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Analog of the giant dipole resonance in ^{4}He

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We studied the giant dipole resonance (GDR) in ^{4}He by observing its analog via the ^{4}He(^{7}Li,^{7}Be) reaction at an incident energy of 455 MeV and at forward scattering angles. The spin-nonflip ($\Delta S = 0$) spectrum was deduced by measuring the 0.43-MeV ^{7}Be γ-ray in coincidence with the scattered ^{7}Be. The total cross section of photodisintegration to the GDR in ^{4}He was derived from the $\Delta S = 0$ and $\Delta L = 1$ spectrum. The result agrees well with the previous total photodisintegration data in which the GDR has a pronounced peak at $E_\gamma \sim 27$ MeV.

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The ^{4}He nucleus is the lightest self-conjugate nucleus with a double closed shell [1]. There is no excited state up to $E_x \sim$ 20 MeV in ^{4}He. Isovector states have been observed at $E_x >$ 20 MeV. Among many excited states, dominant transition strengths attribute to excitation of the giant dipole resonance (GDR) and the spin-dipole resonance (SDR) in ^{4}He. The strength distribution of the dipole resonances in ^{4}He is critical to estimate transition strengths in neutrino-^{4}He scattering processes at the supernova explosion since a contribution from the Gamow-Teller (GT) transition is strongly suppressed [2]. A huge amount of ^{4}He is predicted to exist in the collapsing outer layers and the mean energy of the neutrino is estimated to be about 15 MeV in the thermal bath of a collapsing star core. Thus a considerable amount of neutrinos is expected to have energies above 20 MeV, disintegrating ^{4}He in the outer layer. It is important to determine the resonance shape of the GDR in ^{4}He in the energy region of 20–30 MeV in order to estimate the deposit energy in neutrino-^{4}He scattering processes in the high energy tail of neutrinos, and to infer correctly the nuclear synthesis process.

Unfortunately the current experimental situation concerning the GDR in ^{4}He is not sufficiently settled, although many photodisintegration experiments have been devoted to investigate the cross section and shape of the GDR. In a review article of 1983, Calarco *et al*. [3] assessed all the available experimental data and made a recommendation for the photoproton (γ, p) and photoneutron (γ, n) cross sections for ^{4}He up to a photon energy of 50 MeV. All the photodisintegration cross-section data for the GDR are consistent with each other in the energy region of 40–50 MeV. However, there is a clear discrepancy between the (γ, p) and (γ, n) cross sections in the peak-energy region of 25–30 MeV of the GDR; the former shows a rather sharp peak of the GDR and the latter shows a much less pronounced peak, and the ratio of photoproton-to-photoneutron cross sections amounts to 1.7±0.2 at the resonance peak position, differing substantially from the isospin symmetry consideration. Florizone *et al.* have investigated the ratio by simultaneously measuring the (γ, p) and (γ, n) differential yields at 90°, and found to be 1.15±0.04 at $E_\gamma = 25$–60 MeV [4]. This shows no significant evidence for the charge-symmetry violation in ^{4}He. Subsequently two recent experiments for the photodisintegration cross section of ^{4}He [5,6] have been performed and their results have been in large disagreement with each other in the resonance peak-region. Both experiments have been done by using quasi-monoenergetic photon beams. Shima *et al*. [5] have measured the ^{4}He(γ, p) and ^{4}He(γ, n) cross sections at four energies between 21.8 and 29.8 MeV and reported that both cross sections have monotonically increased with increasing the excitation energy up to $E_\gamma = 29.8$ MeV, and no pronounced peak of the GDR has been observed. The results are in disagreement with both the (γ, p) and (γ, n) data recommended by Calarco *et al*. On the other side, Nilsson *et al*. [6] have measured the ^{4}He(γ, n) cross section at photon energies from 23 MeV to 42 MeV and reported that the cross section has a peak at $E_x \sim 27$ MeV. The ^{4}He(γ, n) results seem to be in agreement with the (γ, p) data rather than the (γ, n) data recommended by Calarco *et al.*

