Total Cross Section for Photon Absorption by Two Protons in ^{3}He

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The $^3\mathrm{He}(\gamma, pp)n$ reaction was investigated in the photon energy range 200–500 MeV using the spectrometer TAGX, which has a solid angle for protons of π sr. Two types of photon absorption, one by two protons and the other by three nucleons, were observed by looking at the undetected neutron momentum distributions. The total cross section for photon absorption by two protons shows that this process is consistent with the $E2$ transition.

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Photon absorption by two protons has been considered to be one of the best reactions for investigating the nucleon-nucleon correlation in nuclei [1,2]. This is because the photon is expected to couple to the two-proton system in the nucleus mainly through the one-body current. In this mechanism, the two protons can share the photon energy only when they are correlated in the nucleus. The two-body current, the meson exchange current (MEC), is believed to play a negligible role, since no charged meson is exchanged between the two protons.

Experimental studies of this photon-absorption process have been hindered so far, since the identification of photon absorption by two protons, denoted as $2N(pp)$ in this paper, is difficult. In order to identify the $2N(pp)$ process, one has to confirm that the photon is absorbed by only two protons and that the residual nucleus is a spectator. Hence, a kinematically complete (γ, pp) coincidence measurement is required. The lack of monochromatic photon beams with a high duty cycle has limited such measurements to only the $^3\mathrm{He}(\gamma, pp)n$ reaction, which does not require a monochromatic photon beam for a kinematically complete measurement [3–7].

Audit *et al.* measured the cross section for the $^3\mathrm{He}(\gamma, pp)n$ reaction with a bremsstrahlung beam by using two spectrometers for proton detection, whose setting was chosen so that the $2N(pp)$ process was favored [3–5]. The measured cross sections were compared with a theoretical calculation which took into account the diagrams corresponding not only to the $2N(pp)$ process, but also to the photon absorption process by three nucleons $(3N)$. The theory reproduced the general tendency of the data, such as the magnitude of the cross section, which is about 2 orders of magnitude smaller than that for photon absorption by a neutron-proton pair $[2N(np)]$. There are, however, still significant discrepancies with the data, which require improvements to the theory.

Experimental efforts to measure the $^3\mathrm{He}(\gamma, pp)n$ cross section over a wider kinematical region is also desired, since all of the previous measurements covered quite narrow momentum and angular ranges for the outgoing protons. In this paper we present the first $^3\mathrm{He}(\gamma, pp)n$ measurement using a large-acceptance detector. The experiment (ES 124) was carried out at the 1.3-GeV electron synchrotron of the Institute for Nuclear Study, University of Tokyo, using the TAGX magnetic spectrometer [8,9], and a cryogenic-^{3}He target [10]. The photon energy (E_γ) range was set to be from 200 to 500 MeV in order to cover the entire Δ-resonance region; the photon energy resolution was ± 5 MeV. The duty cycle was about 10%, and the average photon tagging rate was 5×10^5/s. TAGX, which has a π-sr solid angle for protons, consists of a dipole magnet, two cylindrical drift chambers (CDC) placed in the magnetic field, and two sets of plastic scintillation hodoscopes (IH, OH). The covered angular ranges for protons were 15°–165° in horizontal and 40° in vertical. The cryogenic-^{3}He target, with a thickness of 347 mg/cm^2, was kept at a temperature of 2 ± 0.02 K. The momenta and velocities of the two charged particles detected in coincidence were determined by the curvatures of the tracks in the CDC and

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the time-of-flight between the IH and OH hodoscopes, respectively. The mass deduced from the momentum and velocity was used for particle identification, and events with two protons, $^3\mathrm{He}(\gamma,pp)$, were selected. Measurements with an empty target cell were also carried out for background subtraction.

Figure 1 shows an example of the missing mass distributions of the $^3\mathrm{He}(\gamma,pp)$ events. Since the position and width of the peak at about 930 MeV/c^2 are consistent with the neutron mass and the detector resolution, respectively, events with a missing mass between 750 and 1050 MeV/c^2 are identified as $^3\mathrm{He}(\gamma,pp)n$.

