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Measurement of ^{4}He Photodisintegration in the Giant Dipole Resonance Region

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A comprehensive understanding of the electroweak response of ^{4}He nuclei in the giant dipole region is essential to resolve the process of neutrino nucleosynthesis in supernovae. We simultaneously measured two photodisintegration reactions, ^{4}He(γ,^{1}H^{3}H) and ^{4}He(γ,^{3}He)n, in the energy range of E_γ = 23.0–33.3 MeV. Quasi-mono-energetic γ-ray beams were bombarded on the active He gas target system MAIKo, and shapes of charged particle trajectories inside the sensitive volume were measured. The analysis is still in progress. We are developing a Monte Carlo simulation code to determine photodisintegration cross sections.

KEYWORDS: photonuclear reaction, ^{4}He, GDR, active target, lase-Compton-scattering γ-ray

1. Introduction

Supernova explosions are considered to be one of the major sources of various light elements such as lithium. A large number of neutrinos in few tens MeV are emitted from the core in supernovae and induce light element synthesis through (ν,$\nu' X$) reactions in the outer layer. Especially, the ^{4}He(ν,ν' ^{1}H^{3}H) and ^{4}He(ν,ν' n ^{3}He) reactions are the starting point of the sequence of the light element synthesis process in supernovae [1]. However, the cross sections for neutrino nuclear reactions are very difficult to be measured directly.

The response of ^{4}He to photo absorption is proportional to that of the vector current part of the weak interaction induced by neutrinos even though contributing gauge bosons are different. Since the weak and the electromagnetic (EM) responses have similar spin-isospin operators, the EM responses can be used to evaluate the weak ones [2]. Especially, the ^{4}He photodisintegration reactions, ^{4}He(γ,^{1}H^{3}H) and ^{4}He(γ,^{3}He)n, in the isovector giant dipole resonance (GDR) region are analogous to neutrino reactions in supernovae. The GDR is one of well-known collective excitations in atomic nuclei, and it is interpreted as an anti-phase oscillation of protons and neutrons. ^{4}He nuclei are selectively excited to the GDR by absorption of photons at several tens of MeV, and as consequence, decay to binary final states. The photodisintegration in the GDR region can be a surrogate reaction to probe neutrino nuclear reactions in supernovae.

The ^{4}He photodisintegration in the GDR region has been extensively measured by various groups. However, recent experimental results show remarkably different trends in the beam-energy dependence of the cross sections. T. Shima *et al.* carried out an experiment using an active He gas target system based on a time projection chamber (TPC) [3]. They measured the ^{4}He(γ,^{1}H^{3}H) and

^{4}He(γ,^{3}He)n reactions simultaneously, and claimed that the cross sections for both reactions have no local maximum below E_γ = 30 MeV but monotonically increase. They performed the experiment and the data analysis very carefully, but their result is neither consistent with previous experimental studies nor recent *ab initio* calculations [4]. The Duke university group performed a measurement using an active target system based on a gaseous scintillator [5, 6]. They measured both of the two reactions with the identical method. They obtained high-statistics data accordance with theoretical studies and showed that there are resonance peaks around E_γ = 25 MeV in the cross sections for the ^{4}He(γ,^{1}H^{3}H) reactions. However, one can not perceive a peak structure in the ^{4}He(γ, ^{3}He)n cross sections due to the lack of data points below E_γ = 26 MeV. A more precise measurement using an improved active target system based on TPC is desired in order to resolve the discrepancy.

2. Experimental Method

The measurement was performed at the beam line 01 (BL01) [7] in the New SUBARU synchrotron radiation facility. In this facility, quasi-mono-energetic γ-ray beams in the energy range suitable for photo-nuclear reactions are produced using the laser Compton scattering (LCS) technique. The principle of the LCS technique is energy amplification of laser photons in the Compton scattering off the relativistic electrons, which is due to the Lorentz boost of the center of mass by the electrons. Infrared to visible light emitted from a laser oscillator is injected to the electron storage ring against the circulating electron beams about 1 GeV, and photons scattered to backward angles were extracted to BL01 as γ-ray beams. Quasi-mono-energetic γ-ray beams are obtained by selecting photons scattered around 180 degrees using a pair of thick lead collimators located at 1,547 and 1,847 cm away from the collision point. The energy of γ-ray beams are tunable by changing the energy of electron beams. The experimental setup is shown in Fig. 1.