There is also a considerable amount of theoretical work on the photodisintegration of ^{4}He. In the calculations, the ^{4}He photodisintegration cross sections were found to be sensitive to final-state interactions, meson exchange currents, effective nucleon-nucleon (NN) interactions, and three nucleon forces $(3NF)$ [7]. Four-body problem should be properly solved for calculations of ^{4}He photodisintegration cross sections. The calculations have been performed by two different methods; one based on the Lorentz integral transform (LIT) method [8] and another based on Faddeev-type Alt-Grassberger-Sandhas (AGS) formalism [9]. Two relevant calculations have provided quite different cross sections for the ^{4}He photodisintegration, though the calculations for ^{3}H and ^{3}He photodisintegration

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cross sections were consistent with each other. The calculations for total and (γ, n) photodisintegration cross sections with the LIT method showed a pronounced peak at $E_x \sim$ 27 MeV, and satisfied fully the $E1$ sum rule. On the other hand, the calculation for the ^{4}He(γ, n) with the AGS method showed no pronounced structure for the GDR, and the calculated cross section amounted to only 60% of the value derived with the LIT method in the GDR peak region at $E_x \sim 27$ MeV.

A different method for measuring the ^{4}He photodisintegration cross section could resolve the considerable controversy regarding the experimental and theoretical situations. In the present work we studied the analog of the GDR in ^{4}He by using the ^{4}He(^{7}Li,^{7}Be) reaction at an incident energy of $E_L =$ 455 MeV and at forward scattering angles. The (^{7}Li,^{7}Be) reaction can provide the spin-nonflip ($\Delta S = 0$) and spin-flip ($\Delta S = 1$) spectra from the ^{7}Be singles and coincidence spectra obtained by measuring scattered ^{7}Be particles in coincidence with the 0.43-MeV ^{7}Be γ-ray [10]. The $\Delta S = 0$ and $\Delta S = 1$ spectra are expected to reflect the nuclear response to isovector electric and magnetic excitations, respectively. The $\Delta S = 0$ spectrum obtained from the (^{7}Li,^{7}Be) reaction provides the total photodisintegration cross sections over a wide excitation energy region [11], whereas the total photodisintegration cross sections must be measured as a function of an incident γ-ray energy. The $\Delta L = 1$ transfer could be confirmed by measuring an angular distribution of differential cross sections at forward scattering angles. The $\Delta S = 0$ spectrum with $\Delta L = 1$ is expected to reflect the $E1$ photodisintegration cross sections.

The present method was recently used to measure the $M1\,\gamma$-d photodisintegration cross sections at the threshold energy region [11]. It was found that the $\Delta S = 1$ spectrum with $\Delta L = 0$ for the ^{2}H(^{7}Li,^{7}Be) reaction was feasible for providing the $M1\gamma$-d cross sections in the Big Bang energy region. In the present case, the $\Delta S = 0$ spectrum with $\Delta L = 1$ for the ^{4}He(^{7}Li,^{7}Be) reaction reflects an excitation function of the $E1\gamma$-^{4}He cross sections under the isospin symmetry, and provides the strength distribution of the GDR in ^{4}He as an analog resonance of the GDR. The $E1$ total photodisintegration cross section for ^{4}He deduced from the $\Delta S = 0$ spectrum with $\Delta L = 1$ derived in the ^{4}He(^{7}Li,^{7}Be) reaction is compared with the previous photodisintegration data.

A 455-MeV ^{7}Li^{3+} beam was provided from the ring cyclotron at the Research Center for Nuclear Physics (RCNP), Osaka University, and bombarded a ^{4}He gas target. A typical beam intensity was about 1 nA. To increase the target thickness, we cooled the ^{4}He gas down to $\sim$10 K with a cryogenic refrigerator [14]. A thickness of the ^{4}He gas target was about 7 mg/cm^2 with a pressure of 1.5 atm. The gas cell has windows of Aramid [aromatic polyamid: $(C_{14}O_2N_2H_{10})_n$] foils with a thickness of 12 μm and with diameters of 10 and 12 mm at the beam entrance and exit, respectively. Abundance of ^{12}C in the Aramid is about 71%. We measured the spectrum for an Aramid target with a thickness of 48 μm to evaluate backgrounds due to the Aramid windows. Scattered ^{7}Be particles were analyzed by using the magnetic spectrometer "Grand RAIDEN" [12] set at scattering angles of $\theta_L = 0^\circ$ and 3°. A Faraday cup (FC) was installed inside the D1-magnet of the Grand RAIDEN in the 0° measurement, and another FC at the entrance of the Q1-magnet of the Grand RAIDEN in the 3° measurement. Background from the FC was negligible.

