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FEW-BODY PHYSICS WITH REAL PHOTONS AT TAGX

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The proton-neutron (pn) pairs in light nuclei such as ^{3}He, ^{4}He, and ^{6}Li have been investigated with the photon beam from the 1.3-GeV Tokyo Electron Synchrotron. Photodisintegration of the nuclei has been measured in the Δ-resonance region with the large-acceptance spectrometer TAGX. The strengths of the photon absorption by the pn-pairs vary depending on nuclei and on the photon energy. The pair in ^{3}He is found to be three-times more active than the deuteron in absorbing the photon. The photon absorption cross sections by the pn-pairs in ^{4}He show a jump at the pion-production threshold. The total cross sections for five ^{4}He-breakup channels including new data are illustrated.

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1. *Introduction*

A two-nucleon pair in the nucleus is a good tool to test the ability of modern nuclear physics in describing the nuclear system at short distances. The wave function of the pair, calculated in many models, has not been experimentally determined. We aim at the observation of two-nucleon pairs in few-body nuclei using real photons. The two-nucleon pair in free space is the deuteron. Critical tests have been made by the deuteron-photodisintegration calculations. A comprehensive review article of the reaction by Arenhövel and Sanzone is available [1]. Sophisticated microscopic calculations include meson-exchange currents and nucleon-resonance excitations applied to the wave functions derived from various nucleon-nucleon potentials. These are necessary to reproduce the experimental observables (σ, $\mathrm{d}\sigma/\mathrm{d}\Omega$, Σ, P) of the reaction.

One essential point is the dominant contribution of the electric-dipole transition. The total cross section for deuteron photodisintegration rises steeply from the threshold at $E_\gamma = 2.2$ MeV to a maximum of 2.5 mb at 4.5 MeV, then it monotonously decreases to 75 μb at 100 MeV [1]. These rising and falling E_γ dependencies of the cross section are reproduced fairly well by the Bethe-Longmire equation derived in the effective range approximation [2],

$$\sigma = \frac{\sigma_{BP}}{1 - r_0\sqrt{ME}} \tag{1}$$

where σ_{BP} is given by the Bethe-Peierls formula [3], taking into account the E1 transition only in the long-wave-length approximation, M is the deuteron mass, E the deuteron binding energy and r_0 the effective range. The dominance of the E1 transition in this E_γ range, with less than 20% contribution from the transitions of M1, E2 and higher multipoles, is supported by more recent calculations [1].

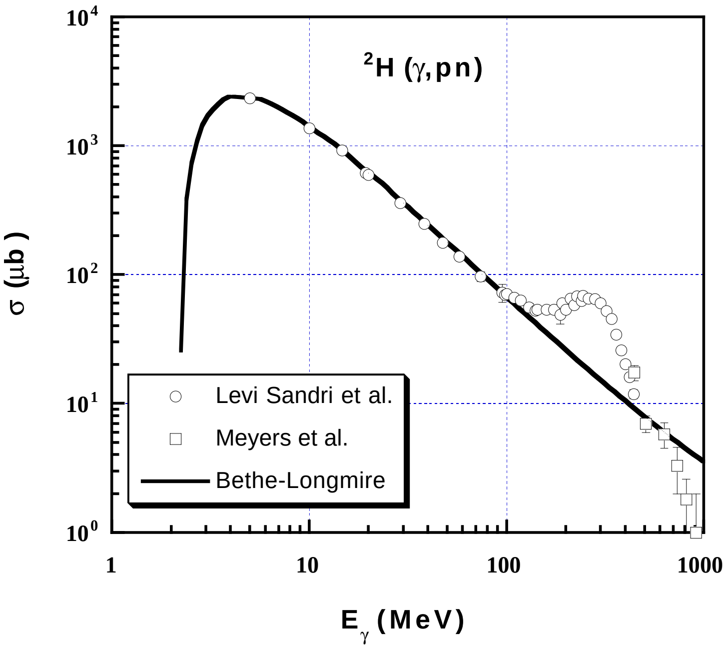

Fig. 1. Comparison between the data for $\sigma(^2\mathrm{H}(\gamma,\mathrm{pn}))$*, open circles [4] and squares [5], and the theoretical curve by Bethe-Longmire [2]. A peaking structure off the curve is due to* Δ*-excitation.*

