New probe to M1 strengths in GDR region for supernova neutrino interactions

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Abstract. The M1 strength (or level density of $1^+$ states) is of importance for estimation of interaction strengths between neutrinos and nuclei for the study of the supernova neutrino-process. We have proposed a method using $(\gamma, n)$ reactions with linear polarized laser Compton scattering $\gamma$-rays to measure M1 strength. In 1957, Agodi predicted theoretically angular distribution of neutrons emitted from states excited via dipole transitions with linearly polarized $\gamma$-ray beam at the polar angle of $\theta=90^\circ$ can be described by a simple function, $a + b \cos(\phi/2)$, where $\phi$ is azimuthal angel. However, this theoretical prediction has not been verified over the wide mass region. We have measured neutron angular distributions with (polarized gamma, n) reactions on Au, NaI, and Cu. We have verified the Agodi’s prediction for the first time over the wide mass region. This suggests that (polarized gamma, n) reactions may be useful tools to study M1 strength in giant resonance regions.

1. Introduction

During core-collapse supernovae copious amounts of energetic neutrinos are emitted from the proto-neutron star. As these neutrinos pass through the outer layers of the star they can induce nuclear reactions on ambient nuclei. This process is referred to as the neutrino process. This has been proposed as the mechanism responsible for the origin of some rare isotopes of light and heavy elements [1]. The neutrino process is also of importance for constraining the neutrino spectra from SNe [2, 3] and for studying neutrino oscillations [2, 4]. Although many nuclides can be synthesized by the neutrino process, the produced abundance is usually negligibly small compared to production by other major nucleosynthesis processes such as s-process or r-process. Thus, the neutrino process can only play a significant role in the synthesis of isotopes which are bypassed by other major processes. The astrophysical origin of $^{180}$Ta has been unresolved problem for long time. Hayakawa et al. [5] presented that the neutrino process reproduces systematically the solar abundances of $^{138}$La and $^{180}$Ta with a new isomer model, whereas other scenarios can explain partly their abundances. $^{92}$Nb is a beta unstable isotope with a half-life of about $3.5 \times 10^7$ y, which does not exist at the present solar system. The abundance of $^{92}$Nb at the solar system formation has been measured by primitive meteorite analysis. However, its origin has been also unresolved problem. Hayakawa et al. [6] has proposed the neutrino process origin for $^{92}$Nb and calculated a theoretical abundance at the solar system formation.
using a supernova model with neutrino-nucleus interactions calculated by a QRPA model. The origin of \(^{92}\)Nb can be explained by the supernova neutrino process and the duration time between the time when the supernova explosion occurred and the time of the solar system formation is \(10^6 - 3 \times 10^7\) y. In this way, the supernova neutrino process has important role for understanding of origin of rare isotopes, the cosmological history before the solar system formation, and neutrino physics.

![Neutral Current Reaction](image1)

![Charged Current Reaction](image2)

FIGURE 1. Schematic view of neutrino-induced reactions. Neutral current reactions (left) and Charged current reaction (right). In the neutral current reactions, nuclei are firstly excited by neutrino-induced reactions and subsequently decay by a nucleon such as a neutron, whereas, in the charged current reactions, a change exchange occurs and decays though emission of a gamma-ray or a nucleon.

Neutrino-nucleus interactions are key physics for understanding the neutrino process. However, individual neutrino reaction cross sections depend on the detailed nuclear structures of the nuclei involved [7]. Experimental measurements of neutrino–nucleus interactions for heavy nuclei are almost impossible because the associated weak reaction cross-sections are extremely small. Thus, one should calculate cross sections using nuclear structure models based on experimental data for detailed nuclear structure. The neutrino-process isotopes are predominantly synthesized by neutral current reactions and charged current reactions (see Fig. 1). In the neutral current reactions, the pre-existing seed nuclei are firstly excited by neutrino-induced reactions and subsequently de-excited by emission of nucleons such as neutron or γ-ray. On the other hand, in the charged current reactions, excited states on neutrino-isotopes are populated by electron neutrinos and subsequently decay to the ground state. The M1 strengths (or level density of 1+ states) are of importance for the estimation of the interaction strengths between neutrinos and atomic nuclei for the study of the supernova neutrino-process [7, 8]. However, there is no effective method to measure the M1 strength in the GDR region because of its large E1 strength.

The progress of relativistic engineering provides a new generation of photon beam, laser Compton scattering (LCS) gamma-rays. The energy tunable quasi-monochromatic LCS gamma-ray beam with MeV energy has been used for studying fundamental science and various applications at Duke University [9] and NewSUBARU [10] at present. The LCS gamma-rays have advantages that the maximum energy is sharply determined by the basic QED process and that the brightness near the...
maximum energy is relatively high. In addition, an advantage of the LCS gamma-ray is that it is almost 100% linearly (circularly) polarized, since the polarization of the laser is directly transported to the scattering photons.

