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Evidence for isovector giant resonances at $2\hbar\omega$ via the (^{7}Li,^{7}Be) reactions on ^{12}C and ^{28}Si

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We identify two electric isovector giant resonances at $E_x=28$ and 33 MeV in ^{12}C, and at $E_x=27$ and 31 MeV in ^{28}Si, distinguishing them from a continuum background in the (^{7}Li,^{7}Be) reaction at $E_L=26$ MeV/nucleon and $\theta_L=0°$. The shape of the underlying continuum is determined from a comparison of $\Delta S=0$ and $\Delta S=1$ energy spectra deduced with a ^{7}Be-γ coincidence method. The excitation energies of these resonances are consistent with those of the isovector giant quadrupole and monopole resonances previously observed by the electron scattering and the $(\pi^\pm,\pi^0)$ reaction, respectively, though the widths presently observed are much narrower.

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Electric ($\Delta S=0$) isovector giant resonances (IVGR's) in nuclei have been studied extensively [1]. Theoretical studies [2] have predicted IVGR's of various multipolarities. This prediction is partly established experimentally. Only the giant dipole resonance (GDR; $\Delta L=1$, $\Delta S=0$) has been systematically observed in a wide mass range of nuclei with various hadronic or electromagnetic probes. The isovector giant quadrupole resonance (IVGQR; $\Delta L=2$, $\Delta S=0$) and monopole resonance (IVGMR; $\Delta L=0$, $\Delta S=0$) have also been reported in medium and heavy mass nuclei from the electron scattering [3] and the $(\pi^\pm,\pi^0)$ reaction [4], respectively. However, in many other nuclear reactions, evidence for the electric IVGR's at $E_x\sim 2\hbar\omega$ has been rather scarce. Thus, the electric IVGR's other than the GDR are, from the experimental point of view, not well established. This is mainly due to the following two adverse circumstances in nuclear reactions. First, there is no appropriate probe for the $\Delta S=0$ isovector excitation. Second, it is very difficult to distinguish the IVGR's in the high excitation energy region of $2\hbar\omega$ from a large continuum "background" which is mainly due to quasifree scattering [5] and/or multistep reaction processes [6]. Hence, uncertainty of the underlying continuum shape induces considerable ambiguity in identifying IVGR strength distributions. In particular, existence of a resonancelike structure via breakup and pickup sequential processes makes it more difficult to identify the IVGR's in the high excitation energy region. A new measurement which distinguishes IVGR's from the underlying continuum is needed to confirm their systematic behavior.

Recently, we showed that the (^{7}Li, ^{7}Be) reaction is a good probe for simultaneously measuring the $\Delta S=0$ and $\Delta S=1$ spectra under similar kinematical conditions [7]. This measurement may make it possible to distinguish the IVGR's from the underlying continuum because the shape and magnitude of the underlying continuum are expected to be determined by the kinematical conditions, independent of angular momenta ΔS and ΔL transferred to relevant residual nuclei [5,6]. Hence, the shape of the underlying continuum is almost the same for the $\Delta S=0$ and $\Delta S=1$ spectra under similar kinematical conditions. In particular, a resonancelike structure excited via any multistep process should be, if it exists, commonly observed in both the $\Delta S=0$ and $\Delta S=1$ spectra. Therefore, we will be able to determine the shape of the underlying continuum from a comparison of the $\Delta S=0$ and $\Delta S=1$ spectra. The electric IVGR's would be positively identified in the $\Delta S=0$ spectrum by distinguishing them from the underlying continuum thus determined.

In this Article, we report electric IVGR's at $2\hbar\omega$ excited by the (^{7}Li,^{7}Be) reactions on ^{12}C and ^{28}Si at $E_L=26$ MeV/nucleon and $\theta_L=0°$. The $\Delta S=0$ and $\Delta S=1$ energy spectra are deduced using a ^{7}Be-γ coincidence technique [8]. Besides the GDR, two resonances are identified in the $\Delta S=0$ spectra of both ^{12}C and ^{28}Si.

A 26-MeV/nucleon ^{7}Li^{3+} beam was provided from the AVF cyclotron of the Research Center for Nuclear Physics, Osaka University. Targets used were self-supporting $^{\mathrm{nat}}$C (^{12}C; 98.9%) and $^{\mathrm{nat}}$Si (^{28}Si; 92.2%) foils with thicknesses of 0.46 and 0.70 mg/cm^2, respectively. A typical beam intensity as about 0.5 nA.

The ^{7}Be particles emitted at $\theta_L=0°$ were analyzed with the magnetic spectrograph "RAIDEN" [9]. The ^{7}Li^{3+} beam passing through the target was stopped at a chamber wall located midway between the dipole magnets of the RAIDEN, about 3 m downstream from the target. The accepted solid angles were 6.0 and 8.1 msr for ^{12}C and ^{28}Si, respectively. We measured ^{7}Be energy spectra with an energy resolution of about 200 keV up to excitation energies of 18 and 23 MeV for ^{12}B and ^{28}Al, respectively, which correspond to an excitation energy of about 33 MeV in both ^{12}C and ^{28}Si.