The scattered ^{7}Be particles were detected with the focal plane detector system consisting of two multiwire drift chambers backed by a ΔE-E plastic scintillator telescope [12]. The scattering angle for the ^{7}Be particles was limited within $\pm$20 mrad horizontally (θ) and vertically (ϕ) with respect to the central orbit of ^{7}Be particles by tracing back their positions and incident angles at the focal plane of the Grand RAIDEN. The angular resolution was about 2 mrad in θ, and was about 15 mrad in ϕ. An overall energy resolution was about 500 keV, which was mainly due to the beam energy spreading and the target thickness. We estimated uncertainty in the excitation energy to be about 300 keV by observing the known states excited by the ^{12}C(^{7}Li,^{7}Be) reaction.

In the (^{7}Li,^{7}Be) reaction, the scattered ^{7}Be populates either the ground state ($3/2^-$; ^{7}Be$_0$) or the first excited state ($1/2^-$, 0.43 MeV; ^{7}Be$_1$) [13]. The ^{7}Be$_0$ state is produced when the reaction proceeds via the $\Delta S = 0$ or $\Delta S = 1$ transfer, and the ^{7}Be$_1$ state via the $\Delta S = 1$ transfer. The ^{7}Be$_1$ decays to the ^{7}Be$_0$ by emitting the 0.43-MeV γ-ray. The ^{7}Be$_1$ spectrum can be identified by tagging the 0.43-MeV γ-ray of ^{7}Be. The (^{7}Li,^{7}Be) reaction can provide separately the $\Delta S = 0$ and $\Delta S = 1$ spectra from the ^{7}Be singles and ^{7}Be$_1$ coincidence spectra obtained by measuring scattered ^{7}Be particles in coincidence with the 0.43-MeV γ-ray of ^{7}Be. In the 0° measurement, the 0.43-MeV γ-ray from ^{7}Be was measured using a Gd_2SiO_5(Ce) (GSO) γ-detector system "NYMPHS" [10], which consists of 18 GSO scintillators surrounding a scattering chamber. The 0.43-MeV γ-ray was observed as a prominent peak in the coincident γ spectra. The coincident ^{7}Be spectrum was obtained by gating on the photopeak of the 0.43-MeV γ-ray from the ^{7}Be particles. The absolute detection efficiency for the ^{7}Be γ-ray photopeak was determined to be 12.5$\pm$0.5 % by measuring the $\Delta S = 1$ transitions of $0^+ \to 1^+$ and 2^- in the (^{7}Li,^{7}Be) reaction on ^{12}C in the Aramid windows of the ^{4}He gas target, which means that the detection efficiency for the setup of γ-detectors was in-beam calibrated.

Figure 1 shows the ^{7}Be singles and coincidence spectra for ^{4}He and Aramid targets. The (^{7}Li,^{7}Be) spectrum for ^{4}He was obtained by subtracting the spectrum for the Aramid target from that for the ^{4}He target. Here two spectra for ^{4}He and Aramid targets were normalized by peak-yields in the (^{7}Li,^{7}Be) reaction on ^{12}C in the Aramid foils. A resonance-like structure is clearly observed at $E_x > 20$ MeV. The singles spectrum was compared with the ^{4}He(p, p') spectrum [14] measured at $E_p = 300$ MeV and $\theta_L = 8^\circ$ where the $\Delta L = 1$ transition is dominant. The spectral shapes are very similar to each other.