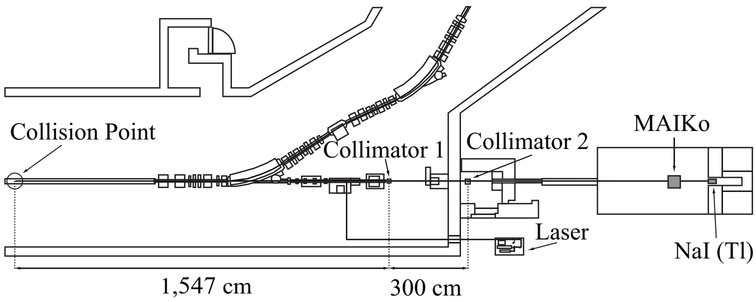

Fig. 1. Experimental setup at BL01 in New SUBARU. Photons generated in the laser oscillator are guided inside the electron storage ring and collide with electrons around the collision point. Back scattered high-energy photons are delivered to MAIKo.

In this measurement, γ-ray beams at 23.0, 24.0, 25.0, 27.0, 28.0, 30.0, and 33.3 MeV were generated from the collisions between laser photons at λ = 532 or 1064 nm and electron beams in 0.982–1.310 GeV. A typical beam rate was 10^6 photons per second. The uncertainty of beam flux is 3.5% [8], and the energy spread of beams, which was estimated with the same method as Ref. [9], was 2.6–3.9% in full width at half maximum for E_γ = 22.0–33.3 MeV when the aperture of the lead collimator is 2 mm in a diameter. A cylindrical shape NaI (Tl) detector with a diameter of 6 inches and a thickness of 12 inches was put at the end of beam line to monitor the γ-ray flux.

Charged decay particles from ^{4}He were measured using the MAIKo active gas target system [10] which is a TPC filled with a target gas. The MAIKo active target was installed on BL01 as shown in Fig. 1. Figure 2 is a schematic picture of the MAIKo active target. A cubic object at the center is the sensitive volume where an upward electric field is formed. Charged particles ionize gas molecule, and the generated electrons are drifted along the electric field and collected on the micro pixel chamber (μ-PIC) [11]. μ-PIC consists of 256 anode strips and 256 cathode strips with a pitch of 400 μm. The anode and cathode strips are arranged orthogonally. Electric signals induced on the strips are read out from the dedicated electronics [12]. By using timing and position information of the electric signals, the charged particle trajectories are reconstructed three-dimensionally. Since the reaction occurs inside the sensitive volume of the MAIKo active target, low-energy particles can be measured over large solid angle.

In this measurement, mixed gas of He and CH_4 in the molecular number ratio of 90 to 10 was filled in the MAIKo active target. The dimension of the sensitive volume is 10 cm × 10 cm × 11 cm in width, depth, and height. The target gas density was tuned between 1.04–4.16 mg/cm^3 (50–200 kPa) depending on the energy of γ-ray beams. This density was determined to fulfill two conditions. Most of ^{3}He nuclei from the ^{4}He(γ,^{3}He)n reactions stop inside the sensitive volume, and most of ^{1}H and ^{3}H nuclei from the ^{4}He(γ,^{1}H^{3}H) reactions escape from the sensitive volume. Kinetic energy of escaping charged particles were measured using 600 μm-thick silicon strip detectors.

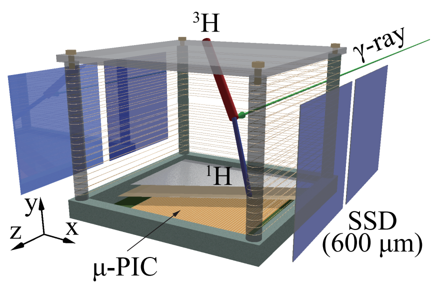

Fig. 2. Schematic picture of the MAIKo active target. Four pieces of silicon strip detectors (SSDs) were mounted on the both sides of MAIKo.

The trigger signals for the data acquisition procedure was generated using signals read out from the MAIKo active target. The threshold level for the signal to fire the trigger was set to sufficiently low so as not to miss the photo-disintegration events. The trigger rate was less than 100 Hz, and the data acquisition efficiency was higher than 99%. During the measurement, more than 500 ^{4}He(γ,^{1}H^{3}H) and ^{4}He(γ,^{3}He)n events were acquired at each beam energy.

3. Analysis

We acquired two black-and-white images for each event. Each image shows particle trajectories projected onto the plane perpendicular to the anode or cathode strips on the μ-PIC. Figure 3 presents typical track images recorded in a ^{4}He(γ,^{1}H^{3}H) event. The abscissas of the graphs show horizontal positions of electrodes, and the ordinates represent vertical positions deduced from timing information. In addition to the track images, we also acquired the pulse shapes of analog signals using flash-analog to digital convertors (FADCs) with a sampling rate of 25 MHz. Signals from adjacent 32 strips of electrodes are summed and input to FADCs. From the time integration of the signal pulse, energy loss of charged particles in the target gas can be deduced.