Emitted ^{7}Be particles are in either the ground state ($3/2^-$; $^{7}\mathrm{Be}_0$) or the first excited state ($1/2^-$, $E_x=0.43$ MeV; $^{7}\mathrm{Be}_1$). The ejectile excitation component was separated with a ^{7}Be-γ coincidence technique [8]. The 0.43-MeV γ ray emitted from the $^{7}\mathrm{Be}_1$ was detected using four 5 cm (inner diam) × 7 cm NaI(Tl) scintillators surrounding the target. The total absolute photopeak efficiency of the 0.43-MeV γ ray was about 0.1. The experimental technique has been described in more detail in Ref. [8]. The energy spectra of $^{7}\mathrm{Be}_0$ and $^{7}\mathrm{Be}_1$ were obtained without and with the ^{7}Be-0.43 MeVγ coincidence, respectively.

The $\Delta S=0$ and $\Delta S=1$ spectra are deduced using the $^{7}\mathrm{Be}_0$ and $^{7}\mathrm{Be}_1$ spectra as follows. The (^{7}Li, ^{7}Be) reaction at $E_L \geq 21$ MeV/nucleon has been shown to proceed predominantly via the one-step reaction process in the forward scattering angular range [10]. In this case, cross sections are expressed to a good approximation as an incoherent sum of the $\Delta S=0$ and $\Delta S=1$ cross sections for the $^{7}\mathrm{Be}_0$ reaction channel [$\sigma(^{7}\mathrm{Be}_0)$], and as only the $\Delta S=1$ cross section for the $^{7}\mathrm{Be}_1$ reaction channel [$\sigma(^{7}\mathrm{Be}_1)$]. As a result, the $\Delta S=0$ and $\Delta S=1$ cross sections [$\sigma(\Delta S=0)$ and $\sigma(\Delta S=1)$] are approximately described by cross sections observed for the $^{7}\mathrm{Be}_0$ and $^{7}\mathrm{Be}_1$ reaction channels as follows [11]:

$$\sigma(\Delta S=0)=\sigma(^{7}\mathrm{Be}_0)-\sigma(^{7}\mathrm{Be}_1)/\alpha\ , \tag{1}$$

$$\sigma(\Delta S=1)=\sigma(^{7}\mathrm{Be}_1)/\beta\ , \tag{2}$$

where the factor α in Eq. (1) is the cross section ratio $\sigma(^{7}\mathrm{Be}_1,\ \Delta S=1)/\sigma(^{7}\mathrm{Be}_0,\ \Delta S=1)$, and the factor β ($=1.11$) in Eq. (2) is the Gamow-Teller (GT) reduced transition probability in the β decay of $^{7}\mathrm{Be}(3/2^-)\rightarrow{}^{7}\mathrm{Li}(1/2^-)$ [12]. The factor α has been experimentally obtained to be 0.72 ± 0.04 for spin-flip transitions to the low-lying unnatural-parity states of ^{12}B [7]. In the excitation energy region presently measured, a linear momentum transfer q varies from 0.3 to 0.7 fm^{-1}. The q dependence of α may be rather small, because the ratios of Gamow-Teller transition strengths in $^{7}\mathrm{Li}\rightarrow{}^{7}\mathrm{Be}_0$ and $^{7}\mathrm{Li}\rightarrow{}^{7}\mathrm{Be}_1$ transitions have been found to be almost constant within a range of $q \leq 1.5$ fm^{-1} from the angular distributions measured for spin-flip transitions to the low-lying states of ^{12}B in the (^{7}Li,^{7}Be) reaction at 21 MeV/nucleon [13]. Hence, adopting a value of 0.72 for the factor α, we can deduce the $\Delta S=0$ and $\Delta S=1$ spectra from the cross sections for the $^{7}\mathrm{Be}_0$ and $^{7}\mathrm{Be}_1$ reaction channels using Eqs. (1) and (2), respectively. Since a reaction Q-value difference (0.43 MeV) between the (^{7}Li, $^{7}\mathrm{Be}_0$) and (^{7}Li,$^{7}\mathrm{Be}_1$) reactions is negligible as compared with the incident energy of 26 MeV/nucleon ($=180$ MeV), the energy spectra for $\Delta S=0$ and $\Delta S=1$ thus obtained have essentially the same kinematical conditions.

The $\Delta S=0$ and $\Delta S=1$ energy spectra are shown for ^{12}C and ^{28}Si in Figs. 1 and 2, respectively. The data in these figures were obtained by sorting them into excitation energy bins with a 0.26-MeV width to reduce fluctuations in the data due to counting statistics. Errors indicated in the $\Delta S=1$ spectra are entirely from counting statistics, and errors in the $\Delta S=0$ spectra from counting statistics and uncertainty of α in Eq. (1). Uncertainty of α yields an error comparable to the statistical error in the peaks where spin-flip transitions dominantly contribute.