Above $E_\gamma = 100$ MeV, there appears a peak that deviates from the curve, as shown in Fig. 1. This was supposed to relate to the Δ-resonance because of its location, and it is beautifully proved by the theoretical calculations which take into account Δ-excitation [1]. These calculations show that the dominant feature in the E_γ range of 200-300 MeV is the M1 N-Δ-excitation, and the contribution is 60-65% of the total cross section. The calculation that reproduces the data excellently well is the one by Arenhövel and Sanzone [1], who calculate the contributions of one-body current, meson-exchange currents as incorporated in the Siegert operator, explicit meson-exchange currents and Δ-excitation. Calculations by Laget [6] and by Tanabe-Ohta [7] are successful in reproducing the data.

The understanding of deuteron photodisintegration can be a basis to study the nuclear pn-pairs. This led to the measurements of (γ,pn) (as well as (γ,pp), and (γ,nn)) on nuclear target for the observation of the nuclear pn-pairs. Attempts for a long time have proved that such measurements are not suitable in identifying the photon absorption by the two-nucleon pair [8], because other reaction channels, such as many body absorption and final-state interactions, disturb the pure two-nucleon absorption. Thus, the scenario for the observation of the intranuclear pn-pair is to measure (γ,pn) on few-body nuclei. We limit ourselves to isoscalar pn-pairs and avoid discussion about the isovector pp and nn pairs. In the following, the studies of pn-pairs in ^{3}He and ^{4}He at Tokyo are reviewed.

2. *Observation of the* pn-*pairs in* ^{3}He

2.1. *The TAGX spectrometer*

A detector for the observation of the intranuclear pn-pair was designed to measure (γ,pn) on few-body nuclei. The detector, which is capable to measure simultaneously the angular and momentum distributions of the emitting nucleons in a wide kinematical region, was constructed in Tokyo. This is the large-acceptance TAGX spectrometer [9], which is located at a tagged-photon beam line at the 1.3-GeV electron synchrotron (ES). The tagged-photon beam delivered from the ES is:

1) in the energy range from almost zero up to 1.2 GeV,

2) of an energy resolution of 5 MeV (rms),

3) with the duty factor up to 20%, and

4) with the intensity of 10^6 photons/s.

The beam is incident on the cryogenic (or solid) target surrounded by the detector components of the TAGX spectrometer which has two large-acceptance detector parts of medium energy resolutions:

1) a magnetic spectrometer for charged-particle-momentum measurements with a solid angle of π sr,

2) a time-of-flight (TOF) neutron spectrometer with a solid angle of 0.85 sr.

The spectrometer is equipped with a set of fast electronics and data acquisition systems. Data calibration and analyses follow the standard method developed by the TAGX collaboration, and the results can be compared to the calculations with dedicated simulation codes, TAGX-FMC. As a whole, TAGX is an easy-to-handle detector system for the photoreaction studies in the 1-GeV region [9].

2.2. *The* pn-*pairs in* ^{3}He

The ^{3}He three-body breakup reaction was measured in a kinematically-complete experiment. According to the momentum distributions of the observed nucleons, events are categorized into three types; pn-absorption, pp-absorption, and three-nucleon absorption [10,11]. The ratio of the total cross sections for pn-absorption in ^{3}He, ^{3}He $(\gamma,\mathrm{pn})\mathrm{p_{sp}}$, where index sp represents for a spectator particle, and deuteron photodisintegration, ^{2}H(γ,pn), shows a remarkable scaling, i.e.,

$$\sigma(^3\mathrm{He})/\sigma(^2\mathrm{H}) = 1.24 \pm 0.26 \qquad (2)$$

in the wide E_γ range of 50 to 425 MeV [10], as shown in Fig. 2. This scaling reminds one of the quasi-deuteron model by Levinger for pn-photon absorption in nuclei [12], but the model does not explain the cross section ratio. There is a theoretical calculation that predicts the presence of 1.38 deuterons in ^{3}He [13], and this figure can reproduce the data when photon absorption by these deuterons is assumed to be the reaction mechanism responsible for ^{3}He$(\gamma,\mathrm{pn})\mathrm{p_{sp}}$.