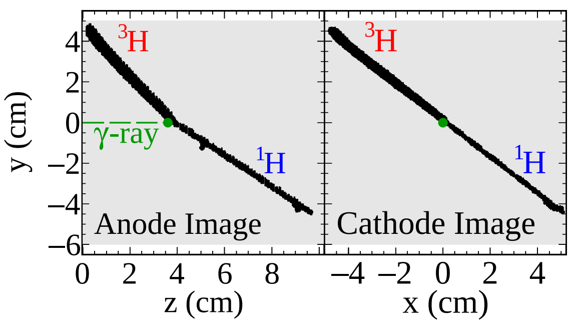

Fig. 3. Typical track images in a ^{4}He(γ,^{1}H^{3}H) event. The y-axis is parallel to the direction of gravity, and the z-axis is along the beams. The x-axis is determined to define the right-handed coordinate system. The filled areas indicate the sensitive volume.

Since most of the acquired events are background events due to the Compton scattering, ^{12}C photodisintegration, and electric noises, the ^{4}He(γ,^{1}H^{3}H) and ^{4}He(γ,^{3}He)n events must be selected from all the acquired events. The event selection was done using the kinematic information obtained from topology of the particle trajectories and energy losses of the particles along the trajectories. In the ^{4}He(γ,^{1}H^{3}H) events, ^{1}H and ^{3}H are emitted in the opposite direction, and the decay energy is distributed to ^{1}H and ^{3}H in the inverse ratio of their masses. On the other hand, in the ^{4}He(γ,^{3}He)n events, only one trajectory is observed, and its length is much shorter than those of ^{1}H and ^{3}H.

The γ-ray beam profile was understood from the simulation using Geant4 [13] taking into account the electron beam profile. The parameters in the calculation were tuned to reproduce the response of the NaI(Tl) beam monitor at the end of the beam line.

The tracking efficiency of the MAIKo active target must be considered to determine the cross sections. There were some inevitable counting losses of photodisintegration events due to insensitivity of MAIKo and defects of the tracking and event selection algorithms. These contributions were evaluated using another simulation code. Assuming the ^{4}He photodisintegration occurs inside the sensitive volume of the MAIKo active target at different energies according to the energy profile of γ-ray beams, trajectories of emitted charged particles, ^{3}H and ^{1}H or ^{3}He were simulated. Ionization process along the trajectories was calculated by the SRIM code [14], and transportation and gas-amplification processes of generated electrons were computed employing the Garfield++ code [15]. Analog signals read out from the μ-PIC were generated by folding the arrival timing of electrons on the μ-PIC with a response function of the readout circuit. The analog signals were virtually processed and encoded to be the same data format as the real experiment. This simulated data were analyzed by the same manner as that for the real data, and the tracking efficiency was estimated. Further tuning of the simulation calculation is still on the way.

4. Summary and Future Prospect

The cross sections for the ^{4}He(γ,^{1}H^{3}H) and ^{4}He(γ,^{3}He)n reactions are controversial around the GDR region ($E_\gamma \sim$ 20–30 MeV). We performed a measurement of the ^{4}He photodisintegration at E_γ = 23.0–33.4 MeV. Quasi-mono-energetic γ-ray beams were generated by means of the LCS technique at BL01 in the New SUBARU synchrotron facility and bombarded on the MAIKo active target. More than 500 events of the ^{4}He photodisintegration at each energy were acquired using the MAIKo active target. An event selection algorithm was established. A simulation code estimating the tracking efficiency was developed, but its tuning is still in progress. The final result will be reported elsewhere soon.

References

[1] T. Suzuki and T. Kajino, J. Phys. G **40**, 083101 (2013).
[2] H. Ejiri, Physics Reports **338**, 265 (2000).
[3] T. Shima *et al.*, Phys. Rev. C **72**, 044004 (2005).
[4] W. Horiuchi, Y. Suzuki, and K. Arai, Phys. Rev. C **85**, 054002 (2012).
[5] R. Raut *et al.*, Phys. Rev. Lett. **108**, 042502 (2012).
[6] W. Tornow *et al.*, Phys. Rev. C **85**, 061001 (2012).
[7] S. Miyamoto *et al.*, Radiation Measurements **41**, S179 (2006).
[8] T. Kondo *et al.*, Nucl. Instrum. Methods A **659**, 462 (2011).
[9] H. Utsunomiya *et al.*, IEEE Transactions on Nuclear Science **61**, 1252 (2014).
[10] T. Furuno *et al.*, Nucl. Instrum. Methods A **908**, 215 (2018).
[11] A. Ochi *et al.*, Nucl. Instrum. Methods A **478**, 196 (2002).
[12] T. Mizumoto *et al.*, Nucl. Instrum. Methods A **800**, 40 (2015).
[13] S. Agostinelli *et al.*, Nucl. Instrum. Methods A **506**, 250 (2003).
[14] J. F. Ziegler *et al.*, Nucl. Instrum. Methods B **268**, 1818 (2010).
[15] `http://garfieldpp.web.cern.ch/garfieldpp/`.