A method used to identify the photon-absorption processes in the $^3\mathrm{He}(\gamma,pp)n$ reaction is to find a spectator nucleon in the final state. If there is one spectator, the photon is considered to be absorbed by the other two nucleons in the ^{3}He nucleus. In the case of no spectator in the final state, it should be concluded that the photon energy is shared by the three nucleons. [Note: the photon-absorption process by one nucleon ($1N$), which leaves the other two nucleons as spectators, is kinematically suppressed.] Of the detected $^3\mathrm{He}(\gamma,pp)n$ events, one can safely assume that none of the protons are spectators, since the momentum bias of TAGX for protons is 300 MeV/c and a spectator nucleon rarely has a momentum larger than 300 MeV/c. This fact restricts the possible photon-absorption processes to be only $2N(pp)$ and $3N$. The other processes, such as $1N$ or $2N(np)$, are not responsible for the $^3\mathrm{He}(\gamma,pp)n$ events, since they leave at least one spectator proton in the final state.

Since the neutron is a spectator in $2N(pp)$, whereas it is not in $3N$, one expects that the $2N(pp)$ process can be identified by looking for the neutron momentum (Pn) distribution of the $^3\mathrm{He}(\gamma,pp)n$ events. Figure 2 shows the reconstructed Pn distributions for all of the E_γ ranges. The dotted and dashed lines in the figures are the results of model calculations of the $2N(pp)$ and $3N$ processes taking the acceptance of TAGX into account by the Monte Carlo method [11]. In the $2N(pp)$ model, the two protons absorb a photon, leaving the neutron as a spectator, whose momentum distribution is determined in order to simulate the single-nucleon momentum distribution obtained in the $^3\mathrm{He}(e,e'p)d$ measurement [12]. The proton angular distribution in the center-of-mass frame of the photon and the two-proton system is assumed to be isotropic. In the case of the $3N$ model, the ^{3}He nucleus is disintegrated into three nucleons whose momenta distribute according to three-body phase space. As shown by the solid line, the sum of the calculated results for $2N(pp)$ and $3N$, whose strengths are determined by the fitting to data, reproduces the measured Pn distribution fairly well for all E_γ ranges. That is to say, the kinematical behavior of the data is well reproduced by the sum, which convinces us to use the $3N$ model to extract the $2N(pp)$ strength.

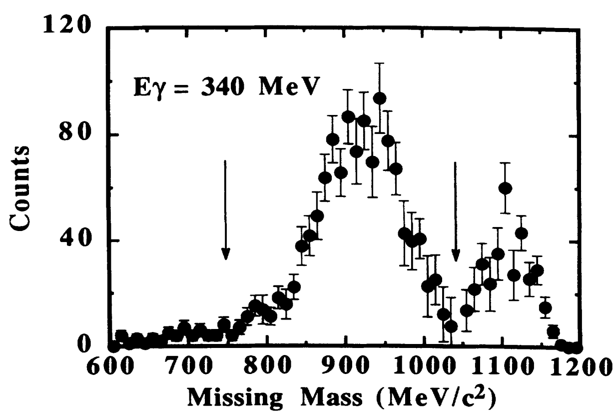

FIG. 1. Missing-mass distribution of $^3\mathrm{He}(\gamma,pp)$ at $E_\gamma = 340 \pm 40$ MeV. The events with a missing mass between the two arrows are identified as $^3\mathrm{He}(\gamma,pp)n$.

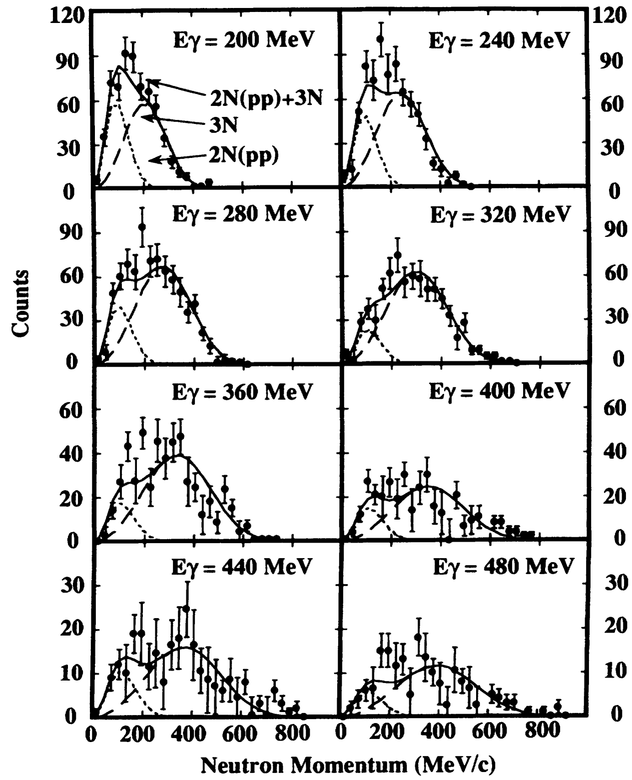

FIG. 2. Undetected neutron momentum distributions. The dotted and dashed lines show the results of the model calculations assuming the $2N(pp)$ and $3N$ processes, respectively. The solid line is the sum of the $2N(pp)$ and $3N$ processes.

