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Three-body ^{3}He photodisintegration in the Δ region

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Three-body ^{3}He photodisintegration was measured in the photon energy range (E_γ) of 145–425 MeV. The total cross section for photon absorption on the np pairs in ^{3}He, $\sigma(^3\text{He}(\gamma,np)p_{sp})$, where p_{sp} is a spectator proton, is reported here for the first time. The E_γ dependence of the σ is found to scale to that of $\sigma(^2\text{H}(\gamma,np))$, and the ratio is determined to be $\sigma(^3\text{He}(\gamma,np)p_{sp})/\sigma(^2\text{H}(\gamma,np)) = 1.24 \pm 0.26$.

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Photodisintegration is the dominant nuclear photon-absorption process below pion production threshold, and is a sizable contributor also in the Δ-resonance region. It was the investigation of this process that established the existence of electric-dipole ($E1$) photon absorption on the isoscalar np pairs in nuclei. This fact has spurred many real photon experiments which aim to investigate the intranuclear np systems.

Photon absorption on the np pairs (npA) in ^{3}He leads to the npp_{sp} final state, where p_{sp} is a spectator proton. There are, in addition, reports on three-nucleon photon absorption (3NA) in ^{4}He [1,2], and in ^{3}He [3–5] which also contributes to the npp final state. The purpose of this experiment is to obtain the cross section for $^3\text{He}(\gamma,np)p_{sp}$ by extracting the npA events from the larger $^3\text{He}(\gamma,np)p$ process. By comparing $\sigma(^3\text{He}(\gamma,np)p_{sp})$ with existing $\sigma(^2\text{H}(\gamma,np))$, one can discuss difference between the np pairs in ^{3}He and the loosely bound np pair in the deuteron.

In this tagged-photon experiment, the three-body ^{3}He photodisintegration reaction $^3\text{He}(\gamma,np)p$ was measured in a kinematically complete way with a proton (> 300 MeV/c) and a neutron (> 100 MeV/c) detected in coincidence, and another proton unobserved. The missing proton momentum is determined by kinematics, and it has no minimum momentum threshold in contrast to the observed particles. This is effective for separating npA and 3NA; it was accomplished by using the momentum distribution of the slower proton as is described later in this Rapid Communication. The momentum-angular coverage for protons and neutrons is summarized in Table I.

The measurements were carried out with the use of the TAGX spectrometer (π sr solid angle for protons and 0.85 sr for neutrons) [1] at the 1.3-GeV electron synchrotron of the Institute for Nuclear Study (INS), University of Tokyo. The experimental details were described previously for a cryogenic ^{3}He target [6,7], trigger and the data acquisition [8], charged particle and neutron detection [1,9], and data analysis of this experiment [10].

The events were analyzed on an event-by-event basis, and the missing mass and missing momentum were reconstructed using the photon energy (E_γ) and the four-momenta of the two observed particles. When the missing mass was consistent with the proton mass, the event was identified as being the npp final state, and the missing momentum was regarded to be that of the unobserved proton. Among the thus identified 5300 npp events, 61% of them came from the liquid ^{3}He target; the background produced in materials other than the target was statistically subtracted by using the yield from empty-target runs. The random threefold-coincidence (tagged γ-proton-neutron) rate was no more than 1%.

The momentum spectra of the observed proton and neutron, and the unobserved proton, are shown in Fig. 1(a). The unobserved protons form a peak at 100 MeV/c, which suggests that these protons act most likely as spec-

TABLE I. Measured ranges of momenta and laboratory angles for neutrons and protons.