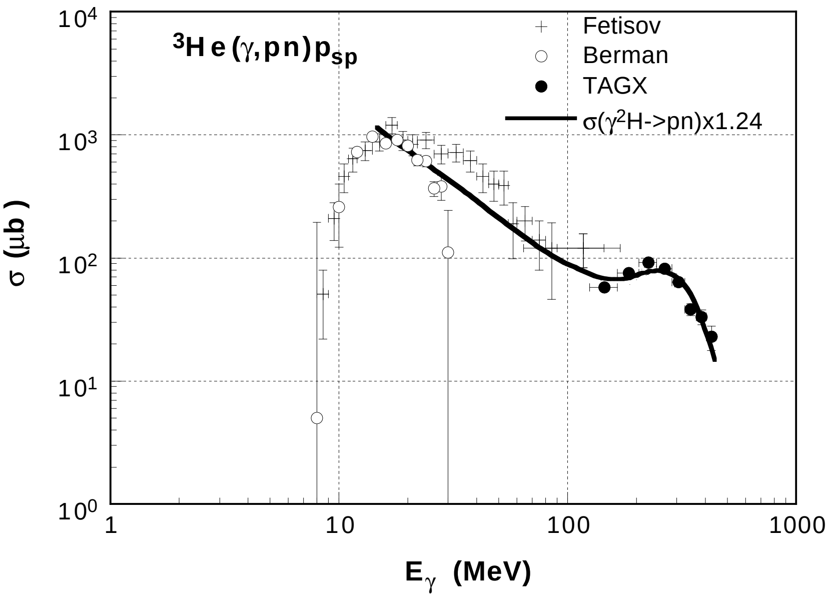

Fig. 2. Total cross section for photon absorption by pn-*pairs in* ^{3}He *as determined by TAGX [10]. The data are plotted together with the existing three-body breakup cross sections below 150* MeV *[17,18]. The behavior of the data can be reproduced well by the deuteron photodisintegration data with the scaling factor of 1.24.*

A calculation with a modified-deuteron wave function by Wilhelm et al. [14] reproduces the $\mathrm{pnp_{sp}}$ cross section fairly well. In the calculation, compression of the two-body wave function to shorter distance in ^{3}He comparing with the deuteron causes an increase of cross section by the factor of 3, but it is reduced by the factor of 1.5 due to the probability in finding the deuteron-like pn-pair. According to their calculation, the pn-pair in the nucleus is more active than the deuteron in absorbing the photon. They obtain a semi-quantitative agreement. Very recently, a quasi-deuteron calculation has been carried out to reproduce the TAGX data [15].

Independently, a multipole analysis was done. Two lowest multipoles of E1 and M1 included in the analysis are sufficient to reproduce the total and the differential cross sections. The result gives a large M1 contribution for the Δ-resonance excitation, and a decreasing contribution from the E1 that is dominant at lower photon energy. These are in line with the calculation by Wilhelm et al.

We find that the $\mathrm{ppn_{sp}}$ cross section is reproduced by the E2 transition [11]. Wilhelm et al. [16] show another possible contribution of the E1 transition due to the spin effects, however, if it is included, their calculation deviates from the data by the factor of two. This is a hot issue to be solved in view of the short-range two-body currents.

