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Measurement of γ Rays from the Giant Resonances in ^{12}C and ^{16}O Excited by the (p, p') Reaction at 392 MeV

Mandeep Singh Reen[1,10], Takashi Sudo[2], Iwa Ou[1], Makoto Sakuda[1], Daisuke Fukuda[1], Ajmi Ali[1], Yusuke Koshio[1], Masaru Yosoi[1], Atsushi Tamii[2], Nori Aoi[2], Eiji Ideguchi[2], Tomokazu Suzuki[2], Tetsuya Yamamoto[2], Chihiro Iwamoto[3], Takahiro Kawabata[4], Shunsuke Adachi[5], Miho Tsumura[5], Michika Murata[5], Tatsuya Furuno[5], Hidetoshi Akimune[6], Takatomi Yano[7], Toshio Suzuki[8], and Rohit Dhir[9]

[1]*Physics Department, Okayama University, 700-8530 Okayama, Japan*
[2]*Research Center for Nuclear Physics (RCNP), Osaka University, 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 and Nanotechnology, SRM Institute of Science and Technology, 603203 Kattankulathur, India*
[10]*Department of Physics, Akal University, 151302 Punjab, India*

E-mail: mandeep_phy@auts.ac.in

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We measured both the differential cross section ($\sigma_{p,p'} = d^2\sigma/d\Omega dE_x$) and the γ-ray emission probability [$R_\gamma(E_x) = \sigma_{p,p'\gamma}/\sigma_{p,p'}$] from the giant resonances of ^{12}C and ^{16}O excited by (p, p') reaction at 392 MeV and 0°, using a magnetic spectrometer and an array of NaI(Tl) counters. The absolute value of $R_\gamma(E_x)$ was calibrated by using the well-known γ-ray emission probability from ^{12}C*(15.11 MeV, 1^+, $T = 1$) and ^{16}O*(6.9 MeV, 2^+, $T = 0$) states within 5% uncertainty. We found that, for ^{12}C, $R_\gamma(E_x)$ starts from zero at $E_x = 16$ MeV, increases to a maximum of 53.3±0.4±3.9% at $E_x = 27$ MeV, and then decreases. For ^{16}O, $R_\gamma(E_x)$ increases, starting from 21.1±0.6±2.0% at $E_x = 16$ MeV and reaches a maximum of 59.8±0.9±5.9% at $E_x = 25$ MeV and then decreases.

KEYWORDS: neutrinos, giant resonances, γ rays, . . .

1. Introduction

Oxygen and carbon are the third and fourth most abundant elements by mass in the solar system [1], respectively, 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 γ-ray emission probability of excited states of ^{16}O and ^{12}C below the proton separation energy has been well measured [7]. However, the giant resonances appear above the separation energy. They mainly decay 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, some of these decays are to excited states as well. If these excited states are below the particle emission threshold, they decay by γ-ray emissions. Kolbe *et al.* [8] and Langanke *et al.* [9] proposed the above decay mechanism of giant resonances and estimated the NC 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 ^{16}O and ^{12}C.

In this paper, we report the first measurement of γ rays from the excited states of ^{16}O and ^{12}C, including giant resonances in the energy region E_x = 16-32 MeV.

2. Experiment and Analysis

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 ($^{\mathrm{nat}}$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].

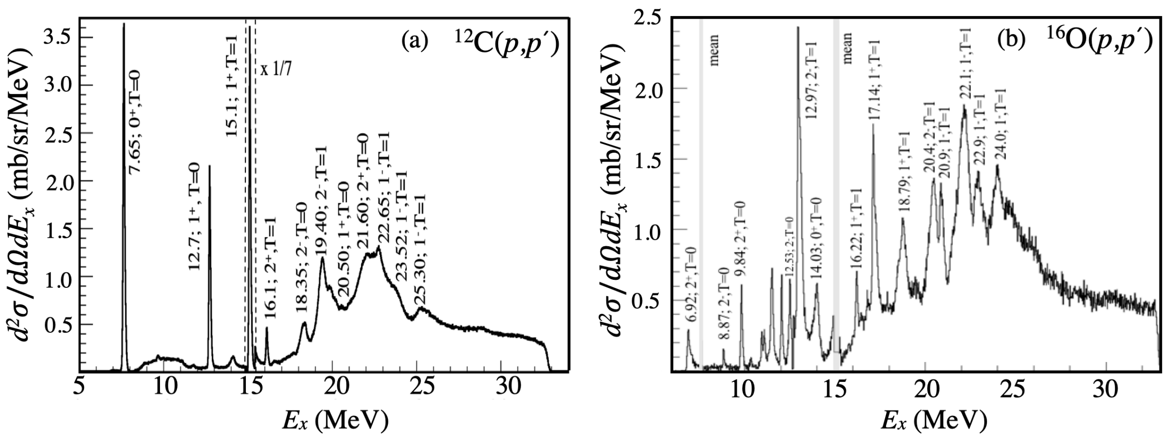

Fig. 1. Double differential cross section of the (a) ^{12}C(p, p') and (b) ^{16}O(p, p') reaction at E_p = 392 MeV and θ = 0°.

The measured cross sections of ^{12}C(p,p') and ^{16}O(p,p') as the function of excitation energy are shown in Fig. 1. The cross sections were found to be consistent with those measured in previous experiment [14, 15] within the systematic uncertainty of 6%.