Particle	p (MeV/c)	θ_{lab}
p (observed)	300–1000	15°–165°
p (unobserved)	0–1000	0°–180°
n (observed)	100–800	18°–162°

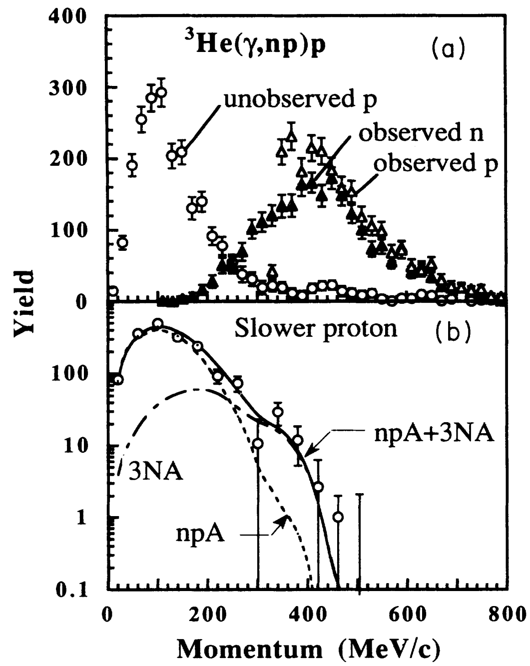

FIG. 1. (a) Momentum spectra of the observed neutrons (solid triangles), protons (open triangles), and unobserved protons (open circles) over the entire E_γ range. (b) Momentum spectra of the slower proton among the observed and unobserved protons at $E_\gamma = 245 \pm 80$ MeV. Data (open circles), *npA* (dashed curve), and 3NA (dot-dashed), and their sum (solid).

tators, while there exists an appreciable tail in the higher-momentum region, which include participant protons. Another characteristic is that the neutron momentum distribution shows no such low-momentum peak, and this indicates a much smaller cross section for the ppn_{sp} final state.

The method used to identify the *npA* event is to look for a spectator proton; the major part of the energy momentum of the incident photon is shared by two nucleons in *npA*, while it is shared among three nucleons in 3NA. The difference between the two absorption modes appears most clearly in the shape of the momentum spectrum of the slower proton among the observed and unobserved protons. Figure 1(b) shows the data at $E_\gamma = 245$ MeV together with the acceptance-corrected spectra expected from 3NA: three-body phase space, and from *npA*: a spectator spectrum via $(e, e'p)$ experiments [11]. A linear sum of these two spectra fits the data very well ($\chi^2/N_{\rm dof} = 1.5$), and this establishes the existence of *npA* and 3NA. In this way, the ratio of the number of *npA* events (Y_{npA}) to that of the total events (Y), $\alpha = Y_{npA}/Y$, is determined as a function of E_γ. Below, we describe the method used to extract the total cross section (σ) for *npA*, which forms the content of this Rapid Communication.

We start from the fourfold differential cross sections with respect to variables for a neutron (subscript n) and a proton (subscript p refers to both the spectator proton and the participant proton; two protons in an event are treated on the same footing):

$$d^4\sigma/d\Omega_n dp_n d\Omega_p dp_p$$
$$= \alpha Y(\mathbf{p}_n, \mathbf{p}_p)/\{N_\gamma N_T \varepsilon(\mathbf{p}_n, \mathbf{p}_p)\Delta\Omega_n \Delta p_n \Delta\Omega_p \Delta p_p\}, \quad (1)$$

where $\mathbf{p}_{n(p)}$ is the momentum, $Y(\mathbf{p}_n, \mathbf{p}_p)$ the yield in an angular-momentum bin, n_γ the number of incident photons, N_T the number of target nuclei per unit area, $\varepsilon(\mathbf{p}_n, \mathbf{p}_p)$ the momentum-dependent detection efficiency, $\Delta\Omega_{n(p)}$ the solid angle, and $\Delta p_{n(p)}$ the momentum bin size. Both $\varepsilon(\mathbf{p}_n, \mathbf{p}_p)$ and $\Delta\Omega_{n(p)}$ are obtained by a Monte Carlo simulation of TAGX [1], in which we take into account the detector geometry, resolutions, efficiencies, and particle properties, such as the range, energy loss, and scattering in materials. The cross sections are integrated with respect to the four variables over the angular-momentum ranges listed in Table I. Since the momentum spectra of the participant proton and neutron are calculable and reproduce the data, we use the spectra to correct for the contributions from the missing momentum ranges. For the missing angular ranges, the angular distributions are determined via fitting a second order polynomial in $\cos\theta_{n(p)}$ ($\theta_{n(p)}$ is the laboratory emission angle) to the present data at each E_γ. The magnitude of the correction for the missing angular ranges is 9–15 % of the σ. Examples of $d\sigma/d\Omega_{n(p)}$, thus obtained by integrating with respect to the three variables and the curves which fit the angular distribution, are shown in Fig. 2.

