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著者	Shima T., Maehara N., Takahisa K., Nagai Y., Makii H., Maeda K., Kobayashi T., Ohtsu H., Kanda H., Abe K., Hirose K., Yamaguchi Y., Matsuda Y., Seki Y., Terasawa T., Tamae T., Ohtsuki T., Inoue M., Hayashi Y.
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Experimental Study of Photonuclear Reactions of ^{4}He below Pion Threshold

T. Shima[1], N. Maehara[1], K. Takahisa[1], Y. Nagai[1], H. Makii[1], K. Maeda[2], T. Kobayashi[2], H. Ohtsu[2], H. Kanda[2], K. Abe[2], K. Hirose[2], Y. Yamaguchi[2], Y. Matsuda[2], Y. Seki[2], T. Terasawa[3], T. Tamae[3], T. Ohtsuki[3], M. Inoue[3] and Y. Hayashi[3]

[1]*Research Center for Nuclear Physics, Osaka University, 10-1, Mihogaoka, Ibaraki 567-0047*
[2]*Department of Physics, Tohoku University, Aramaki, Aoba, Sendai 980-8578*
[3]*Laboratory of Nuclear Science, Tohoku University, 1-2-1, Mikamine, Taihaku, Sendai 982-0826*

An experimental method for the precise measurement of the photonuclear reactions of ^{4}He below the pion threshold has been tested. We used a tagged photon beam and a time projection chamber containing helium gas, which served as an active target. It was proved that the chamber could successfully detect the tracks of the charged particles from the photonuclear reactions in a high radiation level due to the irradiation of a high-intensity photon beam. It was found that the background was mainly due to the noise of the chamber, and could be suppressed by taking coincidence of the signals from the chamber and the tagging counter.

§ 1. Introduction

The photonuclear reactions of ^{4}He provide important information on basic properties of the nuclear force as well as the dynamics of few-nucleon systems. For example, the self-conjugate ^{4}He nucleus is supposed to have a giant-dipole resonance (GDR) state with a pure $T = 1$ component at around the excitation energy of 20~30 MeV, and the cross sections of the $^4\mathrm{He}(\gamma,\mathrm{p})^3\mathrm{H}$ and $^4\mathrm{He}(\gamma,\mathrm{n})^3\mathrm{He}$ reactions should be almost equal, if there is no effect of the charge symmetry breaking (CSB) in nuclear forces. Therefore, the precise comparison of the $^4\mathrm{He}(\gamma,\mathrm{p})^3\mathrm{H}$ cross section and the $^4\mathrm{He}(\gamma,\mathrm{n})^3\mathrm{He}$ cross section can be used as a stringent test of the nuclear charge symmetry [1]. For that purpose the photonuclear reactions of ^{4}He in the GDR energy region have been studied extensively both experimentally and theoretically. However, the previous experimental data have been in severe discrepancy, and that has caused a long-standing problem as described below. Namely, most of the old experimental data [2−8] suggested the $^4\mathrm{He}(\gamma,\mathrm{p})^3\mathrm{H}$ and $^4\mathrm{He}(\gamma,\mathrm{n})^3\mathrm{He}$ cross sections had the maximum values of 1.5~2 mb and 1~1.5 mb near $E_\gamma = 25$ MeV, respectively. From those data, Calarco *et al.* recommended the ratio R_γ of the (γ,p) cross section to the (γ,n) cross section of 1.7 ± 0.2 [9], which implied an extremely large effect of CSB. Those data were supported by a theoretical calculation based on the resonating group method (RGM) [10]. However, later measurements of $^4\mathrm{He}(\gamma,\mathrm{n})^3\mathrm{He}$ [11], $^3\mathrm{He}(\mathrm{n},\gamma)^4\mathrm{He}$ [12,13], $^4\mathrm{He}(\gamma,\mathrm{p})^3\mathrm{H}$ [14] and $^3\mathrm{H}(\mathrm{p},\gamma)^4\mathrm{He}$ [15] gave rather small cross sections of ~1.1 mb for both (γ,p) and (γ,n) reaction channels, and leaded to the value of R_γ near unity. Those new data were supported with a new theoretical calculation by Unkelbach and Hofmann [16], which took into account the contributions of meson-exchange currents (MEC) beyond Siegert's theorem by using Ohta's method [17] together with the refined RGM. Therefore, the anomalous CSB effect seemed to be ruled out at that time. But the problem revived with the later experiments on ^{4}He(γ,p)^{3}H [18] and ^{3}H(p,γ)^{4}He [19], which give the cross sections as large as about 1.8 mb in the region of E_γ = 25~30 MeV. In addition, the total photoabsorption cross section of 2.86±0.12 mb has been obtained at E_γ= 25~26 MeV from the elastic photon scattering measurement [20]. Since the contributions from the reactions other than two-body channels are supposed to be small enough in this energy region, the total cross section is not consistent with the sum of the (γ,p) and (γ,n) cross sections around 1.1 mb. Recently, Efros *et al.* applied a new theoretical method, called the Lorentz integral transform, and succeeded in performing the calculation for the E1 photoabsorption cross section of ^{4}He, fully taking into account the effects of the final-state interaction (FSI) [21]. They claimed that the peak energy of the cross section should be at around 30 MeV, rather than the previously adopted value of about 25 MeV. Also they pointed out that the integrated cross sections obtained from the previous data and calculations exhaust only 60% of the value expected from the E1 sum rule. On the other hand, their calculation is consistent with the sum rule. To solve the above problems, a more precise experiment on the photonuclear reactions of ^{4}He will be demanded. In addition to the importance of the photonuclear reactions of ^{4}He in nuclear physics, they also play crucial roles in astrophysics. It is known that the radiative capture processes of light nuclei play crucial roles in the big-bang nucleosynthesis [22], and the information about the photonuclear reactions of ^{4}He at low energies are useful to establish microscopic theories for those processes. The photonuclear reaction of ^{4}He can be applied to investigate analogous processes of ^{4}He caused by the weak interaction [23] like the ^{3}He(p,e$^+\nu_e$)^{4}He and ^{4}He(ν,ν') reactions, which are relevant to the solar *hep* neutrino production [24] and the stellar nucleosynthesis by r-process in neutrino-driven wind [25], respectively.

