

Laser Compton Scattering Gamma-Ray Experiments for Supernova Neutrino Process^{*)}

Takehito HAYAKAWA^{1,2)}, Shuji MIYAMOTO³⁾, Takayasu MOCHIZUKI³⁾,
Ken HORIKAWA³⁾, Sho AMANO³⁾, Dazhi LI⁴⁾, Kazuo IMAZAKI⁴⁾,
Yasukazu IZAWA⁴⁾, Kazuyuki OGATA⁵⁾ and Satoshi CHIBA⁶⁾

^{1,**) Japan Atomic Energy Agency, Tokai 319-1106, Japan}

^{2) National Astronomical Observatory in Japan, Mitaka 181-8588, Japan}

^{3) University of Hyogo, Kamigouri 678-1205, Japan}

^{4) Institute for Laser Technology, Osaka 565-0871, Japan}

^{5) RCNP, Osaka University, Osaka 565-0871, Japan}

^{6) Tokyo Institute of Technology, Tokyo 152-8550, Japan}

(Received 15 September 2015 / Accepted 18 March 2016)

The neutrino-nucleus interactions are important for understanding nucleosyntheses by neutrino-induced reactions as well as supernova explosion mechanisms. The M1 strength in atomic nuclei is important for estimation of neutrino-nucleus interactions. We have proposed a method using (γ , n) reactions with linear polarized laser Compton scattering (LCS) γ -rays to measure the M1 strength and verified a theoretical prediction for the first time. We have discussed experimental technique using the next generation of LCS beams.

© 2016 The Japan Society of Plasma Science and Nuclear Fusion Research

Keywords: supernova explosion, neutrino-nucleus interaction, laser Compton scattering gamma-ray

DOI: 10.1585/pfr.11.3406066

1. Introduction

Neutrino-nucleus interactions have important roles for understanding of supernova explosion mechanisms and nucleosyntheses in supernovae (neutrino-process). The neutrino process in supernova explosions has been proposed as the astrophysical origin of some rare isotopes such as ${}^7\text{Li}$, ${}^{11}\text{B}$, ${}^{138}\text{La}$, and ${}^{180}\text{Ta}$ [1, 2]. During core-collapse supernovae, a huge number of neutrinos are emitted from the proto-neutron star (see Fig. 1). As these neutrinos pass through outer layers of the star they can induce nuclear reactions on pre-existing nuclei. The neutrino process can only play a significant role in the syntheses of isotopes which are bypassed by other major processes such as rapid (slow) neutron capture processes. The astrophysical origin of a rare isotope ${}^{180}\text{Ta}$ has been unresolved problem for long time. Hayakawa *et al.* [3] presented that the neutrino process reproduces systematically the solar abundances of ${}^{138}\text{La}$ and ${}^{180}\text{Ta}$ with a new time-dependent isomer population model, whereas other scenarios can explain partly their abundances.

${}^{92}\text{Nb}$ is a β -unstable isotope with a half-life of about 3.5×10^7 y. ${}^{92}\text{Nb}$ does not exist at the present solar system. The abundance of ${}^{92}\text{Nb}$ at the solar system formation has been reported by analyses of primitive meteorites.

author's e-mail: hayakawa.takehito@gst.go.jp

^{*)} This article is based on the presentation at the Conference on Laser Energetics 2015 (CLE2015).

^{**)} The current affiliation is National Institutes for Quantum and Radiological Science and Technology.

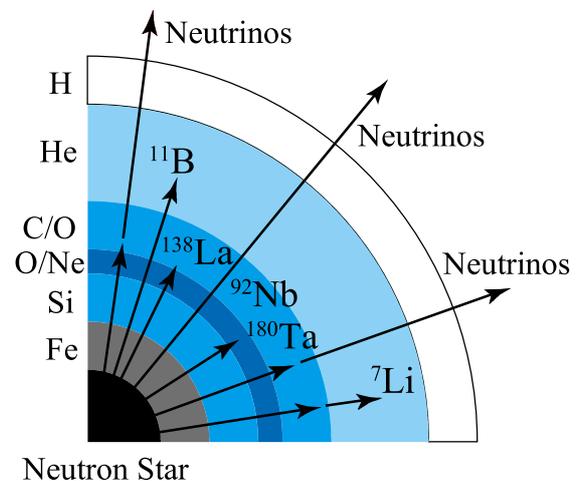


Fig. 1 Schematic view of supernova neutrino process.