Two sets of σ's obtained by integrating the curves of $d\sigma/d\Omega_n$ and $d\sigma/d\Omega_p$ divided by two (the factor is due to the contributions from the participant proton and the spectator) agree with each other within the statistical errors. The averages of the two σ's are listed in Table II and are shown in Fig. 3(a). The systematic error, which is dominated by the uncertainty in calculating the ε in Eq. (1) (it includes the model dependence in extracting the *npA* yield) is 20%. the present σ gradually rises as E_γ increases in the range 145–225 MeV, and then it slowly falls; as a whole it appears as a broad-peak structure with a maximum of 90 μb at 225 MeV. Several data sets on ^{3}He$(\gamma, n)pp$ in the range of $E_\gamma < 100$ MeV are published

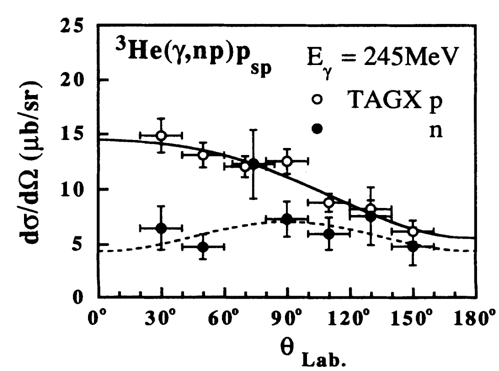

FIG. 2. Laboratory angle dependence of $d\sigma/d\Omega_n$ (solid circles) and $d\sigma/d\Omega_p$ (open circles) at $E_\gamma = 245\pm40$ MeV. Curves are fits to the data (see text): dashed curve for neutron and solid curve for proton.

TABLE II. $\sigma(^3\mathrm{He}(\gamma,np)p_{sp})$. Errors for σ are statistical only.

E_γ (MeV)	$\sigma(\mu b)$
145±20	57.6±4.1
185±20	75.4±4.8
225±20	91.8±7.4
265±20	82.0±6.2
305±20	63.8±5.4
345±20	38.3±4.3
385±20	33.2±4.6
425±20	22.9±5.2

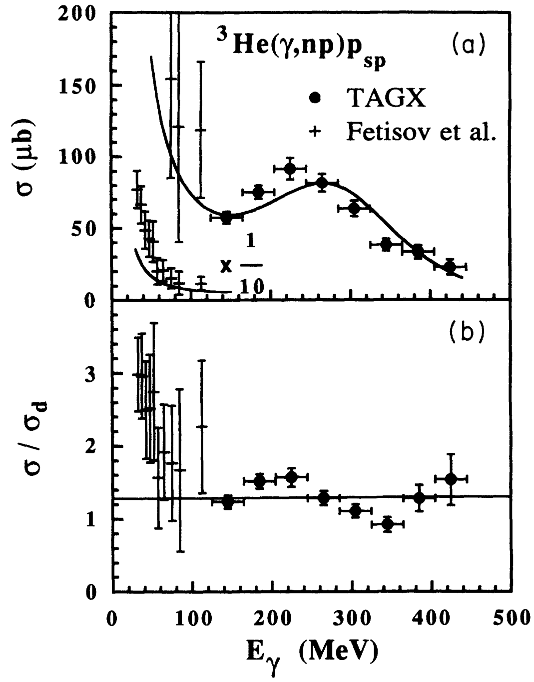

FIG. 3. (a) $\sigma(^3\mathrm{He}(\gamma,np)p_{sp})$. The data at low energies for $^3\mathrm{He}(\gamma,n)pp$ are taken from Fetisov *et al.* [12] (crosses). The curve is σ_d [18] times 1.24. (b) E_γ dependence of the ratios $\sigma(^3\mathrm{He}(\gamma,np)p_{sp})/\sigma_d$ for TAGX, and $\sigma(^3\mathrm{He}(\gamma,n)pp)/\sigma_d$ for Fetisov *et al.* The solid line is an average of the TAGX data, 1.24.