The angular distribution of the differential cross sections of the singles spectrum for the ^{4}He(^{7}Li,^{7}Be) reaction was measured in an angular range of $\theta_L < 4^\circ$ which covers the first maximum of the differential cross sections for transitions with $\Delta L = 0$, 1, and 2. Data were sorted with a horizontal angular bin of 6 mrad. As a result, the angular resolutions were about 20 mrad and 10 mrad at 0° and 3°, respectively. The experimental errors in the differential cross sections are mainly caused from the charge collection of Faraday cups. The observed angular distribution is shown in Fig. 2 and compared with the microscopic DWBA calculations [15] for transitions with $\Delta L = 0$, 1, and 2 which were integrated over a binning

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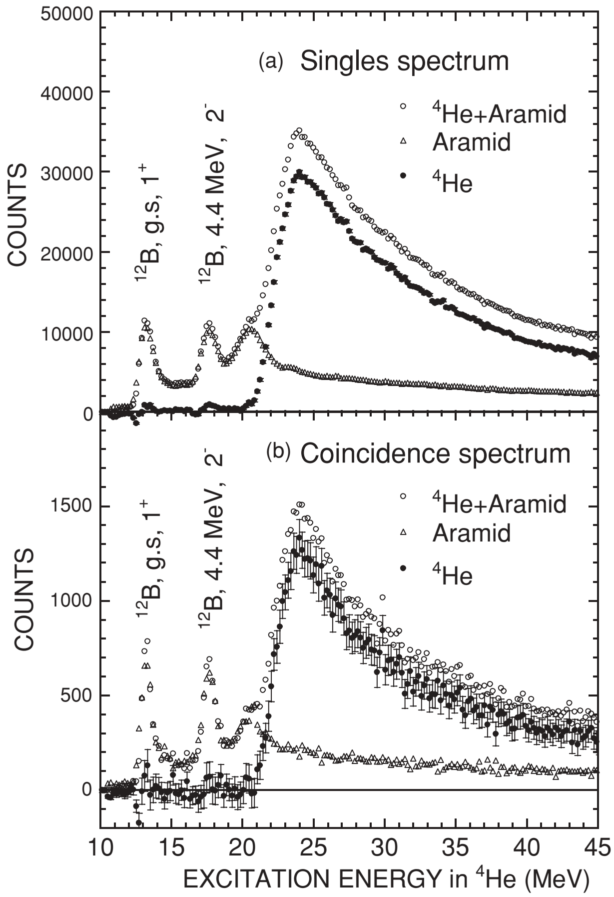

FIG. 1. Singles (a) and coincidence (b) spectra for the ^{4}He and Aramid targets in the (^{7}Li,^{7}Be) reaction at $E_L = 455$ MeV and at $\theta_L = 0^\circ$. The abscissa is the excitation energy E_x in ^{4}He.

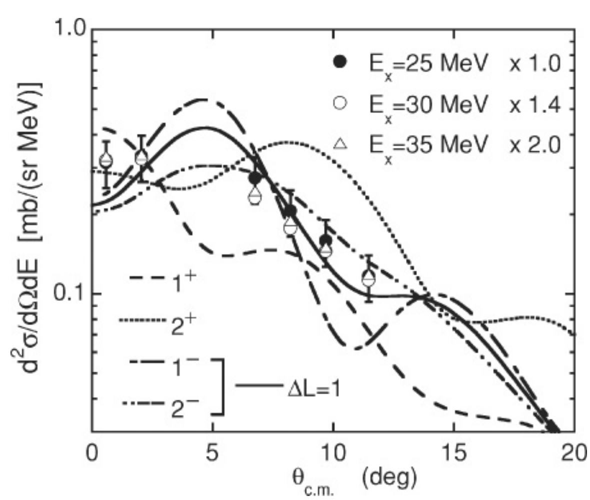

FIG. 2. Angular distribution of the differential cross sections of the singles spectrum for the ^{4}He(^{7}Li,^{7}Be) reaction. The dashed, dotted, dotted-dashed, and two-dotted-dashed lines denote the cross sections given in the DWBA calculations for particle-hole states with 1^+, and 2^+, 1^-, and 2^-, respectively. The solid line is obtained by adding two DWBA cross sections for the 1^- and 2^- states.

accepted angular range. The observed angular distribution for the resonance-like structure was found to be attributed to transitions to 1^- and 2^- ($\Delta L = 1, \Delta S = 0$ and $\Delta L = 1, \Delta S = 1$). The singles spectral shape for the resonance-like structure is found to be similarly independent of scattering angles. The singles spectrum is dominantly due to the $\Delta L = 1$ transition, namely reflecting the strength distribution of the GDR and SDR in ^{4}He. The result is consistent with the data compilation for ^{4}He [1] and the (p, p') data at $E_p = 300$ MeV [14].

