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Spatial anisotropy of neutrons emitted from the ^{56}Fe(γ, n)^{55}Fe reaction with a linearly polarized γ-ray beam

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We have measured the azimuthal anisotropy of neutrons emitted from the ^{56}Fe(γ,n)^{55}Fe reaction with a linearly polarized γ-ray beam generated by laser Compton scattering at NewSUBARU. Neutron yields at the polar angle of 90° have been measured as a function of the azimuthal angle ϕ between the detector and the linear polarization plane of the γ-ray beam. The azimuthal anisotropy of neutrons measured at $\phi = 0°, 10°, 25°, 45°, 60°, 70°$, and $90°$ has been well reproduced using a theoretically predicted function of $a + b\cos(2\phi)$.

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I. INTRODUCTION

Photonuclear reactions have played an important role in developing nuclear physics [1] and in various applications such as nondestructive measurements of nuclear materials [2,3]. The (γ, n) reactions with linearly polarized γ-ray beams have the potential to allow us to study nuclear structures in detail [4,5]. In 1957, Agodi [5] predicted that when nuclei are excited via dipole transitions with linearly polarized photons the azimuthal angle (ϕ) distribution of nucleons emitted from ($\vec{\gamma}, n$) and ($\vec{\gamma}, p$) reactions at the polar angle $\theta = 90°$ should follow a simple function of $a + b\cos(2\phi)$, where a and b are constants regardless of the angle ϕ. This formula was derived from the fundamental principle of angular momentum and parity conservations. It was also presented that the sign of b depends on the excitation mode, i.e., the $E1$ or $M1$ transition. This has suggested that both $M1$ and $E1$ strengths from the ground state to excited states in the giant dipole resonance (GDR) region can be measured.

After the prediction by Agodi [5], in 1966 Kellogg and Stephens [6] measured the azimuthal anisotropy of the ^{12}C($\vec{\gamma},p$)^{11}B reaction with linearly polarized γ rays provided from the ^{3}H(p,γ)^{4}He reaction. Later, the polarization asymmetry of the ^{16}O($\vec{\gamma},p$)^{15}N reaction at $\theta = 90°$ was measured with bremsstrahlung γ rays although its polarization is not high [7]. Progress in accelerator and laser physics has provided us with energy-tunable quasi-monochromatic γ-ray beams generated by laser Compton scattering (LCS). The LCS γ-ray beam sources in the MeV energy region have been developed at the LADON facility [8], HIγS at Duke University [9], and the National Institute of Advanced Industrial Science and Technology in Japan [10] in the 1980s and 1990s. An advantage of the LCS γ-ray beams is the ability to create an almost 100% linearly polarized beam because the polarization of laser photons is directly transferred to scattered γ rays. Using the LCS γ-ray beam, the ^{28}Si($\vec{\gamma},p$)^{27}Al reaction experiment at LADON [11] and the D($\vec{\gamma}$, p)n reaction experiments at HIγS [12,13] were carried out.

Recently, we measured the azimuthal angle distributions of neutrons emitted from ($\vec{\gamma}$, n) reactions on natural Cu, ^{127}I, and ^{197}Au using LCS photons provided from an electron storage ring of NewSUBARU [14,15] to examine whether the neutron anisotropy can be observed in a mass region heavier than that of ^{28}Si [16]. The level density in middle-heavy and heavy nuclides is significantly high [17]. The sign of the parameter b for the $M1$ transition is different from that of the $E1$ transition [5]. Therefore, the neutron azimuthal anisotropy may become weak or even vanish by complicated mixtures of $E1$ and $M1$ transitions via various excited states in middle-heavy and heavy nuclei (see Fig. 1). In the previous study [16], it was found that the anisotropy remained for these heavy nuclei and that the neutron yields measured as a function of ϕ ranging from 0° to 360° could be reproduced well by the function $a + b\cos(2\phi)$. However, the azimuthal angle distributions were measured only in 30° steps [16]. Because of the geometrical symmetry of $\cos(2\phi)$, only a few measured points have an actual meaning for studying the azimuthal anisotropy of the neutron. Therefore, in this study we measure the neutron yields from the ^{56}Fe($\vec{\gamma}$,n)^{55}Fe reaction at seven

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angles of $\phi = 0^\circ, 10^\circ, 25^\circ, 45^\circ, 60^\circ, 70^\circ$, and 90° to verify the azimuthal angle distribution predicted by Agodi [5] in further detail.