The yields for both $2N(pp)$ and $3N$ are extracted by the fitting to the Pn distributions, which are sorted as a function of the proton emission angles. The double differential cross section for $2N(pp)$ with respect to one proton in the observed angular ($\theta = 15°-165°$), and momentum ($p \geq 300$ MeV/c) ranges is determined by the formula,

$$\frac{d^2\sigma}{dp\,d\Omega} = \frac{Y(\theta,p)}{N_\gamma N_t \Delta p \Delta\Omega\, \varepsilon(p,\theta)},$$

where $Y(\theta, p)$, N_γ, N_t, Δp, $\Delta\Omega$, and $\varepsilon(p,\theta)$ represent the yield for $2N(pp)$, the number of photons, the number of target nuclei, the proton-momentum-bin size, the geometrical acceptance, and the detection efficiency, respectively. The geometrical acceptance and detection efficiency are calculated by a Monte Carlo simulation of the TAGX spectrometer [11]. The differential cross sections, $d\sigma/d\Omega$, are determined by integrating $d^2\sigma/d\Omega\, dp$ over the proton momentum, even for the unobserved region ($p < 300$ MeV/c) by the extrapolation method using the $2N(pp)$ model calculation. The total cross section is, then, determined by integrating $d\sigma/d\Omega$ over the proton emission angle. In the unobserved region ($\theta < 15°$, $\theta > 165°$), the isotropic angular distribution is assumed to extrapolate the cross section, as previously noted, which gives the uncertainty of less than 10%. The systematical error is estimated to be less than 20%, which is dominated by an uncertainty in the detection efficiency.

The total cross section for $2N(pp)$, $\sigma(2N(pp))$, is shown in Fig. 3(a) as a function of E_γ. The total cross section for $3N$, $\sigma(3N)$, determined using the yield for $3N$ and the results of the model calculation for $3N$, is also shown in Fig. 3(b) for a comparison. There are significant differences in both the shape and magnitude between $\sigma(2N(pp))$ and $\sigma(3N)$. As E_γ increases, $\sigma(2N(pp))$ gradually decreases over the range of 200–500 MeV, whereas $\sigma(3N)$, shows a peak whose position is consistent with Δ excitation. The magnitude of $\sigma(2N(pp))$ is a few μb, which is approximately 1 order of magnitude smaller than that of $\sigma(3N)$, and 2 orders of magnitude smaller than the total cross section for $2N(np)$ determined by the recent ${}^3He(\gamma, np)p$ measurement [13,14].

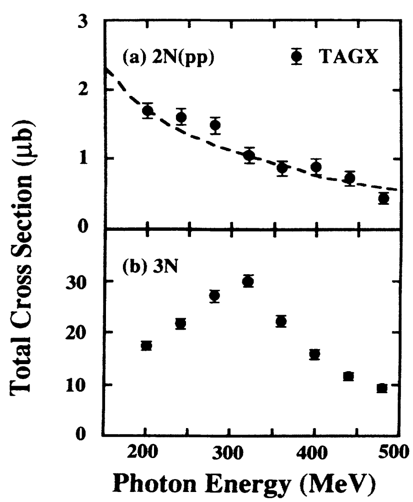

FIG. 3. Total cross sections for (a) photon absorption by two protons, and (b) three nucleons. The error bar is statistical only. The dashed line in (a) indicates the calculated total cross section for deuteron photodisintegration due to the $E2$ transition scaled by a factor of 4.7.

This smallness of the cross section is due to the wave function of the two-proton system in ^{3}He, whose main component is ${}^1S_0$. The dominant $E1$ and $M1$ transitions are forbidden due to a lack of the electric and magnetic dipole moments, and the contribution from the Δ-exciting process (namely γ + "NN" $\rightarrow \Delta N \rightarrow NN$, where N indicates a nucleon) is suppressed when the two-nucleon system is in ${}^1S_0$ [15]. Audit *et al.* pointed out that the cross section for $2N(pp)$ results from either higher multipole transitions than $E1$ and $M1$, or small non-s-wave components of the wave function which allows the ΔN intermediate state [3].