The polarized gamma-ray beams are powerful tools to study nuclear physics. For example, electric-dipole (E1) and magnetic-dipole (M1) transition strengths from the ground state are measured directly with parity assignments using nuclear resonance fluorescence. On the other hand, (γ, n) reactions with linear polarized γ-rays have not been studied well. In 1957, Agodi [11] predicted theoretically angular distribution of neutrons emitted from states excited via dipole transitions with linearly polarized gamma-ray beam at the polar angle of θ=90° should be followed by a simple function, a + b cos(2φ), where φ is azimuthal angel. However, this theoretical prediction has not been verified over the wide mass region except for light nuclei as deuteron for long time. The Agodi’s paper had been cited by previous papers in 50~60’ but it has been almost forgotten at present. We have proposed a method using (γ, n) reactions with linear polarized laser Compton scattering (LCS) γ-rays to measure M1 strength [10]. We have measured neutron angular distributions with (polarized gamma, n) reactions on Au, NaI, Cu targets to examine the Agodi’s prediction [12].

2. Method

We have performed a nuclear experiment using laser Compton scattering γ-rays with linear polarization at NewSUBARU in SPring-8. The γ-ray beam was generated by Compton scattering laser photons with electrons stored in the electron storage ring NewSUBARU. The details of the LCS γ-ray source and typical experimental procedures are described in previous papers [12-14]. The storage ring NewSUBARU was operated with a mode of “Top-up”, in which electron bunches were supplied continuously from an electron linac without extra acceleration into NewSUBARU. We irradiated three targets of Au, NaI, and natural Cu. Their sizes were 10 mmφ × 40 mm, 10 mmφ × 50 mm, and 5 mmφ × 50 mm for Au, NaI, and Cu, respectively. Figure 2 shows a schematic view of photonuclear reactions on the nuclide 197Au as an example. Excited states on 197Au are populated by induced γ-rays. Individual populated states decay predominantly to the ground state or an excited state in the neutron deficient isotope 196Au by emitting a neutron.

![Figure 2: Schematic view of (γ, n) reactions.](image)

The energy of generated γ-rays is determined by the wave length of laser and the energy of electron beam. The energy of the electron beam was 974 MeV. A Q-switch Nd:YVO4 laser system provided...
laser with a wave length of 1064 nm with a power of 4 W. The maximum energy of the generated LCS γ-ray beam was 16.7 MeV. We used pulsed electron beams at a repetition rate of 2.5 MHz with a pulse width of 60 ps. The pulse width of the laser was 8 ns. The energy spread of the γ-ray beam depends on the collimator size and the emittance of the electron beam. We used two collimators as shown in Fig. 3. The first collimator was located inside of the storage ring, whereas the second collimator was located in front of the target. The γ-ray energy width was about 5 MeV for Au and 3 MeV for NaI and Cu. The estimated γ-ray flux was \((1-2) \times 10^7 \) photons/s in an energy range from 12 MeV to 16.7 MeV. The second collimator with a diameter of 6 mm was located before the target position. The diameter of the incident beam was about 6 mm on the target NaI or Cu. This collimator was not used for the Au measurement and the beam diameter was larger than the Au target diameter.

The neutrons were measured using a time-of-flight (TOF) method. The detector was set at a polar angle of \(\Phi = 90^\circ\) outside the experimental room (see Fig. 3). Each target was located inside the irradiation room with a concrete shield with a thickness of 540 mm. Neutrons were guided to the detector through a hole with a diameter of 80 mm and length of 970 mm. A lead shield with a thickness of 2 mm was located in front of the detector. A time-to-amplitude converter (TAC) was used to measure neutron energies. A start signal is generated from an output of the neutron detector. The synthesizer controlled the frequency of electron bunch with 2.5 MHz. A stop signal was generated from this synthesizer signal. Since this signal was also used as the external trigger signal to generate the laser pulse with 25 kHz by the divider, the trigger signal can be used as the stop signal. The generation of the LCS γ-ray was synchronized with the electron bunch. The pulse height of TAC signals were recorded using a multi-channel analyzer.

To measure the angular distribution of neutrons, we changed the linear polarization plane angle of the LCS γ-rays, whereas the detector system was fixed. The advantage of this method is that it deduces the systematic error. The angle of the linear polarization plane of the γ-ray beam was tuned by changing the linear polarization plane of the incident laser. We measured the neutron energy spectra as a function of the laser polarization angle in a range from \(\phi = 0^\circ\) to \(360^\circ\) in 30° steps for NaI and Cu, where the \(\phi = 0\) was defined as the electric polarization vector being in the plane of the detector. A key point of this experiment is how to verify the angle of linear polarization of the incident LCS γ-ray beam. The angle of the linear polarization plane was determined by the linear polarization plane of the incident laser. However, the linear polarization plane of the incident laser may be changed by mirror. Thus, the laser beam was extracted to an area outside of the electron storage ring after LCS without additional mirror and the laser polarization angle was measured.