II. EXPERIMENTAL PROCEDURE

The experiment was carried out at the NewSUBARU electron storage ring [14,15]. The details of the γ-ray source and basic experimental procedures have been described in previous papers [18–20]. The LCS γ-ray beam was generated by the Compton scattering of high-energy electrons with laser photons provided from a Q-switch Nd:YVO$_4$ laser with a wavelength of 1064 nm. The energy of electrons stored at NewSUBARU is 974 MeV. The maximum energy of the generated γ-ray beam was 16.7 MeV, which was determined by the electron energy and the laser wavelength. The lowest energy of the LCS beam was determined by the collimator size and the emittance of the electron beam. A collimator with a diameter of 3 mm was located before the target position and thereby the energy spread of the γ beam was about 3 MeV. The time widths of the electron bunch and the laser pulse were 60 ps and 8 ns, respectively. The storage ring was operated by a single bunch mode with a repetition rate of 2.5 MHz to generate only one γ-ray pulse by one laser pulse. The laser power was 3.8 W and the electron current was up to 20 mA. The evaluated γ-ray flux was (1–2) × 10^6 photons/s in an energy range from 14 to 16.7 MeV. The diameter of the incident γ-ray beam was about 3 mm at the target position. We used a natural iron target with a size of ϕ10 mm × 50 mm. Because the isotopic abundance of ^{56}Fe is 91.7%, in the following discussion we assume that the neutron anisotropy from ^{56}Fe is dominated.

Neutrons emitted from the $^{56}\mathrm{Fe}(\gamma,n)^{55}\mathrm{Fe}$ reaction (see Fig. 1) were measured using a plastic scintillator (Eljen Technology, EJ-232) with a size of ϕ50 mm × 30 mm coupled with a 60-mm-diameter photomultiplier (HAMAMATSU Photonics, H2431-50). The detector was located at the polar angle of $\theta = 90^\circ$. A 2-mm-thick lead shield was set in front of the detector to absorb low-energy γ rays. However, high-energy γ rays generated by the Compton scattering of the incident beam with the target were also observed. The separation between neutrons and γ rays was carried out using the time-of-flight (TOF) method. The target was located inside of the irradiation room with a concrete shield with a thickness of 540 mm. Neutrons were led to the outside of the irradiation room through a hole with a diameter of 80 mm. The distance between the target and the detector was 970 mm. A time-to-amplitude converter (TAC) was used to measure the time interval between a start pulse from the detector and a stop pulse from the electron storage ring. The TAC signals were recorded using a multichannel analyzer.

The neutron anisotropy from the $^{56}\mathrm{Fe}(\overrightarrow{\gamma},n)^{55}\mathrm{Fe}$ reaction was measured by changing the angle of the linear polarization plane of the incident LCS γ-ray beam at the angles of $\phi = 0^\circ$, $10^\circ, 25^\circ, 45^\circ, 60^\circ, 70^\circ$, and 90°, where $\phi = 0^\circ$ was defined as the electric wave being in the plane of the detector. The linear polarization plane angle of the LCS beam was determined by measuring the polarization plane angle of the laser because the polarization of the laser was transferred directly to the LCS γ ray. After the Compton scattering to generate γ rays, the laser was extracted to the opposite side of the electron storage ring without additional mirrors. The laser power transmitted through a Glan-Thompson prism [21] was measured by changing the angle of the Glan-Thompson prism. The linear polarization plane angle of the LCS γ beam was determined as the angle at which the transmitted laser power was largest.