3. *The* pn-*pairs in* ^{4}He

3.1. *Experiment*

In order to determine the strength of the photon absorption by the pn-pairs in more dense nuclei, we measured three-body (pnd) photodisintegration of ^{4}He [19,20]. The tagged photon beam (145 – 425 MeV) hit a liquid ^{4}He target, and broke up the nuclei. TAGX measured momenta of the neutron with TOF and the proton with the magnetic spectrometer. Missing mass of pn was calculated from the measured momenta and identified to be the deuteron. The momentum of the deuteron was determined also by calculations, and it was found that the missing deuteron behaves as a spectator. Thus, the final state was identified unambiguously using TAGX.

Four-body breakup (pnpn) could be background to pnd. The process was already measured using TAGX by detecting three nucleons of ppn [21], and the cross section was determined to be less than 20% of pnd in the Δ-resonance region. Since this background forms a smooth missing-mass spectrum, the background contribution, which is not significantly large, was subtracted from the pnX-data sample.

3.2. *Experimental results*

The photon energy dependence of the total cross section for $^4\mathrm{He}(\gamma,\mathrm{pn})\mathrm{d}$ obtained shows a broad peak at around the energy of 245 MeV, and it drops steeply down to 10% of the peak cross section at 420 MeV. The dependence is very similar to the cross section of deuteron photodisintegration in shape, but its magnitude is six times larger as shown in Fig. 3, i.e.,

$$R = \sigma(^4\mathrm{He}(\gamma,\mathrm{pn})\mathrm{d})/\sigma(^2\mathrm{H}(\gamma,\mathrm{pn})) \simeq 6. \tag{3}$$

In terms of the effective number of the pn-pairs in ^{4}He, which is given to be 2.4 by Schiavilla et al. [13], an additional factor of 2.5 enhancement in the photon-absorbing strength is required to match the data, presumably due to the more compact pn-wave function.

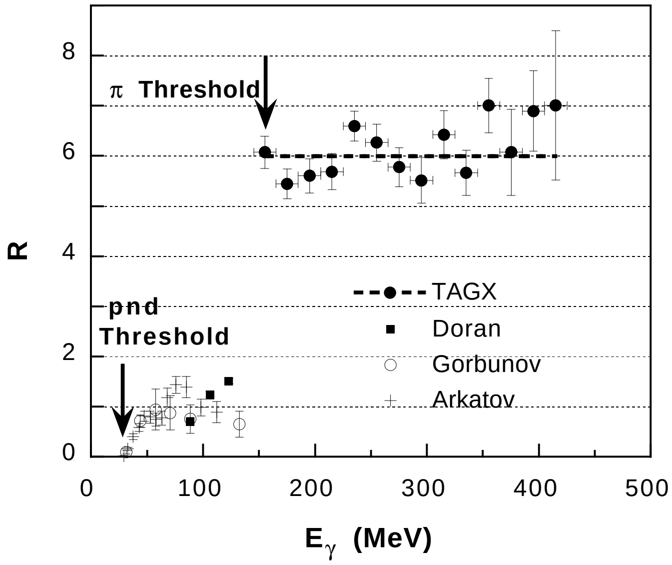

Fig. 3. The cross section ratio R (see text). The total cross sections for three-body ^{3}He *breakup: solid circles are TAGX [20], solid squares Ref. 22, open circles Ref. 23, and pluses Ref. 24. The dashed line is an average of TAGX. Two arrows indicate the reaction threshold and the* π *production threshold.*

3.3. A jump

Doran et al. [22] measured the three-body breakup with the tagged photons of energies 80-131 MeV in Mainz. They detected pn in coincidence, and determined the pnd final state by the missing-mass method. This is the same method as at the TAGX experiment. Three total cross section data determined show increasing photon energy dependence. A direct comparison between these data at lower energies and the TAGX data can be made only in the region at around 140 MeV. The TAGX data at the lowest photon energy of (155 ± 10) MeV are several times larger than the low energy ones (Fig. 3). This jump is also seen in the number R defined above: it is six and stays constant for the TAGX, while it is one for the data by Doran et al. and others in the lower energy region.