However, its astrophysical origin has been also unresolved problem. Hayakawa *et al.* [4] have proposed the neutrino process origin for ${}^{92}\text{Nb}$ and calculated a theoretical abundance at the solar system formation using a supernova model with calculated neutrino-nucleus interactions. The origin of ${}^{92}\text{Nb}$ can be explained by the supernova neutrino process. In this way, the neutrino process is of importance for understanding of the origin of rare isotopes.

Neutrino-nucleus interactions are key physics for understanding the neutrino process. However, individual neutrino-induced reaction cross sections depend on the de-

tailed nuclear structures of the isotopes involved [5]. Experimental measurements of neutrino–nucleus interactions for many nuclei are almost impossible because the associated neutrino-induced reaction cross-sections are extremely small. Thus, one should calculate the cross sections using nuclear structure models based on experimental data for detailed nuclear structures.

The previous studies show that neutrino isotopes as ^{138}La and ^{180}Ta can be produced predominantly by two neutrino-induced reactions of the neutral current reaction and the charged current reaction [1–4]. Figure 2 shows a schematic view of the charged current reaction of $^{138}\text{Ba}(\nu_e, e^-)^{138}\text{La}$ and the neutral current reaction of $^{139}\text{La}(\nu, \nu' n)^{138}\text{La}$. In the neutral current reaction, at first a nucleus ^{139}La is excited by a neutrino and subsequently the excited state decays to the ground state or an excited state in a residual nucleus ^{138}La by the emission of a neutron when the excitation energy of ^{139}La is higher than its neutron separation threshold. The neutral current reaction can be caused by 6 types of neutrinos, ν_τ, ν_μ, ν_e , and their anti-neutrinos. On the other hand, the charged current reaction can be caused by only the electron neutrino. By the charge exchange reaction on ^{138}Ba , an excited state in ^{138}La is populated and it decays to the ground state of ^{138}La . Note that the contribution of the charged current reaction by anti-electron neutrino is negligibly small because the seed nuclei, ^{138}Ce (for ^{138}La) and ^{180}W (for ^{180}Ta), are almost destroyed by neutron-induced reactions in the weak s-process in early evolutionary stages of massive stars.

It is known that the Gamow-Teller transition is dominant in the absorption of neutrinos [5]. This means that $J^\pi = 1^+$ states are predominantly excited in the case of a $J^\pi = 0^+$ nucleus. Therefore, the magnetic-dipole (M1) strength (or level density of 1^+ states) is of importance for the estimation of interaction strengths between neutrinos and nuclei (see Fig. 2). However, there is no established method to measure the M1 strength in the giant dipole resonance (GDR) region because of its large electric-dipole

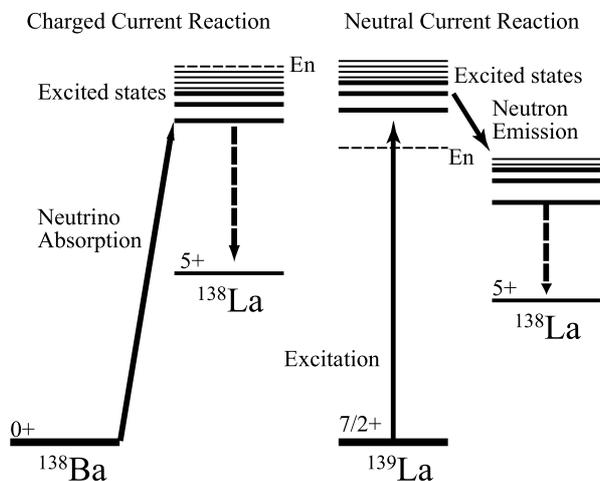


Fig. 2 Schematic view of neutrino-induced reactions for ^{138}La .

(E1) strength. Thus, there are many attempts to measure the M1 strength, for example, the differential cross sections of isoscalar and isovector spin-M1 transitions were measured using proton scattering at $0^\circ - 14^\circ$ [6].

The linear polarized γ -ray beam is useful to study nuclear physics. For example, E1 and 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 [7] predicted theoretically the angular distribution of neutrons emitted from states excited via dipole transitions with a linearly polarized γ -ray beam at the polar angle of $\theta = 90^\circ$ should be followed by a simple function, $a + b \cos(2\phi)$, where ϕ is azimuthal angle. However, this theoretical prediction has not been verified over the wide mass region except for light nuclei as deuteron for long time. This is because there has been no 100% linear polarized γ -ray beam before the advent of laser Compton scattering (LCS) γ -rays. Thus, we have measured neutron angular distributions with (polarized γ, n) reactions on Au, NaI and $^{\text{nat}}\text{Cu}$ targets using a LCS beam at NewSUBARU to examine Agodi's prediction [8].