For the above reasons, recently we have started a new experiment on the photonuclear reactions of ^{4}He by means of a real photon beam and a time projection chamber (TPC). We have already measured the cross sections in the region of E_γ from 22 MeV to 32 MeV, and the result was in nice agreement with the recent theoretical calculations. But the integrated total cross section below E_γ= 32 MeV was about 30% smaller than the value expected from the E1 sum rule. Therefore, it is quite interesting to make a systematic measurement up to higher energies in order to search for the missing transition strength. For that purpose we planned a new measurement using the tagged photon beam at LNS, Tohoku University. The present work was aimed at an experimental check for stable operation of TPC and the possible backgrounds under high radiation environment due to a high-energy (up to 120 MeV) and high-intensity (up to a few 10^6 photons/s) incident γ-ray beam.

§ 2. Experimental Method

The experiment was performed at the BL-V beam line at the Laboratory of Nuclear Science (LNS) of Tohoku University. The experimental set up is schematically shown in Fig. 1. For the γ-ray beam we employed the LNS tagged photon beam. The γ-ray beam impinged upon the ^{4}He gas target contained in TPC, and caused photonuclear reactions. The charged particles emitted from the reactions were detected with TPC. To obtain the timing signal for measurement of the drift times in TPC, the trigger counters (TR) made of 30mm thick plastic scintillators were installed on four side walls of TPC [26]. The timing signals from TR were also used to determine the γ-ray energies event by event, by taking coincidence with the tagging counters (TAG). The details of the experimental method are described in the following.

