

RCNP E398 $^{16}\text{O}, ^{12}\text{C}(p,p')$ Experiment: Measurement of The γ -ray Emission Probability from Giant Resonances in Relation To $^{16}\text{O}, ^{12}\text{C}(\nu,\nu')$ Reactions

I. Ou^a, Y. Yamada^a, T. Mori^a, T. Yano^a, M. Sakuda^a, A. Tamii^b, T. Suzuki^b, M. Yoso^b, N. Aoi^b, E. Ideguchi^b, T. Hashimoto^b, K. Miki^b, T. Ito^b, C. Iwamoto^b, T. Yamamoto^b, H. Akimune^c.

^aDepartment of Physics, Okayama University, Okayama 700-8530, Japan

^bResearch Center for Nuclear Physics (RCNP), Osaka University, Ibaraki, Osaka 567-0047, Japan

^cDepartment of Physics, Konan University, Okamoto 8-9-1, Higashinada, Kobe 658-8501, Japan

Abstract. We propose to measure the γ -ray emission probability from excited states above 5 MeV including giant resonance of ^{16}O and ^{12}C as a function of excitation energy in 1-MeV step. Here, we measure both the excitation energy ($E_x=5\text{-}30\text{MeV}$) at the forward scattering angles ($0^\circ\text{-}3^\circ$) of the $^{16}\text{O}, ^{12}\text{C}(p, p')$ reaction using Grand-Raiden Spectrometer and the energy of γ -rays (E_γ) using an array of NaI(Tl) counters. The purpose of the experiment is to provide the basic and important information not only for the γ -ray production from primary neutral-current neutrino-oxygen (-carbon) interactions but also for that from the secondary hadronic (neutron-oxygen and -carbon) interactions.

Keywords: Supernova neutrinos, neutral-current neutrino reaction, giant resonances of $^{16}\text{O}, ^{12}\text{C}$.

PACS: 13.15+g, 25.30.Pt

INTRODUCTION

If a supernova explosion occurs in our galaxy, a neutrino burst will induce not only the inverse β -decay reaction ($\bar{\nu}_e + p \rightarrow e^+ + n$) but also the neutral-current (NC) $\nu\text{-}^{16}\text{O}$ reaction producing a significant number of observable events containing γ -rays in the Super-Kamiokande detector [1,2,3]. Large detectors using a liquid scintillator can also detect NC $\nu\text{-}^{12}\text{C}$ reaction containing γ -rays [4,5]. We learned from the discovery of the solar neutrino oscillations [6,7] that observing NC events, which are independent of neutrino flavors, is essential to resolving the neutrino oscillations. Further, NC events from supernova explosion favors ν_e and $\bar{\nu}_e$ (and their anti-neutrinos) than ν_μ due to the higher neutrino energy spectra [8] and thus convey different information from inverse β -decay events. So, observing NC events with better accuracy is very important in the future supernova neutrino detection and neutrino oscillation experiments.

Theoretical calculations of γ -ray production in NC $\nu\text{-}^{16}\text{O}$ and $\nu\text{-}^{12}\text{C}$ interactions in the energy range $E_\gamma < 100\text{MeV}$ [1] are schematically illustrated in Figs.1 (a) and (b). The spin-dipole resonances (SDR, $2^-, 1^-, 0^-$) are predominantly excited in the $^{16}\text{O}(\nu,\nu')$ reaction above the particle threshold [1,9,10]. For $^{12}\text{C}(\nu,\nu')$ reaction, the M1 resonance (1^+ , 15.11MeV) below the particle threshold contributes equally to the cross section as well as the SDR ($2^-, 1^-, 0^-$) which are above the particle threshold [9]. Those excited states above the proton and neutron separation energy (12MeV for ^{16}O and 16MeV for ^{12}C) emit nucleon and decay into a ground state or excited states of daughter nuclei, which emit γ -rays.

Several neutrino experiments [11,12] have measured the γ -ray production for $E_\gamma > 100\text{MeV}$, but no neutrino experiments have studied the γ -ray production from excited states above the particle threshold for $E_\gamma < 100\text{MeV}$ [13]. Our goal of this proton beam experiment E398 is to measure the γ -ray emission probability from excited states

above particle threshold, both the SDR and the giant dipole resonance GDR, as a first step, since no such systematic data exist. We explain the experimental method in the next section.