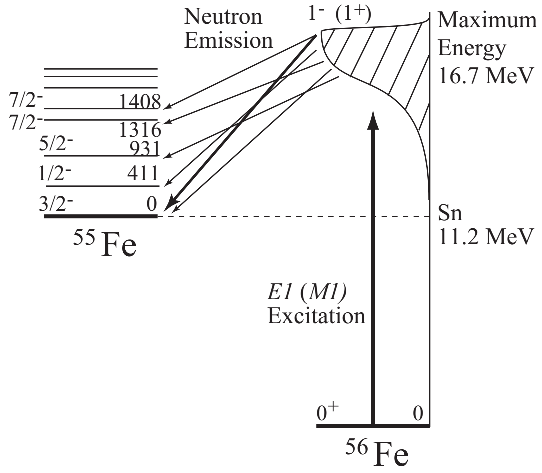

FIG. 1. Schematic view of the $^{56}\mathrm{Fe}(\gamma,n)^{55}\mathrm{Fe}$ reaction using a laser Compton scattering γ-ray beam. Excited states with energies of 14–16.7 MeV, which locate above the neutron separation energy of Sn = 11.197 MeV, are populated by the absorption of γ rays. The individual excited states subsequently decay to states in a residual nucleus ^{55}Fe by neutron emission.

III. RESULTS AND DISCUSSION

Figure 2 shows a typical TOF spectrum. Neutrons due to photodisintegration reactions and prompt γ rays are clearly

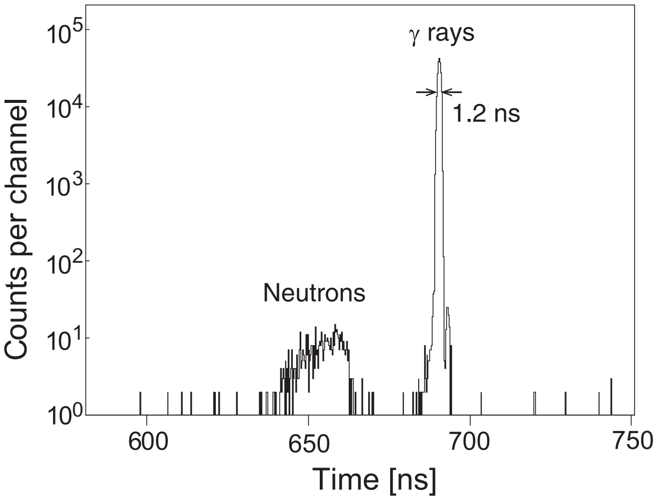

FIG. 2. Time-of-flight spectrum for the $^{56}\mathrm{Fe}(\gamma,n)^{55}\mathrm{Fe}$ reaction with linearly polarized photons. Neutrons and γ rays from the ^{56}Fe target are clearly separated. The natural backgrounds originating from radioactivities and cosmic rays are lower than the neutron yields.

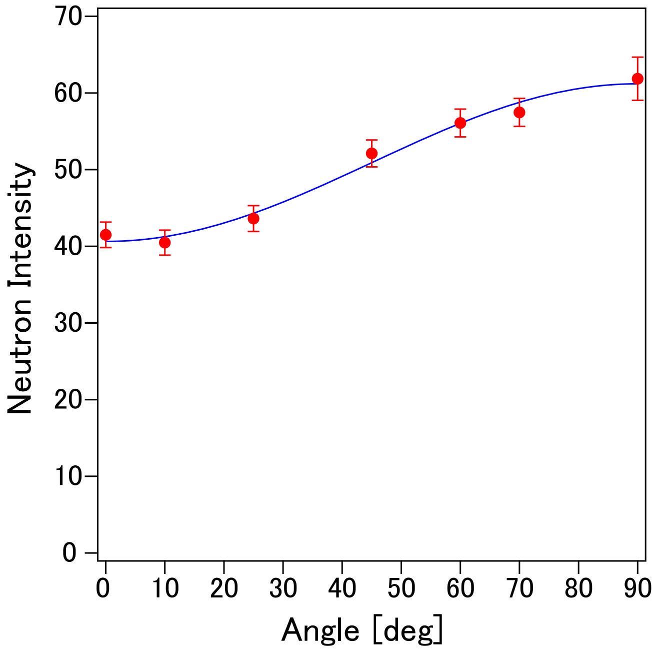

FIG. 3. Neutron anisotropy from the ^{56}Fe(γ,n)^{55}Fe reaction with the linearly polarized γ beam. The solid line is the function of $a + b\cos(2\phi)$ obtained by χ^2 fitting. The measured data are reproduced well.