The $\Delta S = 0$ spectrum was derived by subtracting the $\Delta S = 1$ spectrum from the ^{7}Be singles one, while the $\Delta S = 1$ spectrum was obtained from the coincidence spectrum. Here the coincidence spectrum was normalized with the absolute detection efficiency of the ^{7}Be γ-rays. The cross sections for the $\Delta S = 0$ and $\Delta S = 1$ spectra are described in terms of the singles (σ_s) and coincidence (σ_c) cross sections as ($\sigma_s - 2.13 \times \sigma_c$) and ($0.90 \times \sigma_c$), respectively, by using the transition probabilities deduced from the β-decay of ^{7}Be [13]. The singles spectrum could be decomposed into the $\Delta S = 0$ and $\Delta S = 1$ spectra. The result is shown in Fig. 3. It should be mentioned that the $\Delta S = 0$ spectral shape is rather insensitive to the detection efficiency of the ^{7}Be γ-rays. The two spectra are a little bit different from each other; the $\Delta S = 0$ spectrum is rather broader than the $\Delta S = 1$ one. The $\Delta S = 0$ spectrum is considered to be due to excitation of the GDR from the measured angular distributions which is ascribable to $\Delta L = 1$, and shows a pronounced peak at $E_x \sim 26$ MeV.

The $E1$ photodisintegration cross section is expressed in terms of the $E1\gamma$ transition probability as described in Refs. [11,16]:

$$\sigma_{E1\gamma}(E_\gamma, 0^+ \rightarrow 1^-) = 4.0 \times E_\gamma \frac{dB(E1)}{dE}, \tag{1}$$

where $\sigma_{E1\gamma}(E_\gamma)$, E_γ, and $dB(E1)/dE$ are the $E1$ photodisintegration cross section in units of mb, the incident γ-ray energy in MeV, and the $E1\gamma$ transition probability in e^2fm^2/MeV, respectively. The γ-ray energy E_γ is equal

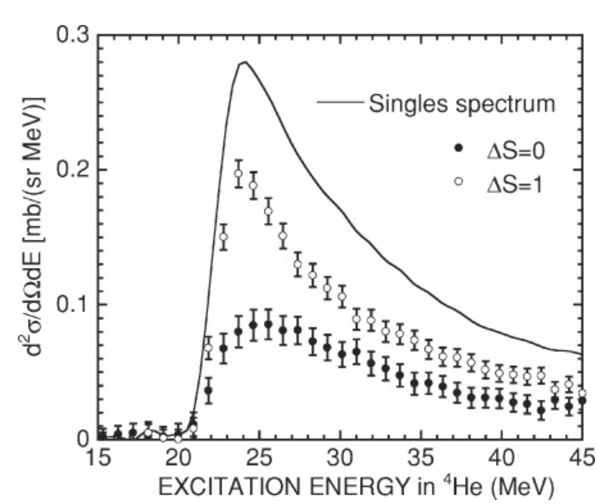

FIG. 3. Singles spectrum in the ^{4}He(^{7}Li,^{7}Be) reaction at $E_L = 455$ MeV and at $\theta_L = 0^\circ$ decomposed into the $\Delta S = 0$ and $\Delta S = 1$ spectra for ^{4}He.

to the excitation energy E_x of a target nucleus. The electric transition probability $dB(E1)/dE$ in the photodisintegration is dominantly described with $e[\tau_3 r Y_1]$ since a contribution from a magnetic moment is negligibly small [16]. Here e is the electronic charge, τ the isotopic spin operator, and Y_1 the normalized spherical harmonics with $L = 1$.

