Measurement of the Reaction ^{4}He$(\gamma, \pi^0)^4$He for $E_\gamma = 290$ MeV

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We report measurements of differential cross sections for the reaction ^{4}He$(\gamma, \pi^0)^4$He with a photon energy of 290 MeV. Use of a good-resolution π^0 spectrometer allowed restriction of events to those where the residual ^{4}He nucleus was left in the ground state (the coherent process). By detecting the π^0 directly, we thus provide the first forward-angle data for this reaction in the Δ-resonance region. Our results are in good agreement with a recent Δ-hole model calculation.

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The study of photopion reactions plays a very important role in the field of intermediate-energy nuclear physics. Much has been learned about intermediate-energy nuclear reactions from the study of pion-induced processes such as elastic and inelastic scattering, single and double charge exchange, and absorption. Theoretical calculations, such as those using the Δ-hole model, have had considerable success in describing the data from pion-induced reactions. Photopion data can provide important additional constraints on such models. Because the photon can interact throughout the nucleus, (γ, π) reactions in the $\Delta(1232)$ resonance region sample more of the nuclear volume than do pion-induced reactions. In addition, the real photon provides a purely transverse coupling in the initial channel.

Photoproduction of neutral pions occupies a special position in the general field of photopion physics. Because the initial and final nuclear states can be the same, the π^0 can be produced coherently from all the nucleons. This generally leads not only to enhanced cross sections compared to charged pion photoproduction but also to some simplifications in theoretical calculations. In particular, within the framework of a microscopic model for the pion-nucleus optical potential, the reaction amplitude is then unambiguously calculable.[1]

Despite its attractions as a constraint on models of pion-nucleus interactions, coherent neutral pion photoproduction has been little studied. This is primarily because of the difficulty in obtaining high-quality data. Experiments[2,3] which used detection of the recoil nucleus to obtain data for ^{4}He$(\gamma, \pi^0)^4$He have been limited, in the Δ-resonance region, to measurements of back-angle differential cross sections. Since almost all of the cross section is expected to be at angles less than 80°, such experiments have not been able to place significant constraints on model calculations. Experiments which detected the decay photons of the π^0 directly have suffered from poor π^0 energy resolution and have thus been unable to restrict events to those which corresponded to leaving the nucleus in its ground state. Davidson[4] measured (γ, π^0) data for several nuclei, at $E_\gamma = 250$ MeV, but the experimental π^0 energy resolution was approximately 20 MeV [full width at half maximum (FWHM)]. The ^{12}C$(\gamma, \pi^0)^{12}$C cross section reported in Ref. 4 has been a source of difficulty for a number of calculations, since inclusion of the effect of absorption of the outgoing π^0 produced cross sections roughly a factor of 2 below the Davidson data. A recent experiment at Bonn[5] reported cross sections for the ^{12}C$(\gamma, \pi^0)^{12}$C process, with $E_\gamma = 235$ MeV, which are indeed about a factor of 2 lower than those of Ref. 4. Unfortunately, because the energy resolution of the detected π^0 is poor in the experiment at Bonn, the cross sections quoted are for events which leave the ^{12}C nucleus in any particle-stable state, not just in the ground state.

In an attempt to provide useful, reliable data for coherent π^0 photoproduction in the Δ region, we have constructed a good-resolution π^0 spectrometer for use with a bremsstrahlung beam at the Bates Linear Acclerator Center. The π^0 spectrometer[6,7] is similar in principle to one previously built at Los Alamos.[8,9] Two independent photon detectors, each consisting of two Pb-glass converter and multiwire proportional chamber arrays followed by total-absorption Pb-glass blocks, made a precise (~ 4 mm) determination of the photon conversion points and a rough (~ 35%) measure of the photon energies. By restricting events to those in which the two photons had roughly equal energies (minimum laboratory opening angle), the π^0 energy was determined primarily by the measured opening angle of the photons. Our spectrometer is capable of a resolution of ~6 MeV (FWHM) at $E_{\pi^0} = 290$ MeV. The overall acceptance of the spectrometer, which peaks at a particular energy for a given opening angle of the photon arms, has a maximum value of approximately 10^{-4} sr. The production angle of the π^0 was determined with an uncertainty of $\pm 1.0°$. More details on the π^0 spectrometer at Bates are contained in Refs. 6 and 7.