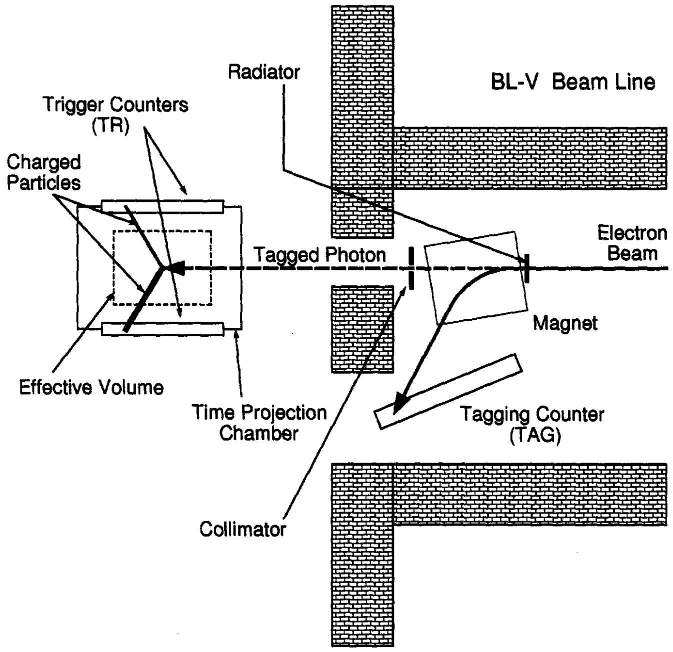

Fig.1. Experimental set up for ^{4}He photodisintegration measurement. The long-dashed line indicates the path of the tagged photon beam.

2.1 Tagged photon beam

The tagged photons were generated via the bremsstrahlung process of the 150 MeV electron beam on a 10 μm thick platinum target, where the primary electron beam was provided from the stretcher-booster ring at LNS, Tohoku University [27]. The energy range of the tagged photons was from 30 MeV to 120 MeV. The average intensity of the photon beam was 2×10^5 photons/s.

2.2 ^{4}He target and time projection chamber

The reaction events were detected with TPC filled with a mixture of 80% natural He gas and 20% CD_4 gas, where the ^{4}He nuclei contained in the counter gas were used as the target. This method has following advantages;

i) Since TPC serves as an active target, an acceptance of 4π and a detection efficiency of nearly 100% are achieved.

ii) TPC has a capability of measuring the track shapes and the energies of the charged particles produced in the reactions, and such information is useful for identification of the reaction events and rejection of backgrounds.

iii) The angular distributions and asymmetries of the emitted particles can be measured, and thus the transition strengths can be determined accurately depending on multipolarities and parities of the transitions.

TPC has an sensitive volume of 120 mm(W)×120 mm(H)×250 mm(D). The electrons ionized by the passage of a charged particle are drifted along the direction of the depth of TPC. The tagged photon beam was injected in the central axis of TPC along the drift direction. The effective depth of TPC was defined so that the detection efficiency ε of TPC was better than 99%, and actually it was 200 mm. The effective thickness of the ^{4}He target was determined from the temperature and the pressure of the counter gas, which were monitored during the measurement. The temperature and the pressure of the counter gas were in average 19.9 ± 0.1 ℃ and 430 ± 2 Torr, respectively. Thus the effective thickness of ^{4}He was determined as $(1.13\pm0.02)\times10^{-5}$ atoms/b. The spatial resolutions of TPC were 2 mm for directions parallel to and perpendicular to the photon beam axis. To monitor the response of TPC during the experiment, an α-ray source (^{241}Am) was installed at the head of the drift region.

2.3 Data acquisition system

The data acquisition was performed by using standard NIM and CAMAC circuits. The signals from the cathode wires were amplified, and converted to logic signals with discriminators. Those logic signals were sent to 32channel multi-hittable TDC's (LeCroy 2277), and were used to measure the drift times of the ionized electrons. The signals from the anode wires were summed, and their pulse shapes were recorded with 100 MHz flash ADC's (REPIC RPC-081). The summed anode signals were also discriminated and converted to anode-logic signals. The pulse heights and the timings of the signals from TR were recorded with current-sensitve ADC's (LeCroy 2249W) and TDC's (LeCroy 2228), respectively. The timing signals from TAG were recorded with TDC's (LeCroy 2228). The data acquisition was carried out when an anode-logic signal of TPC and a signal of TR were obtained in coincidence within a time interval of 70 μs, which was chosen to be sufficiently longer than the maximum drift time of TPC (~40 μs). The data from the CAMAC modules were acquired by an IBM-AT personal computer with the Linux operating system. For the CAMAC device driver, we employed the UNIDAQ system [28].