The γ-ray energy spectra from the giant resonances of ^{12}C and ^{16}O were measured for various E_x values with a 2-MeV energy step. Figure 2 (left) shows the measured energy spectrum (black line) and background spectrum (red line) of γ rays from the giant resonances of ^{16}O . The decay scheme of excited ^{16}O is also shown. Here, we define the measured γ-ray energy (E) as the sum of the pulse height measured in the NaI(Tl) counters. The measured γ-ray energy spectrum for ^{12}C is shown in Ref. [13]. The background spectrum was obtained using both ADC (charge) and TDC (time) information recorded during experiment.

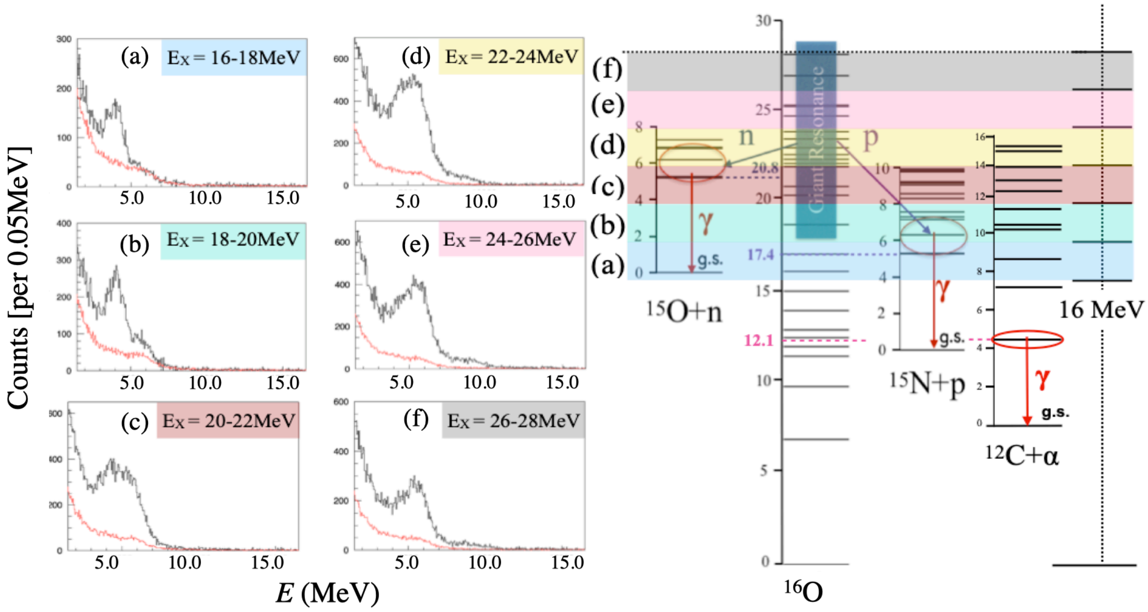

Fig. 2. (a-f) γ-ray energy spectrum (black solid line) and background energy spectrum (red dashed line) at various excitation energies in the giant resonance region of ^{16}O.

The total γ-ray emission probability in different E_x regions can be given as

$$R_\gamma(E_x) = \frac{(N_\gamma - N_{bg})/\bar{\eta}}{N_{E_x}}, \tag{1}$$

where N_γ, N_{bg}, and N_{E_x} are the number of γ-ray events, background events, and excitation events, respectively, and $\bar{\eta}$ is the weighted average efficiency in a particular E_x region. The efficiency was obtained by a fit of the calibrated γ-ray response functions to the measured γ-ray spectrum. The detailed discription of γ-ray background subtraction and the fit function is provided in Ref. [13].

3. Results and Summary

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 [16, 17] 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.

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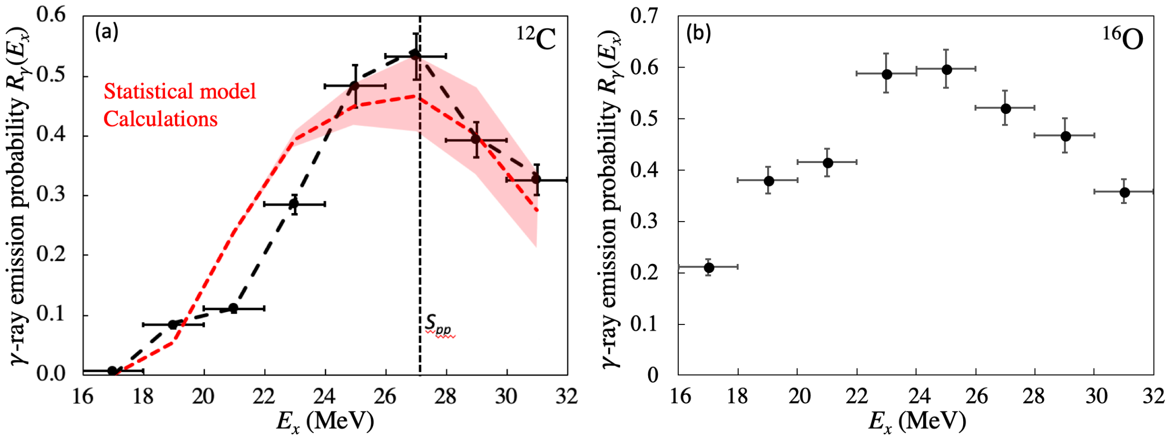

Fig. 3. Total γ-ray emission probability $R_\gamma(E_x)$ as a function of E_x for (a) ^{12}C and (b) ^{16}O. The error bars include both statitstical and systematic uncertainties.

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