3. Result

Prompt γ-rays and neutrons can be separated by the TOF method. As shown in Fig. 4, the neutrons and prompt γ-rays are clearly separated. The measured time width of the prompt γ-ray is about 3 ns (FWHM) which is longer than the expected duration of 60 ps from the electron pulse width because of time fluctuation of the slow rising-time photomultiplier and the time jitter between the laser generation time and the external trigger signal from the electron storage ring. The energy spectra of the neutrons were derived from the TOF signals. The neutrons with energies lower than 2 MeV were not measured because of the detection efficiency. The measured maximum energy of the neutrons is almost 8 MeV for Au. This energy is almost same as the energy of 8.6 MeV, which is the difference between the maximum photon energy of 16.7 MeV and the neutron separation energy of 8.1 MeV. The time resolution, originated from the ratio of the detector depth to the flight pass length, is about 5%. However, the energy width of the incident LCS γ-ray beam is about 3–5 MeV, which is much higher than typical excitation energy differences near the ground state. Thus, the level structure of the residual nucleus cannot be observed in the present TOF spectra.
FIGURE 4. Time-Of-Flight spectrum for the Au target. The peaks corresponding to γ-rays and neutrons are clearly separately.

FIGURE 5. Angular distributions

4. Discussion

The neutron yields are presented as a function of azimuthal angle φ for An and NaI (see Fig. 5). The solid lines in Fig. 5 show functions in form of \( a + b \cos(2\phi) \) obtained by \( \chi^2 \)-fitting. The NaI target includes \(^{23}\text{Na}\) and \(^{127}\text{I}\). The neutron separation energies of these nuclides are 12.4 MeV (\(^{23}\text{Na}\)) and 9.1 MeV (\(^{127}\text{I}\)) and the contribution of \(^{127}\text{I}\) is dominant for the NaI target. The experimental result for Cu is also reproduced by the function \( a + b \cos(2\phi) \) although the anisotropy, \( b/a \), is very low. The three neutron angular distributions are described as the function of \( a + b \cos(2\phi) \) independent of nuclides. Therefore, the theoretical prediction by Agodi is for the first time verified over the wide mass region.

The targets used in the present experiments are odd-\( A \) isotopes. The residual isotope is an odd-odd nucleus. The level density of the odd-odd nuclei is higher than even-even nuclei and odd-\( A \) nuclei. There are many combinations of the transitions as shown in Fig. 2 and it is difficult to calculate realistic values for neutron angular distribution for the odd-\( A \) isotopes. In contrast, in the case of an even-even nucleus target, the spin and parity of states populated by the incident photon is in general
limited only to $J^\pi = 1^\pm$ and $2^+$ since E1, M1, and E2 transitions are dominant. Thus the theoretical calculation is easy comparing with those of odd-A targets.

Agodi [11] indicated that the sign of the parameter $b$ for the M1 transitions is different from that of E1 when the initial and final states are same. This suggests that if we select a transition of which initial and final states are known we can measure, in principle, M1 strength in this transition. For example, the M1/E1 mixing can be evaluated from a polarization asymmetry if by gating with the highest neutron energy to select the transition to the ground state of the residual nucleus (see Fig. 2). For such a purpose, the key point is the energy resolution of neutron measurements. In the present experiment, the energy resolution is finally determined by the energy width of the incident gamma-ray beam, which is either 3 or 5 MeV. In the present available LCS $\gamma$-ray facilities, the typical energy spread of the photon beam is 3-10%. In this case, with 17-MeV $\gamma$-rays, the neutron energy resolution is about 0.5-1.7 MeV. The progress in laser and accelerator physics enables us to realize the next generation of the LCS $\gamma$-ray sources including ELI-NP [15], MEGA-ray [16], and the ERL-LCS [17].

The energy spread of these $\gamma$-ray beams is expected to be lower than $dE/E = 10^{-3}$. If we couple the present experimental method with such high energy resolution $\gamma$-beam, it is possible to study the detailed nuclear structure of the GDR with an excellent resolving power of the order of keV.

5. Conclusion

Agodi predicted theoretically the anisotropic angular distribution of neutrons emitted from states excited via dipole transitions with linearly polarized $\gamma$-ray beam at the polar angle of $\theta=90^\circ$ should be followed by a simple function, $a \pm b \cos(2\phi)$, but it has not been verified experimentally over half a century. We have measured neutron angular distribution using linear polarized $\gamma$-ray beam generated by Compton scattering at NewSUBARU. We have verified this Agodi’s prediction for the first time in the wide mass region. In the near future, the next generation of the LCS $\gamma$-rays will be available. The lost Agodi’s prediction will have a more precious role to study nuclear physics in the GDR region and applications using photonuclear reactions.

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