles of the Cerenkov and scintillation spectrometers, $\theta = u/E_0$ is the number of equivalent photons, and u is the total energy of the bremsstrahlung beam. Using the known relationship between the number of photons from the decay of π^0 mesons and the cross section for their photoproduction,[10] we can calculate the theoretical yield of the partial reaction from

$$Y_T(\theta_C) = \int_{E_t}^{E_0} \int_0^\pi \frac{d\sigma(\theta_\pi,k)}{d\Omega} \frac{F(k)}{k} W(\theta_\pi, \theta_C) d\theta_\pi dk, \tag{3}$$

where $d\sigma/d\Omega$ is the cross section for reaction (1) as a function of the pion emission angle θ_π and of the energy of the incident photon, k; $F(k)/k$ is the bremsstrahlung γ spectrum; E_t is the threshold energy for reaction (1); and $W(\theta_\pi,\theta_C)$ is the angular-resolution function of the apparatus. In calculating this function we took into account the unambiguous relationship among the pion energy E_π, the angle θ_π, and the angular position of the Cerenkov spectrometer, θ_C, for reaction (1). We also took into account the efficiency of the detection of π^0 mesons by the spectrometer which we used. The cross section for reaction (1) was calculated on the basis of a nuclear shell model with intermediate coupling.[1,3] We used two versions of the one-nucleon amplitudes for the photoproduction of pions, found from multipole analyses,[11,12] in the calculations. Each set of amplitudes gives a good description of the set of experimental data on the $\gamma N \to \pi N$ reactions, while the cross sections for reaction (1) calculated with the amplitudes from Ref. 12 lead to cross sections larger by a factor of 8–11 than the cross sections calculated with the amplitudes from Ref. 11. This result is a consequence of the substantial difference in the analyses of Refs. 12 and 11 between the values of the isoscalar multipole $E_{0+}^{(0)}$. Because of the particular features of the nuclear transition $^6Li \to {}^6Li^*$ (3.56 MeV), this multipole dominates the cross section for reaction (1). The measured yield for reaction (1) for $\theta_\pi = 40°$, averaged over the interval $\theta_\pi = 15–55°$, is $Y_e = (1.4 \pm 0.3) \times 10^{-31}$ cm^2/[sr·(eq.ph.)]. The theoretical yields calculated with the one-nucleon amplitudes from Ref. 11, Y_{T1}, and from Ref. 12, Y_{T2}, are $Y_{T1} = 1.8 \times 10^{-33}$ cm^2/[sr·(eq.ph.)] and $Y_{T2} = 1.6 \times 10^{-32}$ cm^2/[sr·[eq.ph.)]. Consequently, the decrease in the values of the isoscalar multipoles which was found in the analysis of Ref. 11, primarily by virtue of a contribution from the exchange of vector mesons, leads to a significant discrepancy between the calculations and experiment. Estimates show that agreement with experiment apparently cannot be reached if we use other nuclear wave functions in the calculations or incorporate the final-state interaction of the pions. A significant increase (by a factor ~ 10) in the cross section for reaction (1) can be achieved by assuming the isotensor contribution to the one-nucleon amplitude, E_{0+}^T, to be larger than the isoscalar contribution, E_{0+}^0 (Ref. 13) (e.g., $E_{0+}^T = 6E_{0+}^0$). For the reaction $(\gamma + {}^{12}C \to \pi^0 + {}^{12}C^*(2^+;0)$, the differential yield is $Y_e = (4 \pm 0.3) \times 10^{-30}$ cm^2/[sr·(eq.ph.)].

We note in conclusion that the broad peak observed in the measured spectra for $E_\gamma = 15–25$ MeV is evidence of a significant fraction of the photoproduction of neutral pions with the excitation of a nucleus in the region of a giant resonance.

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