To obtain reasonable event rates for detection of π^0's from coherent neutral pion photoproduction, it was necessary to use a bremsstrahlung beam. Bremsstrahlung photons were produced by electrons from the Bates linear accelerator passing through a 0.2% radiation length Al and BeO radiator. The remaining electron beam was bent out of the beam line by a dumping magnet. The bremsstrahlung photons then passed through collimators and another sweeping magnet to form a uniformly intense spot 2.5 cm (vertical) × 0.6 cm (horizontal) at the target position 10 m downstream of the radiator. Because of the care taken in collimation and shielding, it was found that the photon beam spot was quite stable and that singles rates in the spectrometer counters (the limiting factor in determing the allowed instantaneous beam rate) were dominated by photon beam-on-target processes. The average photon beam flux was typically 2×10^7/sec in the top 15 MeV and was monitored with a Wilson quantameter[10]; the calibration of the quantameter contributed an overall uncertainty of 3%.

Because of the use of the bremsstrahlung beam and the strong energy dependence of the π^0 spectrometer acceptance, it was important to verify that we had a good understanding of these and other effects before attempting to measure data for coherent neutral pion photoproduction. Fortunately, high-quality differential cross sections for $^1H(\gamma,\pi^0)^1H$ do exist[11] for comparison at $E_\gamma \sim 300$ MeV. Using a liquid-hydrogen target we measured the π^0's produced at a laboratory angle of 72.5° by a bremsstrahlung beam with a tip energy of 298 MeV. The data are shown in Fig. 1 as a yield of π^0's as a function of photon energy. The photon energy was calculated from the measured π^0 energy under the assumption of the process $\gamma + p \rightarrow \pi^0 + p$. The cutoff on the low-energy side of the curve is due to the π^0 spectrometer acceptance; on the higher-energy side it is due to the bremsstrahlung shape. The solid curve in Fig. 1 is the yield expected from convolving the bremsstrahlung flux,[12] the previously measured differential cross sections,[11] and the calculated energy-dependent π^0 spectrometer acceptance. No normalization factors have been applied. The excellent agreement between the measured and expected yield curves gives us confidence that we have a good understanding of the π^0 spectrometer performance.

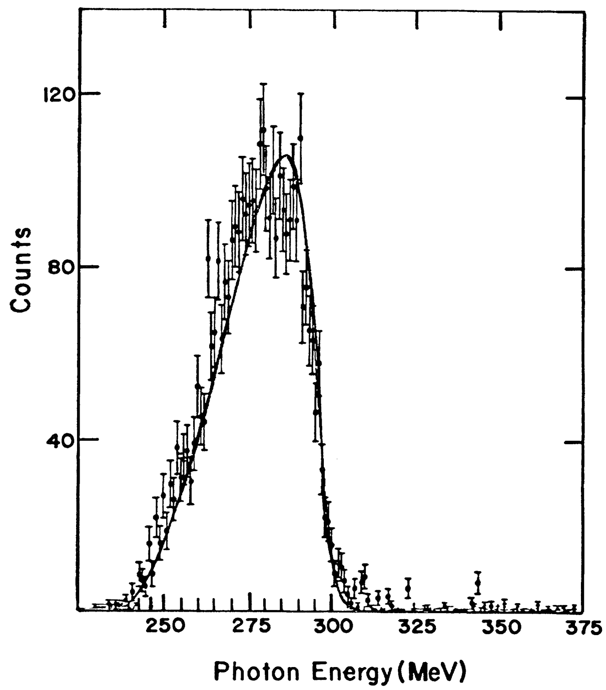

FIG. 1. Comparison of the measured yield at $\theta_{lab} = 72.5°$ for $^1H(\gamma,\pi^0)^1H$ with the expected curve with a bremsstrahlung end point of 298 MeV. The expected yield (solid line) includes the bremsstrahlung flux, previously measured[11] cross sections, and the calculated energy-dependent spectrometer acceptance, with no adjustable parameters.

Liquid helium was chosen to be among the first targets for investigation because the large separation (~ 20 MeV) between the ground state and any excited states of ^{4}He minimizes π^0 resolution concerns and because recent Δ-hole calculations[1,13,14] exist for the process $^4He(\gamma,\pi^0)^4He$ in the resonance region. The target used was a vertical cylinder of liquid helium, 5 cm in diameter and 25 cm high. The photon beam, centered on the target, was thus much smaller in the cross-sectional area than was the target vessel. The quantity of He contained in the target cylinder was determined after the experiment by measuring the attenuation of

14.4-keV γ's from a ^{57}Co source. The uncertainty in the knowledge of the target thickness was 5%. Data were also taken with the target empty to provide a correction for π^0's produced in the target windows and surrounding material. This correction was typically of order 5%.