$^{16}\text{O}, ^{12}\text{C}(p,p')$ IN RELATION TO $^{16}\text{O}, ^{12}\text{C}(v,v')$

T.Kawabata et al. [14] took data of $^{16}\text{O}(p,p')$ reaction at scattering angles of $\theta_{\text{lab}}=0^\circ, 2.5^\circ, 4^\circ, 6^\circ, 8^\circ, 10^\circ, 12^\circ$ and 14° using the Grand-Raiden Spectrometer at Research Center for Nuclear Physics (RCNP, Osaka University). Fig.2 is taken from Ref. [15]. At $\theta_{\text{lab}}=0^\circ$, the non-spin-flip transition, GDR (1^-), dominates, while the contributions of the spin-flip transition, SDR ($2^-, 1^-$), show up at $\theta_{\text{lab}}=4^\circ$. We make best use of this feature and take data at $\theta=0^\circ$, which covers $\theta_{\text{lab}}=0^\circ-3^\circ$, to measure the γ -ray emission probability as a function of excitation energy E_x over 5-30 MeV (1 MeV step). Thus, we can measure the γ -ray emission probability at each E_x containing the GDR near $\theta_{\text{lab}}=0^\circ$ and also the SDR near $\theta_{\text{lab}}=3^\circ$. The theoretical calculation predicts the larger cross section for the SDR ($2^-, 1^-$) as θ_{lab} increases from 0° to 5° [16].

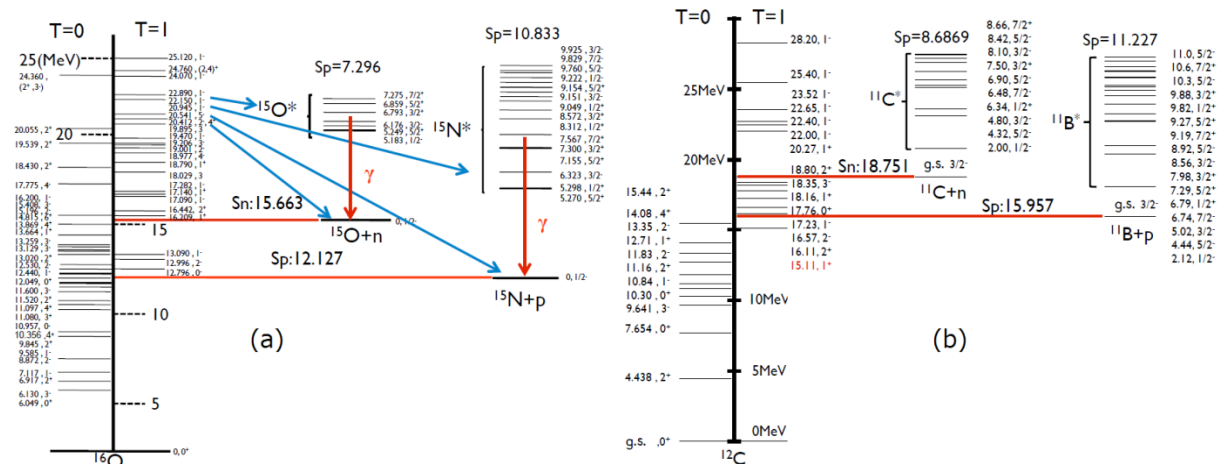


FIGURE 1. Excited states of ^{16}O and ^{12}C , and those of daughter nuclei, relevant to $^{16}\text{O}(v,v,\gamma)$ and $^{12}\text{C}(v,v,\gamma)$.

We note that the measurement of the γ -ray emission probability in $^{16}\text{O}, ^{12}\text{C}(p,p')$ at 0° will be used for that in $^{16}\text{O}, ^{12}\text{C}(n,n')$. The estimation of the γ -ray emission probability in $^{16}\text{O}(v,v')$ reaction with accuracy of a few %, including $^{16}\text{O}, ^{12}\text{C}(n,n')$ reactions, is also important to the neutrino physics at $E > 200$ MeV [12,17,18].