2. Measurements of Neutron Angular Distribution from (polarized γ, n) Reactions

The progress of relativistic engineering provides us with a new generation of photon beams, LCS γ -rays. The energy tunable quasi-monochromatic LCS γ -ray beams with MeV energy have been used for studying fundamental science and various applications at Duke University [9] and NewSUBARU [10]. Figure 3 shows a schematic view of generation of LCS γ -rays. The energy of the scattered photon is determined by the angles of θ_1 and θ_2 . In the case of “head-on collision”, namely $\theta_1 = \theta_2 = 180^\circ$, the energy of the scattered photon is maximum. On the other hand, the lowest energy can be determined by the size of a hole of a collimator. The LCS γ -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 γ -ray is that it is possible to generate almost 100% linearly

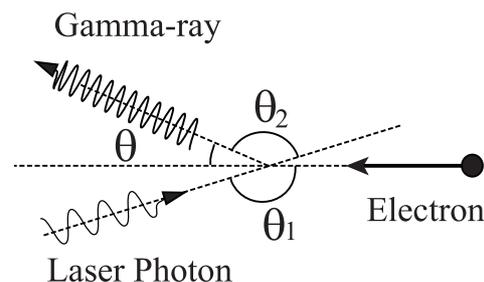


Fig. 3 Schematic view of laser Compton scattering.

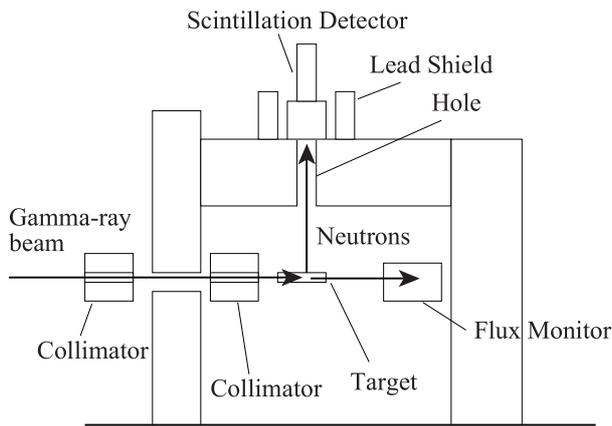


Fig. 4 Experimental setup.

(circularly) polarized beam, since the polarization of the laser is directly transported to the scattering photon.

We performed an experiment using LCS γ -rays with linear polarization at NewSUBARU in SPring-8. The γ -ray beam was generated by Compton scattering of laser photons with electrons stored in the electron storage ring NewSUBARU. The storage ring was operated with a mode of “Top-up”, in which electron bunches were supplied continuously from an electron linac without extra acceleration into NewSUBARU. A Q-switch Nd:YVO₄ laser was used to provide laser pulses. The energy of generated γ -rays was determined by the wave length of the laser and the electron energy. The energy of the electron beam was 1 GeV. The wave length of Nd:YVO₄ laser was 1064 nm. The maximum energy of the generated LCS γ -ray beam was 16.7 MeV. The γ -ray energy width was 3-5 MeV. We irradiated targets of Au, NaI, and natural Cu. Their sizes were typically $\phi 10 \text{ mm} \times 40 \text{ mm}$. The estimated γ -ray flux was $(1-2) \times 10^6$ photons/s in the energy range from 12 MeV to 16.7 MeV.

Neutrons from (γ, n) reactions on targets were measured using a time-of-flight (TOF) method. Figure 4 shows the experimental setup for the target and the TOF detection system. A plastic scintillation detector was set at a polar angle of $\phi = 90^\circ$ at outside the experimental room. Each target was located inside of the irradiation room with a concrete shield with a thickness of 540 mm. The neutrons were guided to the detector through a hole with a diameter of 80 mm and length of 970 mm. A time-to-amplitude converter (TAC) was used to measure neutron energies. A start signal was generated from an output of the scintillation detector when the detector measured a signal originated from a neutron or a γ -ray. A stop signal with 25 kHz was generated from a synthesizer signal with 500 MHz, which is used to operate the electron storage ring, by the divider. This signal is also used as the external trigger signal to generate the laser pulse. As a result, in the present LCS system, the time of the LCS γ -ray beam is synchronized with the laser pulse generation time.