§ 3. Result

3.1 Event selection and background

With the above trigger condition for the data acquisition, 401,638 events were acquired as the raw data during the measurement time of 42,300 s. To select the candidates of the true events of the photonuclear reactions, we rejected the events in which the signals of TR and TAG were not detected in coincidence within the time width of 100 ns. Here the time width of 100 ns for the coincidence condition was defined from the distribution of the time difference between TR and TAG. 19,975 events survived after this requirement, and then those events were inspected event by event, by checking the tracks of the charged particles emitted by the reactions. The events could be categorized to seven types as listed in Table 1. Figures 2(a)~(g) show the examples of the tracks of the events of Type-1~7, respectively.

In Fig. 2, tracks are indicated as the areas surrounded by dots, which correspond to the timing of the drift electrons in TPC. Here, the pulses from the cathode wires of TPC were converted to logic signals with the discriminators, and both the leading edge and the trailing edge of the logic signals were recorded with TDC's. Therefore, the width of a track along the drift direction is correlated to the energy loss of the particle in TPC. Using such information, we made event identification as follows. The events of Type-1 is considered to be caused by the accidental coincidence of the noise of TPC and TAG, because no track of the charged particles from photonuclear reactions was observed. Type-2 is an α particle from the α-ray source, since the track is originated from the position of the α-ray source. Type-3 is possibly an event of ^{4}He(γ,n)^{3}He, ^{4}He(γ,p)^{3}H or ^{4}He(γ,pn)^{2}H at relatively high excitation energy,