We examine these assumptions based on the determined total cross section for the $2N(pp)$ process. To begin with, let us assume that $\sigma(2N(pp))$ results mainly from the contribution of the non-s-wave component of the wave function. In this case, since the contribution of the ΔN intermediate state to the cross section is allowed, one expects that the effect of the Δ excitation will be observed in the E_γ dependence of the total cross section. An example of such a Δ-excitation effect is the total cross section for deuteron photodisintegration in this E_γ range, which shows a bump due to the dominant contribution of the ΔN intermediate state [16]. No such sign of a Δ-excitation effect in the E_γ dependence of $\sigma(2N(pp))$, however, indicates that the non-s-wave components play a minor role.

Next, another assumption of a higher multipole transition is examined. It is reasonable to consider the $E2$ transition as being the lowest allowed transition multipole. In this case, one finds several similarities between $\sigma(2N(pp))$ and the total cross section for deuteron photodisintegration due to the $E2$ transition, namely $\sigma(\gamma + d : E2)$. As for the reaction mechanism, Arenhövel and Sanzone have shown that $\sigma(\gamma + d : E2)$ is dominated by the one-body current operator, and that MEC plays a minor role [16]. This is the same reaction mechanism which is expected to dominate $\sigma(2N(pp))$. Furthermore, a Faddeev calculation shows that the radial wave function of the ${}^1S_0$ two- nucleon system in ^{3}He, such as the two-proton system, is similar to that of the deuteron [17]. Motivated by these similarities, we compare $\sigma(2N(pp))$ directly with the calculated $\sigma(\gamma + d : E2)$. The dashed line in Fig. 3(a) shows $\sigma(\gamma + d : E2)$ scaled by a factor of 4.7, which is determined by adjusting the absolute magnitude of $\sigma(\gamma + d : E2)$ to that of $\sigma(2N(pp))$. The E_γ dependence of $\sigma(2N(pp))$ is well reproduced by that of $\sigma(\gamma + d : E2)$, which does not show any Δ-excitation effect due to the electric transition. As for the absolute magnitude, the factor of 4 in the scaling factor of 4.7 is due purely to the isospin (T) difference between the two-proton system ($T = 1$) and the deuteron ($T = 0$), which is calculated using the isospin part of the one-body current operator and the isospin wave functions. These agreements show that the $2N(pp)$ process is consistent with the $E2$ transition. The dominant reaction mechanism of the $2N(pp)$ process—the coupling of the photon to the two-proton system through the one-body current—is confirmed by its dominant role in $\sigma(\gamma + d : E2)$. The difference between the scaling factor of 4.7 and the simple isospin factor of 4 may come from a difference in the radial wave function between the two-proton system in ^{3}He and deuteron.

Because of the dominant reaction mechanism of the $2N(pp)$ process, this process is considered to be sensitive to the proton-proton correlation in the ^{3}He nucleus, which is at a short distance due to the large photon energy (momentum): $E_\gamma = 200-500$ MeV. For quantitative discussions concerning the nucleon-nucleon correlation in ^{3}He, however, a full theoretical calculation for $\sigma(2N(pp))$ with an exact wave function is obviously desired.

Finally, we comment on the possible final-state-interaction (FSI) effects which simulate the observed $2N(pp)$ events. Since the dominant photonuclear reactions in this E_γ range are one-pion photoproduction on a single nucleon ($\gamma + N \rightarrow \pi + N'$) and the $2N(np)$ process (γ + "np" $\rightarrow n + p$), the FSI effects following these two processes must be considered as being the leading contributions. That is, pion photoproduction followed by pion reabsorption by two other nucleons, and/or $2N(np)$ followed by rescattering on the third nucleon. Since these FSI events, however, are subject to three-body kinematics, they may simulate a part of the $3N$ events, but not the $2N(pp)$ events. This consideration, together with the different E_γ dependence of $\sigma(2N(pp))$ to that of the FSI processes, which show the Δ-excitation effects [13], confirms that there is little contamination of the FSI processes to $2N(pp)$.

In conclusion, the $^3\mathrm{He}(\gamma, pp)n$ reaction was investigated in the Δ-resonance region using the large-acceptance magnetic spectrometer, TAGX. Two processes: photon absorption by two protons and by three nucleons, are required to reproduce the undetected neutron momentum distribution for $^3\mathrm{He}(\gamma, pp)n$ events. The extrapolated total cross sections for photon absorption by two protons and by three nucleons are determined in the E_γ range of 200–500 MeV. The photon-absorption process by two protons is consistent with the $E2$ transition process.

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