The energy resolution for the neutrons depends on the

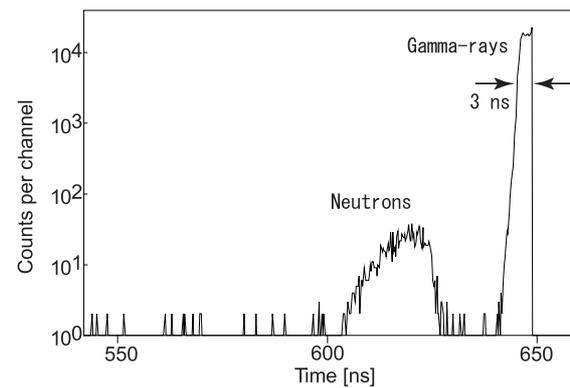


Fig. 5 TOF spectrum measured by the scintillation detector.

duration of the incident γ -beam and the time resolution of the detector system. In the case of the LCS photon beam, the duration of the generated LCS γ -ray pulse is equal to the shorter of the electron bunch width and the laser width. The widths of the laser and the electron were 8 ns and 60 ps, respectively. Thus, the pulse width of the LCS γ -ray beam should be only 60 ps. This is shorter than typical time resolution of the scintillation detector in order of ns by an order of magnitude. The time width of the measured prompt γ -rays is, however, about 3 ns (see Fig. 5) 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.

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° in 30° steps for NaI and Cu, where the $\phi = 0^\circ$ was defined as the electric polarization vector being in the plane of the detector.

Note that the determination of the angle of the linear polarization plane of the LCS beam is critical for this type of experiments. In general, there was a possibility that the angle of the laser polarization plane may be changed by a reflection mirror, which was used to guide the laser beam to the LCS γ -ray generation point. To verify the linear polarization plane, the laser beam was extracted to the outside of the electron storage ring after the laser Compton scattering without additional mirrors. The polarization angle of the laser was measured by a combination of a laser power meter and a Glan-Thompson prism. The angle at which the transmitted laser power was largest was determined with changing the angle of the Glan-Thompson prism.

3. Verification of Agodi's Prediction

The scintillation detector measured γ -rays from the

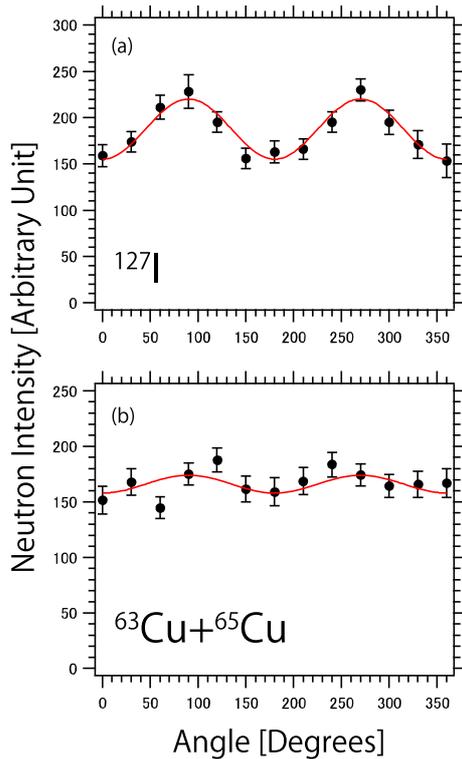


Fig. 6 Angular distributions of neutrons. The solid lines are obtained by χ^2 fitting with the function of $a + b \cos(2\phi)$.

target as well as neutrons. The γ -rays were predominantly generated by Compton scattering in the target when the LCS beam irradiated the target. The prompt γ -rays and neutrons can be separated by the TOF method. As shown in Fig. 5, the neutrons and prompt γ -rays are clearly separated. The neutron energies were derived from these TOF spectra but the detailed structure was not observed because of the poor statics and the large neutron energy uncertainty. In the present experiment, the final uncertainty of the neutron energy is determined by the LCS γ -beam energy width of 3 MeV. This energy width is much higher than level spacing of the residual nuclei.