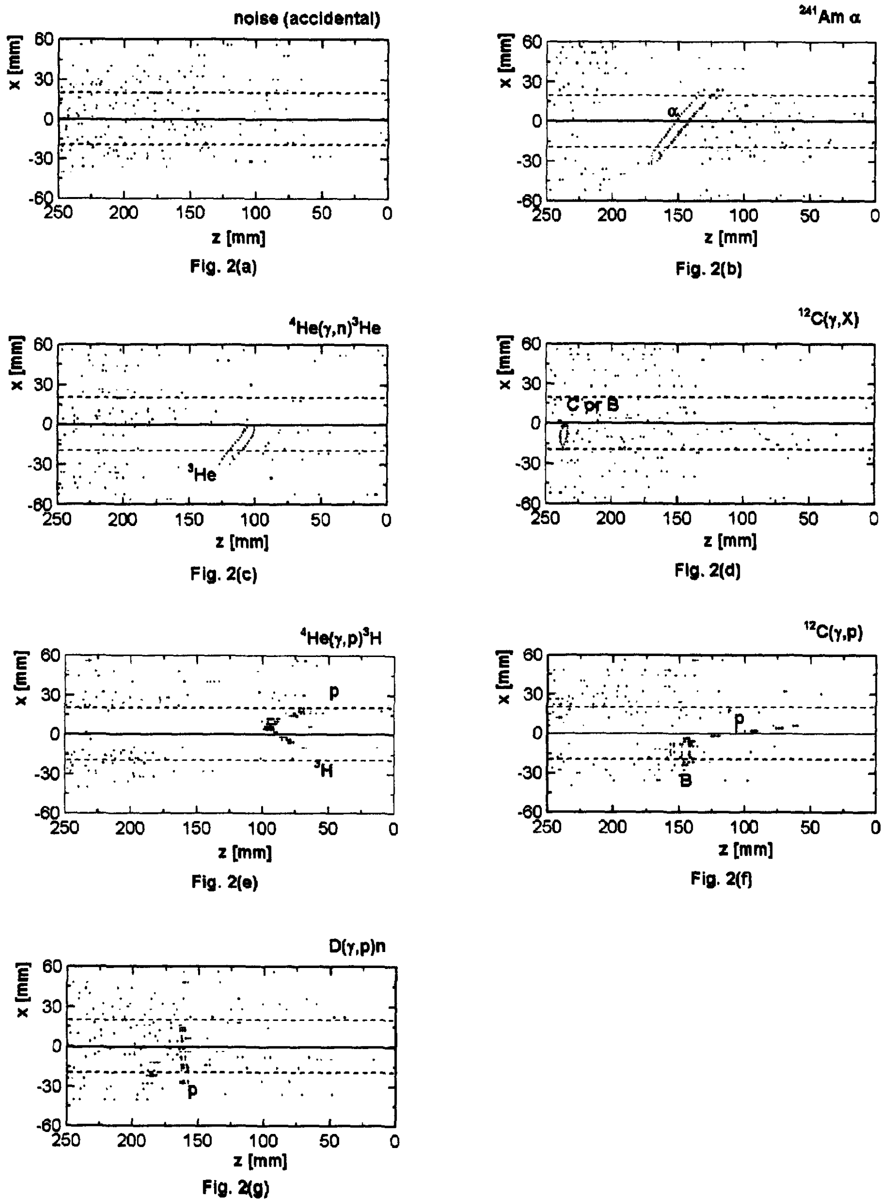

Fig. 2(a)

Fig. 2(b)

Fig. 2(c)

Fig. 2(d)

Fig. 2(e)

Fig. 2(f)

Fig. 2(g)

Fig.2. Examples of the observed tracks. The rectangular frames indicate the side view of the active volume of TPC. The photon beams come from the left ; (a) accidental noise, (b) α-ray from ^{241}Am source, (c) ^{4}He(γ,n)^{3}He, ^{4}He(γ,p)^{3}H or ^{4}He(γ,pn)^{2}H, (d) ^{12}C(γ,p)^{11}B or ^{12}C(γ,n)^{11}C, (e) ^{4}He(γ,p)^{3}H or ^{4}He(γ,pn)^{2}H, (f) ^{12}C(γ,p)^{11}B, and (g) ^{2}H(γ,p)n.

because only one track with a medium width can be found. Here, photoneutrons and photoprotons with small energy losses cannot be detected, because TPC is insensitive to them. With the similar consideration, Type-4 can be attributed to ^{11}C or ^{11}B from the photodisintegration of ^{12}C. Type-5 is a candidate of ^{4}He(γ,p)^{3}H or ^{4}He(γ,pn)^{2}H. Type-6 and Type-7 are identified as (γ,p) reactions of ^{12}C and ^{2}H, respectively. Table 1 shows the number of events of Type-1~7.

The present result shows that the main background is caused by the accidental coincidence of the noise of TPC and TAG, and they can be identified and rejected by checking the track shape.

Table 1. Number of events of Type-1~7.

Event type	Number of events
Total	19,975
Type-1	17,930
Type-2	2,000
Type-3	36
Type-4	3
Type-5	3
Type-6	2
Type-7	1

Table 2. Trigger rate and dead time of data acquisition.

γ-ray intensity [photons/s]	Trigger rate [counts/s]	Dead time [%]
1×10^6	230	85.9
2.5×10^5	13.7	26.6
1×10^4	5.9	13.3

3.2. Trigger rate and dead time of data aquisition

To check the efficiency of the data acquisition of the present experimental system, the dead time of the system was measured as a function of the photon beam intensity, as shown in Table 2. Therefore, to make an effective measurement with the photon intensity as high as 10^6 photons/s, the trigger rate should be decreased to about 10 counts/s. That can be achieved by requiring the coincidence of TPC, TR and TAG at the hardware level.

§ 4. Summary

In this work, the feasibility of the present experimental method was examined. We could observe the tracks of the particles emitted by the photonuclear reactions of ^{4}He, ^{12}C and ^{2}H successfully even under high radiation environment due to a high-intensity incident photon beam. The background is mainly due to the accidental coincidence between the noise signals of TPC and TAG. By requiring the coincidence of TPC, TR and TAG for the trigger condition, most of such background events can be rejected, and the efficiency of the data acquisition of ~80% can be achieved with the photon beam intensity of ~10^6 photons/s. With the present result, we can expect our experimental method will be useful for the precise measurement of the photonuclear reactions of ^{4}He.

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