Existing theories do not explain the behaviour of the cross sections, nor the jump. This suggests that the jump formed by the TAGX data and the former experiments may indicate a not-yet-established reaction mechanism.

4. Conclusion

Figure 4 shows the total cross sections for three- and four-body ^{4}He breakups from TAGX experiments, which are dominant contributors to the total breakup cross section, together with existing two-body breakups. n ^{3}He channel is similar in size to pt. No microscopic calculation either for three- or four-body breakup reproduces the data. These are challenging problems to theory.

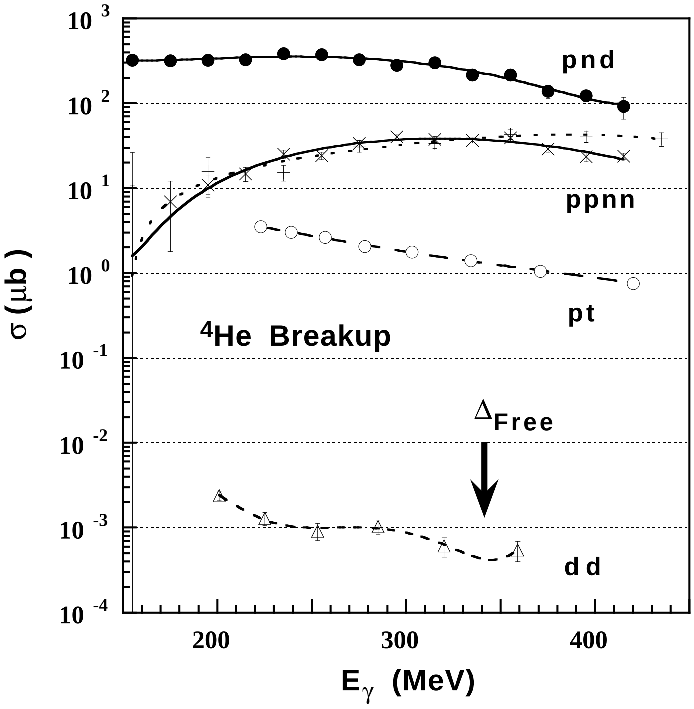

Fig. 4. Total cross sections for three- and four-body ^{4}He *breakups from TAGX measurements [20,21] are shown together with existing two-body breakups [25,26].* n^{3}He *channel is similar to* pt *in size. The arrow indicates the* Δ*-peak energy on the free nucleon. The curves are eye-guided.*

The conclusions of this paper are:

1) Photon absorption cross sections by the pn-pairs in ^{3}He and ^{4}He are measured by the TAGX collaboration in the Δ-resonance region.

2) pn-absorption in ^{3}He can be understood by a reasonable calculation in a semi-quantitative way.

3) Photon-absorption cross sections by the pn-pair in ^{4}He, ^{4}He(γ,pn)d, show a jump of a factor of six at the π-production threshold. This suggests a not-yet-established mechanism related to Δ-excitation.

4) The cross sections for five channels of ^{4}He breakup show different magnitude and shapes in the Δ-resonance region. No satisfactory explanation is available for these cross section data.

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PROUČAVANJE MALONUKLEONSKIH SUSTAVA FOTONIMA PRI TAGX

Fotonskim snopom iz Tokijskog elektronskog sinhrotrona energije 1,3 GeV istraživali smo parove proton-neutron u lakim jezgrama ^{3}He, ^{4}He i ^{6}Li. Fotorascjep tih jezgri smo mjerili sa spektrometrom velikog zahvaćanja (TAGX) u području Δ-rezonancije. Nukleonski par u ^{3}He tri puta jače apsorbira fotone nego u deuteronu. Udarni presjeci za apsorpciju fotona u ^{4}He pokazuju skok kod praga tvorbe piona. Prikazuju se ukupni udarni presjeci za pet kanala rascjepa ^{4}He, uključivši nove podatke mjerenja.