To obtain the π^0 photoproduction cross section to the ground state of ^{4}He, we summed events corresponding to π^0's up to 15 MeV below the maximum allowed π^0 energy. The acutal π^0 energy resolution depended on the size, and orientation relative to the spectrometer, of the π^0 source (the intersection of the photon beam with the target volume). A typical resolution was 9 MeV (FWHM), which kept us comfortably away from π^0's resulting from breakup reactions of ^{4}He. With previously measured cross sections[15] we estimate[7] that such incoherent events would have contributed less than 2% to the cross sections we quote. The weighted average photon energy over the 15-MeV interval is 290 MeV.

The $^4\mathrm{He}(\gamma,\pi^0)^4\mathrm{He}$ data are shown in Fig. 2. Differential cross sections were obtained for laboratory angles of 25°, 40°, 60°, 70°, and 80°. Corrections have been made for effects mentioned above, as well as for detection inefficiencies and for accidental coincidences between the photon arms. As described above, such accidentals were related primarily to beam-on-target processes. The error bars shown in Fig. 2 include all relative uncertainties; in addition, there is an overall normalization uncertainty of 8%. The data are in good agreement with one previous large-angle measurement[3] at this energy with the recoil alpha technique, and in disagreement (at 88°) with another.[2] The curve shown in Fig. 2 is a recent Δ-hole model calculation at $E_\gamma = 290$ MeV by Koch and Moniz.[1,14] The calculation uses Δ-nucleus interaction parameters derived from fitting pion elastic-scattering data, with no additional degrees of freedom. It is clear that the calculation is in good agreement with our data.

It should be noted that the shape of the angular distribution is determined primarily by model-independent factors: Coherent photoproduction of a pion from a spin-zero nucleus must vanish at 0°, and the decrease at backward angles is due to the nuclear form factor. It is possible to integrate our measured angular distribution to obtain a total cross section for the process $^4\mathrm{He}(\gamma,\pi^0)^4\mathrm{He}$ at $E_\gamma = 290$ MeV. Because not all of the angular range is covered by our data, we have used an assumed shape for the angular distribution (that of Refs. 1 and 14) and have fitted the magnitude to our data.

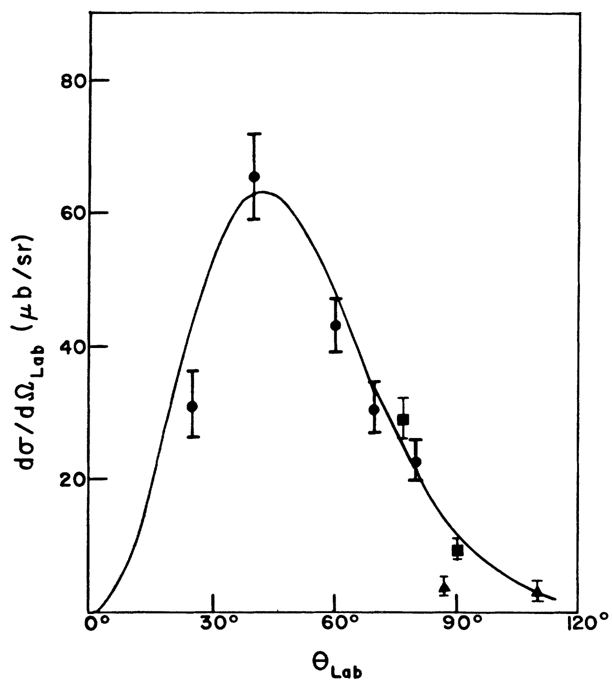

FIG. 2. Measured differential cross sections for the reaction $^4\mathrm{He}(\gamma,\pi^0)^4\mathrm{He}$ at $E_\gamma = 290$ MeV. The circles are the data from this experiment, the squares are data from Ref. 3, and the triangles are data from Ref. 2. The line is a recent Δ-hole model calculation by Koch and Moniz (Refs. 1 and 14).

As described above, there is little model dependence to the shape. The result, including all uncertainties, is $\sigma = 250 \pm 37$ μb, to be compared with the Koch and Moniz prediction[1,14] of 275 μb. The agreement of the calculated magnitude of the cross section with our data is an important success for the Δ-hole model.

In conclusion, we have provided the first data on coherent neutral pion photoproduction in the Δ-resonance region using good-resolution detection of π^0's. The data are in very good agreement with a recent calculation using the Δ-hole model. Additional data at other energies around the resonance and from heavier nuclei should provide further tests of models of photon-nucleus and pion-nucleus interactions.

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