The neutron yields are presented as a function of azimuthal angle ϕ for ^{nat}Cu and NaI (see Fig. 6), where $\phi = 0^\circ$ is defined as the electric polarization vector being in the plane of the detector. The NaI target includes two nuclides of ^{23}Na and ^{127}I . Since the neutron separation energies of these nuclides are 12.4 MeV (^{23}Na) and 9.1 MeV (^{127}I), the contribution of ^{127}I is dominant for the NaI target. The target of ^{nat}Cu consists of stable isotopes of ^{63}Cu (69.2%) and ^{65}Cu (30.8%). The neutron separation energies of these two isotopes are 10.8 and 9.9 MeV for ^{63}Cu and ^{65}Cu , respectively. Since the neutron separation energies of both isotopes are lower than the maximum energy of the incident LCS beam of 16.7 MeV, neutrons from both isotopes were measured at the same measurement.

The solid lines in Fig. 6 are obtained by χ^2 fitting with the function of $a + b \cos(2\phi)$. The neutron angular distri-

butions for NaI can be reproduced by this function. The experimental results for ^{nat}Cu is also reproduced by this function although the anisotropy, b/a , is very low. The anisotropy of b/a is 0.18 ± 0.03 (^{127}I) or 0.04 ± 0.03 (^{nat}Cu). These neutron angular distributions can be 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.

4. New Method to Measure E1/M1 Mixing Ratio

The isotopes ^{127}I , ^{63}Cu , and ^{65}Cu in the targets are odd-Z isotopes. The odd-Z isotope means the proton number of the isotope is odd and the neutron number is even. The residual isotope from (γ, n) reactions on the odd-Z nucleus is the odd-odd nucleus, which both proton and neutron numbers of are odd. The level density of the odd-odd nucleus is in general higher than the odd-Z and even-even nuclei. Thus the number of combinations of an initial state and a final state is higher than that in the case of the even-even nucleus and it is difficult to calculate realistic values for neutron angular distribution for the odd-Z isotope.

In contrast, if an even-even nucleus is used as a target, the spin and parity of states populated by photon induced reactions 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-Z targets. It is possible to derive an explicit form of E1, M1, and E2 transition matrix elements from a $J^\pi = 0^+$ target nucleus, with the long wave-length approximation to the photon field. We have planned to measure the asymmetry using linear polarized LCS photon beams on targets of even-even isotopes such as ^{12}C , ^{28}Si , ^{32}S , and ^{56}Fe . Since these nuclides have large isotopic abundances of 92 - 98%, it is easily to prepare experimental targets with weights of a few grams. In viewpoint of nuclear astrophysics, these nuclides are the dominant composition of outer layers of massive stars (see Fig. 1) and thus the interactions between neutrinos and these nuclei are important for understanding supernova explosion mechanisms. In addition, since light isotopes of ^7Li and ^{11}B are synthesized from ^4He and ^{12}C , neutrino reactions on ^{12}C are also important.

As shown by Agodi, both E1 and M1 transitions give the ϕ dependence of $a + b \cos(2\phi)$ for the angular distribution of neutrons of (γ, n) reactions with linearly polarized photon beam. It was also 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 [7]. This suggests that if we select the neutron emission transition, of which initial and final states are known, we can measure the M1 strength in this transition. For such a purpose, the key point is the energy resolution of the neutron measurement.

With the incident LCS beam with an energy spread of 3 - 5 MeV, the neutron energy resolution is finally

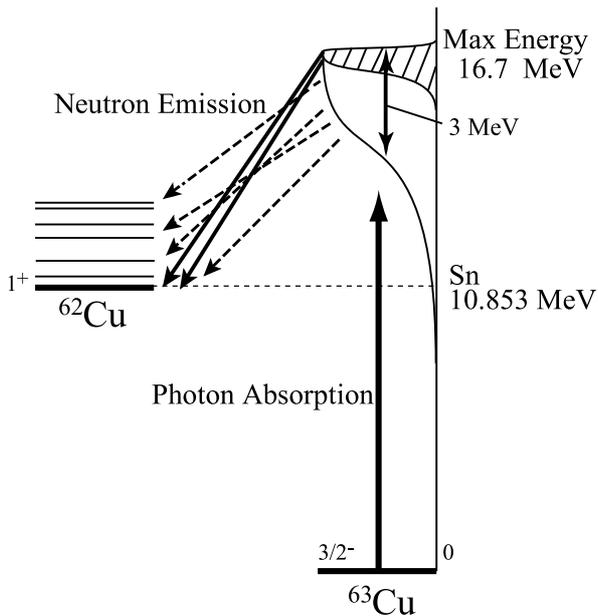


Fig. 7 Schematic view of photodisintegration reactions using LCS γ -ray beam.