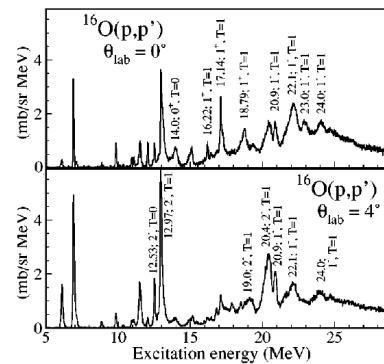


FIGURE 2. Cross section $d\sigma/dE_x$ of $^{16}\text{O}(p,p')$ at $\theta_{\text{lab}}=0^\circ$ and 4° .

E398 EXPERIMENTAL SETUP

In the E398 experiment, we measure the γ -ray emission probability for $E_x > 5$ MeV including giant resonances, both the SDR and GDR ($E_x = 16\sim 30$ MeV), of ^{16}O and ^{12}C , as a function of excitation energy (E_x) at $\theta_{\text{lab}}=0^\circ-3^\circ$. The proton beam and the Grand Raiden of RCNP provide precise measurement of the excitation energy ($\Delta E_x \sim 20$ keV at

the beam energy (E_p) = 298MeV). We implement a new γ -ray detector array to the Grand Raiden. The new γ -ray detector consists of an array of 5x5 NaI(Tl) counters of 5.1cmx5.1cmx15.2cm each and an array of 1x6 CsI(Tl) counters of 6.5cmx6.5cmx30cm each behind the NaI array. We will use the same NaI counters used in RCNP E148 experiment [19]. For CsI counters, CsI crystals are wrapped with Millipore (light reflector) and attached to light guides and 2" PMTs. The energy resolutions of NaI and CsI with PMT are 2% and 3% for 2.5MeV, respectively (Fig.3). Signals will be read out by ADC and TDC modules. We are upgrading now from CAMAC modules to VME modules to improve the live time of DAQ system in RCNP.

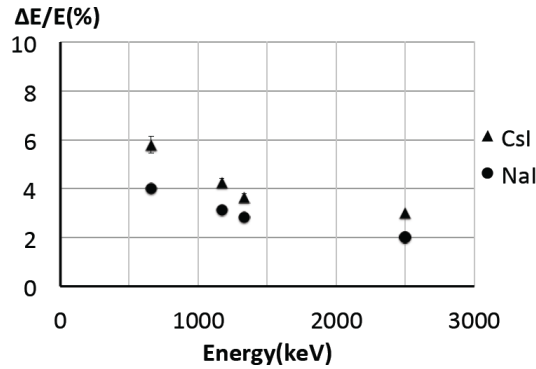


FIGURE 3. Energy resolution of a NaI(Tl) and a CsI(Tl) counter.

The performance of the detector is evaluated with Monte Carlo simulation (GEANT4) to determine the present design. We found that the γ -ray energy incident in the NaI array spreads over more than 2 counters by multiple Compton scattering. Thus, in order to measure the total energy of incident γ -ray, we decided to make an array of 5x5 NaI counters using the inner 3x3 counters as active counters and the surrounding 16 counters as veto counters (Compton suppression), and to place 6 CsI counters behind the NaI array as veto counters (Fig.4). We will place this γ -ray detector as close as 20 cm to the target. The detection efficiency of inner 3x3 array for an γ -ray with energy of 6MeV is estimated by the GEANT4 simulation to be about 1%.

We will make the best use of the known excited states of ^{16}O and ^{12}C : 6.9 MeV from $J^p=2^+$ (γ -ray emission probability: 100%) in $^{16}\text{O}^*$ and 4.4 MeV from 2^+ (100%) and 15.1MeV from 1^+ (76%) in $^{12}\text{C}^*$ [20]. The γ -rays from those known states will be used to monitor the gain of PMTs and the detection efficiency of the γ -ray detector, and more importantly, the γ -ray emission probability of those states can be checked *in-situ* throughout the experimental period.