The $\Delta S = 0$ double differential cross section with $\Delta L = 1$, $d^2\sigma/d\Omega dE$, obtained in the (^{7}Li,^{7}Be) reaction reflects the transition probability, $dB(E1)/dE$, for the GDR which is described with $V_\tau[\tau_+ r Y_1]$ via a multipole expansion of central NN interactions [17]. The V_τ is dependent on the incident ^{7}Li energy and the linear momentum transfer q. As shown in Fig. 2, the angular distribution of differential cross section observed for the singles spectrum is rather flat in the angular region of $\theta < 1^\circ$, namely the cross section with $\Delta L = 1$ is constant at $q = 0.4 \sim 0.7$ fm^{-1} for the relevant excitation energy. We assumed that the proportionality between $d^2\sigma/d\Omega dE$ and $dB(E1)/dE$ is realized for the 1^- transition with $\Delta S = 0$ in the region of relevant excitation energy. Here the proportionality has been established for the GT transitions in various charge exchange reactions [18], and has been suggested to be also applicable to the 1^- transition with $\Delta S = 1$ in the ^{12}C$(p,n)^{12}$N reaction at intermediate incident energies [17]. Using the proportionality between $d^2\sigma/d\Omega dE$ and $dB(E1)/dE$, one gets

$$\sigma_{E1\gamma}(E_\gamma, 0^+ \to 1^-) = K \times E_x \frac{d^2\sigma}{d\Omega dE}, \qquad (2)$$

where K is a proportionality coefficient reflecting the relevant interaction strengths. The excitation energy E_x and the double differential cross section are given in units of MeV and mb/(sr MeV), respectively. The proportionality coefficient K would be determined to be about 1.25 by normalizing the $\sigma_{E1\gamma}(E_\gamma)$ to the data of the $E1$ total photodisintegration measured at $E_x \sim 40$ MeV where all the photodisintegration cross-section data for the GDR are consistent with each other.

The result of $\sigma_{E1\gamma}(E_\gamma)$ is shown as the closed circles in Fig. 4. Though the uncertainty of the absolute cross sections derived from the (^{7}Li,^{7}Be) reaction is 20% or more, one can nevertheless determine more precisely the resonance shape for the GDR over a wide excitation energy of ^{4}He by normalizing the $\sigma_{E1\gamma}(E_\gamma)$ to the data of the $E1$ ^{4}He photodisintegration measured at $E_x \sim 40$ MeV. The GDR was found to have a pronounced peak at $E_x \sim 27$ MeV. In Fig. 4, we compare the $\sigma_{E1\gamma}(E_\gamma)$ presently obtained with previous data of the total photodisintegration cross sections for ^{4}He. The present results are in good agreement with the previous data $\sigma(\gamma,n) + \sigma(\gamma,p)$ recommended by Calarco *et al.* [3], the recent data of $\sigma(\gamma,n) \times 2$ obtained by Nilsson *et al.* [6], and the calculation with the LIT method [8]. The photodisintegration cross section to the GDR in ^{4}He derived from the $\Delta S = 0$ spectrum deduced in the (^{7}Li,^{7}Be) reaction shows that the peak of the GDR is observed at $E_x \sim 27$ MeV, and is in serious contradiction with the recent result given by Shima *et al.* [5].

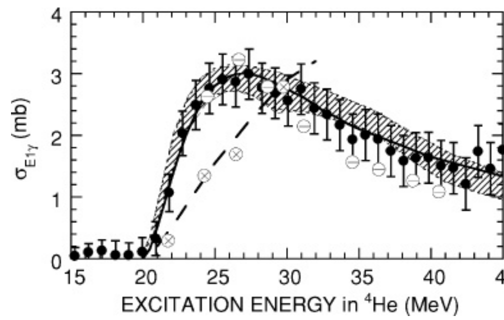

FIG. 4. $E1$ photodisintegration cross sections (●) evaluated from the $\Delta S = 0$ cross section for ^{4}He by using Eq. (2) in the text. The hatched area is the sum of (γ,n) and (γ,p) data recommended by Calarco *et al.* [3]. Two recent data are also shown: total photodisintegration cross sections (⊗) measured by Shima *et al.* [5] and (γ,n) (⊖) measured by Nilsson *et al.* [6]. The (γ,n) data obtained by Nilsson *et al.* are simply multiplied by a factor of two. The dashed curve is drawn to guide the eye for data obtained by Shima *et al.* The solid curve represents the cross sections calculated by using the LIT method with the $NN + 3NF$ potentials [8].

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