determined by the beam energy spread. In such cases, all combinations of initial and final states (both of the solid and dashed arrows in Fig. 7) were measured. At the present available LCS γ -ray facilities, the typical energy spread of the photon beam is 3 - 10%. In this case, with 17-MeV γ -rays, the neutron energy resolution is about 0.5 - 1.7 MeV. If we select the neutron transition by the highest neutron energy gate, the M1/E1 mixing can be evaluated from the polarization asymmetry of the transition from the highest populated state on the target to the ground state of the residual nucleus (the solid arrows in Fig. 7). A neutrino-process isotope ^{11}B is directly produced from ^{12}C or through β -decay from ^{11}C which is at first produced from ^{12}C . In both reactions, the level density of 1^+ states on ^{12}C is important. If the level density on ^{12}C will be measured using our proposed method, the $^{12}\text{C}(\gamma, n)^{11}\text{C}$ reaction is suitable. The excitation energy of the first excited state on the residual nucleus ^{11}C is as large as 2 MeV. Thus, it is possible to measure the polarization asymmetry for ^{12}C at the available LCS facilities. In contrast, the first excitation energy of ^{55}Fe is only 411 keV. If the energy spread of the incident beam is much wider than 411 keV, we cannot distinguish between two transitions which decay to the ground state or the first excited state in ^{55}Fe . This suggests that we should use a new γ -ray beam with an energy spread lower than $dE/E \sim 3\%$.

The progress in laser and accelerator physics enables us to realize the next generation of LCS γ -ray sources including ELI-NP [11], MEGA-ray [12], and the ERL-LCS [13]. The energy spread of these γ -ray beams is

expected to be lower than $dE/E = 10^{-3}$. If we couple the present experimental method with such high energy resolution γ -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

Neutrino-nucleus interactions are important for understanding the origin of some isotopes (neutrino-process) and supernova explosion mechanisms. The neutrino-induced reactions generate short-lived radioactivities as well as stable isotopes. Because direct measurements of neutrino-induced reactions on various isotopes are practically impossible, the neutrino-nucleus reaction cross sections should be calculated by theoretical models based on measured nuclear structures. The measured M1 strength (or level density of $J^\pi = 1^+$ states for even-even nuclei), in particular, contributes to theoretical calculations. Agodi [7] predicted theoretically the angular distribution of neutrons emitted from states excited via dipole transitions with linearly polarized γ -ray beam at the polar angle of $\theta = 90^\circ$ should be followed by a simple function, $a + b \cos(2\phi)$, but it has not been verified experimentally over half a century. Horikawa *et al.* [8] have measured neutron angular distributions using linear polarized γ -ray beam generated by Compton scattering at NewSUBARU. As a result, Agodi's prediction was verified for the first time over the wide mass region.

When we use an even-even nucleus as a target, we can measure the polarization asymmetry for specific transitions. For such a purpose, we need the next generation of the LCS γ -rays which will be available in the world. Agodi's function has been almost forgotten at present. The lost Agodi's prediction will have a more precious role for studying the detailed structure of the giant resonances and for supernova neutrino-process.

Acknowledgments

This work has been supported in part by Grants-in-Aid for Scientific Research (15H03665) of Japan.

- [1] S.E. Woosley *et al.*, *Astrophys. J.* **356**, 272 (1990).
- [2] A. Herger *et al.*, *Phys. Lett. B* **606**, 258 (2005).
- [3] T. Hayakawa *et al.*, *Phys. Rev.* **C81**, 052801(R) (2010).
- [4] T. Hayakawa *et al.*, *Astrophys. J. Lett.* **779**, L9 (2013).
- [5] M. Cheoun *et al.*, *Phys. Rev.* **C82**, 035504 (2010).
- [6] H. Matsubara *et al.*, *Phys. Rev. Lett.* **115**, 102501 (2015).
- [7] A. Agodi, *Il Nuovo Cimento* **5**, 21 (1957).
- [8] K. Horikawa *et al.*, *Phys. Lett.* **B737**, 109 (2014).
- [9] V.N. Litvinenko *et al.*, *Phys. Rev. Lett.* **78**, 4569 (1997).
- [10] S. Miyamoto *et al.*, *Radiat. Meas.* **41**, S179 (2007).
- [11] D. Habs *et al.*, *Nuclear Physics News* **21**, 23 (2011).
- [12] F. Albert *et al.*, *Phys. Rev. ST-AB* **14**, 050703 (2011).
- [13] R. Hajima *et al.*, *J. Nucl. Sci. Technol.* **45**, 441 (2008).