, and

Measurement of γ rays from the giant resonances in ^{12}C and ^{16}O excited by the (p, p') reaction.

M. S. Reen[1,10],* T. Sudo[2], I. Ou[1], M. Sakuda[1], D. Fukuda[1], A. Ali[1], Y. Koshio [1], M. Yosoi[1], A. Tamii[2], N. Aoi[2], E. Ideguchi[2], T. Suzuki[2], T. Yamamoto[2], C. Iwamoto[3], T. Kawabata[4], S. Adachi[5], M. Tsumura[5], M. Murata[5], T. Furuno[5], H. Akimune[6], T. Yano[7], T. Suzuki[8], and R. Dhir[9]
[1]*Physics Department, Okayama University, 700-8530 Okayama, Japan*
[2]*Research Center for Nuclear Physics (RCNP), 567-0047 Osaka, Japan*
[3]*Faculty of Arts and Science, Kyushu University, 819-0395 Fukuoka, Japan*
[3]*Center for Nuclear Study, University Of Tokyo (CNS) RIKEN campus, 351-0198 Saitama, Japan*
[4]*Department of Physics, Osaka University, 567-0043 Osaka, Japan*
[5]*Department of Physics, Kyoto University, 606-8502 Kyoto, Japan*
[6]*Department of Physics, Konan University, 658-8501 Hyogo, Japan*
[7]*Department of Physics, Kobe University, 657-8501 Hyogo, Japan*
[8]*Department of Physics, Nihon University, 156-8550 Tokyo, Japan*
[9]*Department of Physics , SRM University, 603203 Kattankulathur, India and*
[10]*Department of Physics, Akal University, 151302 Punjab, India*

Introduction

Oxygen and carbon are the third and fourth most abundant element by mass in the solar system, respectively [1] after hydrogen and helium, and ^{16}O and ^{12}C are their most abundant isotopes. Thus, they have been used as the target materials in the form of water and organic liquid scintillators in many large-scale neutrino experiments designed to detect low-energy neutrinos (E_ν<100 MeV) [2–4]. These detectors must be massive to compensate for the extremely small neutrino cross section ($\approx 10^{-42}$ cm^2). One of the most interesting applications is the detection of neutrinos from supernova explosion in our Galaxy [5]. The main reaction for neutrino detection is the charged-current (CC) anti-neutrino reaction with a proton ($\bar{\nu}_e + p \rightarrow e^+ + n$), also known as the inverse β-decay reaction (IBD). Of special interest is the neutral-current (NC) neutrino or anti-neutrino inelastic scattering with ^{16}O and ^{12}C, followed by the emission of γ rays that can be observed with the detector [6]. This process is of a special interest because the cross section is significant enough to be detected and is independent of neutrino oscillations.

The first observation of ^{12}C$(\nu, \nu')^{12}$C*(15.11 MeV, 1^+, $T = 1$) reaction with 15.11-MeV γ ray came from the KARMEN experiment [3] with a neutrino beam. The observation was based on the detection of the electromagnetic decay of ^{12}C excited by neutral current interactions. The γ-ray emission probability (Γ_γ/Γ) of excited states of ^{12}C below the proton separation energy ($S_p = 16.0$ MeV) has been well measured [7]. However, the giant resonances appear above the separation energy and they decay mainly hadronically via particle emission (p, n, d and α) to the daughter nuclei. Although they decay mainly to the ground state of the daughter nuclei (^{11}B, ^{11}C, etc.), some of these decays are to excited states. If these excited states are below the particle emission threshold in ^{11}B ($S_{p'} = 11.2$ MeV) or ^{11}C ($S_{p'} = 8.7$ MeV), they decay by γ-ray emissions. Kolbe *et al.* and Langanke *et al.* [8, 9] proposed the above decay mechanism of giant resonances and estimated the NC

*Electronic address: mandeep_phy@auts.ac.in

neutrino and anti-neutrino reaction cross sections for ^{12}C and ^{16}O.