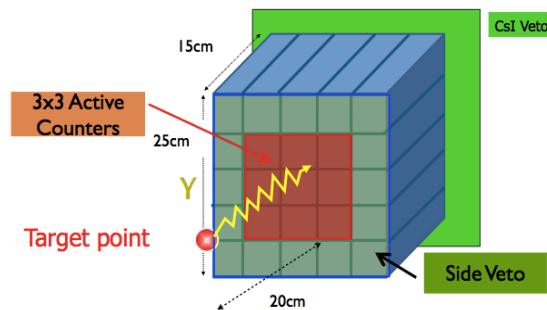


FIGURE 4. Design of γ -ray detector array.

We estimated the γ -ray event rate with proton beam energy of 298 MeV, intensity of 10nA and target thickness of 30mg/cm². We use a cellulose (C₆H₁₀O₅) film and a carbon film (^{12}C) for targets. Oxygen data will be extracted by subtracting carbon data from cellulose data. In 4 days of datataking with cellulose target and 2 days with carbon target, we can get at least 20K of γ -ray event for $E_{\bar{x}}=16\sim 30\text{MeV}$ in 1-MeV bin for both ^{16}O and ^{12}C . So, we expect to measure the γ -ray emission probability with statistic error of a few %. We hope that E398 datataking will happen in 2013.

SUMMARY

The E398 experiment will measure the γ -ray emission probability from excited states above 5 MeV including giant resonance (SDR and GDR) of ^{16}O and ^{12}C as a function of excitation energy in 1-MeV step, using the RCNP Grand-Raiden Spectrometer and a γ -ray detector. Such systematic measurements are new. The γ -ray emission probability from SDR and GDR of ^{16}O and ^{12}C will be very useful to not only for the γ -ray production from primary NC ν - ^{16}O and ν - ^{12}C interactions but also for that from hadronic neutron- ^{16}O and neutron- ^{12}C interactions. The understanding of NC interactions containing γ -rays is very important for the future supernova neutrino detection and neutrino oscillation experiments.

REFERENCES

1. K. Langanke, P. Vogel, and E. Kolbe, *Phys. Rev. Lett.* **76**, 2629 (1996).
2. J.F. Beacom and P. Vogel, *Phys. Rev. D* **58**, 053010 (1998).
3. M. Ikeda et al. (Super-K Collab.), *Astrophys. J.* **669**, 519 (2007).
4. K. Tolich et al. (KamLAND Collab.), *Nucl. Phys. Proc. Suppl.* **221**, 0355 (2011).
5. M. Wurm et al. (LENA Collab.), *Astropart. Phys.* **35**, 685 (2012).
6. Y. Fukuda et al. (Super-K Collab.), *Phys. Rev. Lett.* **86**, 5651 (2001).
7. Q.R. Ahmad et al. (SNO Collab.), *Phys. Rev. Lett.* **89**, 011301 (2002).
8. K. Nakazato et al., *Astrophys. J. Supp.* **205**, 2 (2013).
9. N. Jachowicz, S. Rombouts, K. Heyde, J. Ryckebusch, *Phys. Rev. C* **59**, 3246 (1999).
10. T. Suzuki, in this Proceedings.
11. J. Kameda (K2K Collab.), *Nucl. Phys. B. Proc. Suppl.* **159**, 44 (2006).
12. K. Ueno, Ph.D Thesis (T2K), University of Tokyo (2012).
13. B. Ambruster et al. (KARMEN Collab.), *Phys. Lett. B* **423**, 15 (1998).
14. T. Kawabata et al, *Phys. Rev. C* **65**, 064316 (2002).
15. T. Kawabata, Ph.D Thesis, Kyoto University (2002).
16. F.T. Baker et al., *Phys. Rev. C* **48**, 1106 (1993).
17. A. Ankowski, O. Benhar, T. Mori, R. Yamaguchi, and M. Sakuda, *Phys. Rev. Lett.* **108**, 052505 (2012).
18. A. Gando et al. (KamLAND Collab.), *Astrophys. J.* **745**, 193 (2012).
19. K. Kobayashi et al. (RCNP E148), arXiv:nucl-ex/0604006 (unpublished).
20. Table of Isotopes: 1999 Update with CD-ROM, edited by R. B. Firestone, C. M. Baglin, and S.Y. F. Chu (Wiley, New York, 1999), 8th ed.