distinguished. The γ-ray pulse width is equal to the shorter of the electron and laser pulse widths. In the present experiment, the γ-beam pulse width should be 60 ps, which is the pulse width of the electron bunch. The time spread of the prompt γ rays is, however, about 1.2 ns, which is longer than 60 ps. This discrepancy is inferred to be caused from the time resolution of the detector, the length of the target, and the time jitter between the laser generation time and the external trigger signal from the electron storage ring. In the present experiment, excited states with excitation energies of 14–16.7 MeV in ^{56}Fe are populated by absorption of the LCS γ-ray beam with an energy spread of about 3 MeV. Each excited state decays to the ground state or an excited state in ^{55}Fe by neutron emission (see Fig. 1). The energy spread of 3 MeV is much wider than the energy level spacing in the residual nucleus ^{55}Fe. Thus, neutron peaks in the TOF spectra are broad as shown in Fig. 2.

In the previous experiment [16], the azimuthal angle distribution was measured as a function of ϕ ranging from 0° to 360° in 30° steps [16]. Taking into account the geometrical symmetry of $\cos(2\phi)$, only a few measured points have an actual meaning for studying the neutron anisotropy. In the present experiment the measured angles were selected to study the azimuthal angle distribution in further detail. Figure 3 shows the integrated neutron yields from the ^{56}Fe($\vec{\gamma}$,n)^{55}Fe reaction as a function of ϕ. The solid line shows the Agodi function of $a + b\cos(2\phi)$ obtained by χ^2 fitting, which reproduces well the measured neutron yields. In a recent paper [22], the azimuthal angle distributions of neutrons from ($\vec{\gamma}$, n) reactions on ^{76}Se and ^{100}Mo were calculated, where the neutron azimuthal angle distributions from nuclei excited by $E2$ transitions were described by a function of $a + b\cos(4\phi)$. If this prediction is correct and the $E2$ strength in ^{56}Fe is strong enough, we can observe the deviation from the solid line in Fig. 3 around $\phi = 45°$. As one sees from Fig. 3, this is not the case because the LCS γ-ray energy is near the peak energy of the GDR excitation and the $E1$ strength is strong in the present experiment.

As discussed in a previous paper [16], many excites states are populated by the photon reaction with a wide energy spread and subsequently decay through neutron emission. If the energy spread of an incident γ-ray beam is narrower than the level spacing of a residual nucleus, the neutron anisotropy of a specific transition can be selectively measured. The next generation of high-intensity LCS beam facilities, ELI-NP [23], MEGa-ray [24], and ERL-LCS [25], has been developed. It is expected that the energy widths of these γ beams are narrower than $\Delta E/E \sim 1\%$. Because the excitation energy of the first excited state in ^{55}Fe is 411 keV, we can determine the parameters a and b of the transition from the highest excited level in ^{56}Fe to the ^{55}Fe ground state if we use a LCS beam with an energy width narrower than about 500 keV.

IV. SUMMARY

We measured the neutron azimuthal anisotropy in the ^{56}Fe(γ,n)^{55}Fe reaction with linearly polarized γ rays generated by laser Compton scattering at the NewSUBARU electron storage ring. Neutrons and γ rays were clearly separated using the TOF method. The neutron yields at the polar angle $\theta = 90°$ have been measured by changing the angle of the linear polarization plane of the LCS γ-ray beam. The neutron yields at $\phi = 0°$, 10°, 25°, 45°, 60°, 70°, and 90° were reproduced well by Agodi's function, i.e., $a + b\cos(2\phi)$, where ϕ is the azimuthal angle between the linear polarization plane and the detector. We have verified the robustness of Agodi's function in more detail than in the previous study [16]. The obtained result suggests that we can measure the parameters a and b for transitions from excited states in ^{56}Fe to the ^{55}Fe ground state if we can use a γ beam with an energy spread narrower than about 500 keV.

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