They stressed the importance of measuring NC events, since they are more sensitive to ν_μ and ν_τ neutrinos than to ν_e neutrinos. However, there are no experimental measurements of γ rays from the giant resonances of these nuclei. In this paper, we report the first measurement of γ rays from the excited states of ^{12}C and ^{16}O, including giant resonances in the energy region E_x = 16-32 MeV.

1. Experiment and Results

The experiment (E398) to measure the γ rays emitted from giant resonances in ^{12}C and ^{16}O was carried out at the Research Center for Nuclear Physics (RCNP), Osaka University. An unpolarized proton beam at 392 MeV bombarded a natural carbon ($^{\rm nat}$C) and cellulose ($C_6H_{10}O_5$) target. The scattered protons were measured around 0° and were analyzed by the high-resolution magnetic spectrometer Grand Raiden (GR) [10–12]. The γ rays were measured in coincidence with the scattered protons using a γ-ray detector made from an array of 5×5 NaI(Tl) counters. The details of the experimental setup are described in Ref. [13].

We measured the double differential cross section ($d^2\sigma/dE_x d\Omega$) for both ^{12}C(p,p') and ^{16}O(p,p') inelastic reaction at 392 MeV and 0° for the energy range E_x = 7-32 MeV.

For the measurements of γ rays from the giant resonances, the absolute values of the γ-ray emission probability $R_\gamma(E_x)$ and the response functions were verified using in-situ γ rays (15.1 and 6.9 MeV) with an accuracy of ±5% during the experiment [13]. This calibration made it possible to measure $R_\gamma(E_x)$ reliably as a function of the excitation energy of ^{12}C and ^{16}O in the energy range E_x = 16-32 MeV. We found that the measured value of $R_\gamma(E_x)$ starts from zero at E_x = 16 MeV and increases to 53.3±0.4±3.9% at E_x = 27 MeV and begins to decrease with further increase in E_x. For ^{16}O, the measured value of $R_\gamma(E_x)$ starts from 21.1±0.6±2.0% at E_x = 16 MeV and increases to 59.8±0.9±5.9% at E_x = 25 MeV, then decreases. We compared the measurements of γ-ray emission probability with a statistical model calculation based on Hauser-Feshbach formalism [14, 15] and observed a 30-40% lower γ-ray emission probability in the energy region E_x = 20-24 MeV than that predicted by the calculation.

The present results are very important for understanding the γ-ray emission probability of the giant resonances of the typical light nuclei (^{12}C and ^{16}O) and for the neutrino detection in liquid scintillator and water based detectors through neutral-current interactions.

References

[1] E. Anders and N. Grevesse, Geochim. Cosmochim. Acta **53**, 197 (1988).
[2] A. Suzuki, Nucl. Phys. B (Proc.Suppl.) **77**, 171 (1999).
[3] B. Bodmann *et al.*, Phys. Lett. B **267**, 321 (1991).
[4] K. Hirata *et al.*, (Kamiokande Collab.), Phys. Rev. Lett. **58**, 1490 (1987).
[5] H. A. Bethe, Rev. Mod. Phys. **62**, 801 (1990).
[6] J. S. O'Connell, T. W. Donnelly, and J. D. Walecka, Phys. Rev. C **6**, 719 (1972).
[7] 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.
[8] E. Kolbe, K. Langanke, S. Krewald, and F. K. Thielemann, Nucl. Phys. **A540**, 599 (1992).
[9] K. Langanke, P. Vogel, and E. Kolbe, Phys. Rev. Lett. **76**, 2629 (1996).
[10] M. Fujiwara *et al.*, Nucl. Instrum. Meth. A **422**, 484 (1999).
[11] P.von Neumann-Cosel and A. Tamii, Eur. Phys. J. A **55**, 110 (2019).
[12] A. Tamii *et al.*, Nucl. Instrum. Meth. A **605**, 326 (2009).
[13] M. S. Reen *et al.*, Phys Rev. C **100**, 024615 (2019).
[14] T. Rauscher, F. K. Thielemann, and K. L. Kratz *et al.*, Phys. Rev. C **56**, 1613 (1997).
[15] F. Puhlhofer, Nucl. Phys. **A280**, 267 (1977).