[12–15]. These data rise sharply from the threshold at 7.7 MeV and form a peak of 1 mb at around 20 MeV; then they decrease to 120 μb at 100 MeV. Although none of the experiments identified the absorbing np pair or proton spectator, unlike the case in this work, the dominant contribution in the low-E_γ region is expected to be $E1$ npA. A comparison between the present data and the overall feature of (γ,n) above 30 MeV, represented by the data of Fetisov *et al.* [12], shows a smooth continuation as seen in Fig. 3(a). One should note that a final state interaction (FSI) between one of the outgoing nucleons and a spectator proton reduces the present npA strength to mimic 3NA. Our estimation of this reduction probability by a cascade calculation is about 7% or less, but we have not corrected for this. No visible effect from soft FSI [16] is obtained.

In the quasideuteron photon absorption model (QDM) by Levinger [17], the total cross section σ_{qd} for the $\gamma A \to np + (A-2)$ reaction on the mass number A, the atomic number Z, and $N = A - Z$ is given by

$$\sigma_{qd} = L(NZ/A)\sigma_d, \qquad (2)$$

where L is the Levinger factor and $\sigma_d = \sigma(^2\mathrm{H}(\gamma,np))$. Motivated by the QDM, we draw σ_d times a constant value in Fig. 3(a), where σ_d is a fit to the data by Rossi *et al.* [18]. The curve describes the present data, and even part of the low-energy data. It is remarkable that the σ/σ_d ratios by TAGX and Fetisov *et al.* in Fig. 3(b) show roughly a constant behavior over such a wide E_γ range 50–425 MeV. Below this E_γ region, disagreement between the data sets prevents further comparison. The scaling of the cross section suggests a similarity of the two-nucleon wave functions of the absorbing np pair in ^{3}He and the np in the deuteron over a wide neutron-proton distance: the reduced wave lengths are 3.9 fm for $E_\gamma = 50$ MeV and 0.46 fm for 425 MeV. The photon absorption mechanisms of $^2\mathrm{H}(\gamma,np)$ are dominantly $E1$ below pion threshold and $M1$ due to Δ excitation in the Δ region [19,20]. The scaling implies that $^3\mathrm{He}(\gamma,np)p_{sp}$ is also subject to similar mechanisms.

The averaged ratio of the present data is $\sigma(^3\mathrm{He}(\gamma,np)p_{sp})/\sigma_d = 1.24 \pm 0.26$. By inserting this value into Eq. (2), one obtains $L = 1.9$, which is incompatible with the commonly used values of $L > 6$ for heavier nuclei [17,21]. The constancy of the ratio is naturally explained by the QDM, although the value is not. Other experimental ^{3}He/d ratios obtained by comparing $d\sigma/d\Omega_p$, 1.68±0.07 by d'Hose *et al.* [3] for data at a few forward angles and 1.67±0.27 by Kolb *et al.* [22] for one angle at $E_\gamma < 80$ MeV, are larger, but they are not completely inconsistent with the present value.

Gibson and Lehman [23] calculate the structure of the $^3\mathrm{H} \to n + d$ vertex and, under the assumption of isospin invariance, they obtain the fraction of the pd component in ^{3}He to be 0.435±0.004; while Schiavilla *et al.* [24] find that 92% of the isoscalar np pairs in ^{3}He are in the deuteron state: 1.38 deuterons in a ^{3}He nucleus. The present ratio is in accordance with this value. Finally, we emphasize the importance of testing the constancy of the ratio $\sigma(^3\mathrm{He}(\gamma,np)p_{sp})/\sigma_d$ both at higher energies and at lower energies.

In conclusion, photon absorption on the np pairs in ^{3}He is extracted from three-body ^{3}He photodisintegration in the E_γ range 145–425 MeV. The total cross section for photon absorption on the np pairs, $\sigma(^3\mathrm{He}(\gamma,np)p_{sp})$, is obtained for the first time. The measured cross section scales to $\sigma(^2\mathrm{H}(\gamma,np))$ with a normalization factor of 1.24±0.26, which is in accordance with a theoretical prediction by Schiavilla *et al.*, 1.38 deuterons in ^{3}He.

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