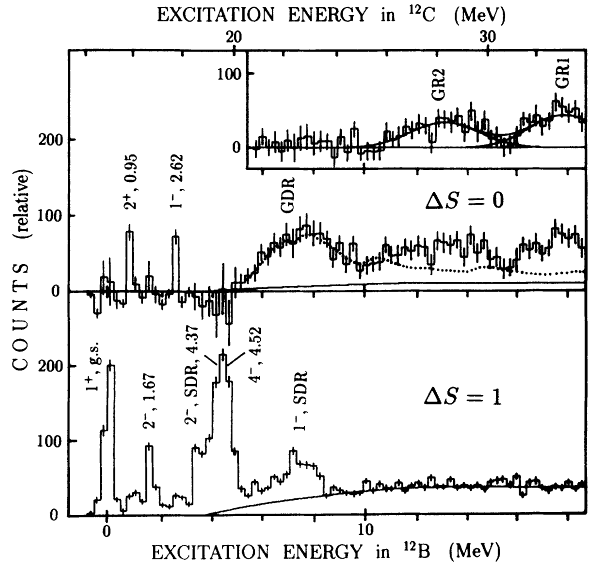

FIG. 1. Energy spectra of $\Delta S=0$ and $\Delta S=1$ in the ^{12}C(^{7}Li,^{7}Be)^{12}B reaction at $E_L=26$ MeV/ nucleon and $\theta_L=0°$. Smooth lines are the assumed underlying continuum (see text). The spectrum in the inset is obtained by subtracting the assumed underlying continuum and the arbitrarily normalized energy spectrum in the photonuclear reaction (Ref. [14]) as a background (a dotted line) from the $\Delta S=0$ spectrum. The background-subtracted spectrum is fitted by two Gaussian curves.

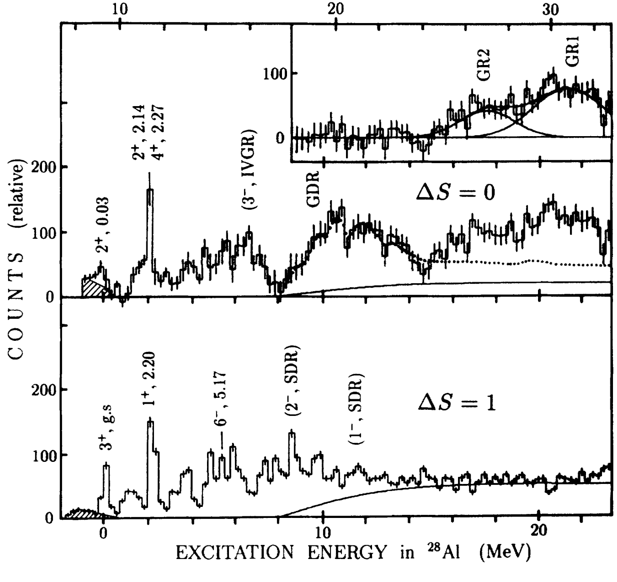

FIG. 2. Energy spectra of $\Delta S=0$ and $\Delta S=1$ in the ^{28}Si(^{7}Li,^{7}Be)^{28}Al reaction at $E_L=26$ MeV/ nucleon and $\theta_L=0°$. Hatched areas are contributions from a contamination of hydrogen. See also the caption of Fig. 1.

However, the error due to α is about one order of magnitude smaller than the statistical error in the continuum region above the excitation energy of the GDR.

The GDR is observed at 23 MeV of ^{12}C and at 20 MeV of ^{28}Si in the $\Delta S=0$ spectra. The excitation energy and width observed for the GDR are in good agreement with those obtained by the photonuclear reactions on both ^{12}C and ^{28}Si [14] which are renormalized and shown as dotted curves on an assumed underlying continuum (discussed in the next paragraph) in the $\Delta S=0$ spectra of Figs. 1 and 2. Above the excitation energy of the GDR, there is an evident enhancement of $\Delta S=0$ relative to $\Delta S=1$ cross sections in both ^{12}C and ^{28}Si, as shown in Figs. 1 and 2. In such a high excitation energy region, in general, it is very difficult to distinguish a resonance from the background. In the present case, the background is expected to be caused by two sources: the high-energy tail of the GDR contribution, and the underlying continuum due to quasifree scattering and/or multistep reaction processes. Since the former background is expected to reflect the GDR strength function, it is reasonable to assume that the shape is proportional to the photonuclear spectrum [14].

On the other hand, the latter background is deduced from the comparison of the $\Delta S=0$ and $\Delta S=1$ spectra. The $\Delta S=1$ spectra are found to be structureless in the excitation energy region above the spin-dipole resonance (SDR; $\Delta L=1$, $\Delta S=1$) for both ^{12}C ($E_x \sim 23$ MeV) and ^{28}Si ($E_x \sim 20$ MeV), as shown in Figs. 1 and 2. Excitation of intrinsic resonances with $\Delta S=1$ is not identified in this excitation energy region. In particular, no resonancelike, multistep process structures are observed in the $\Delta S=1$ spectrum. These monotonous spectra are very consistent with other data from the (p,n) reactions on ^{12}C [15] and ^{28}Si [16] at intermediate incident energies in which $\Delta S=1$ excitations are dominant. It is then reasonable to regard the $\Delta S=1$ spectrum in the excitation energy region above the SDR as the underlying continuum due to quasifree scattering and/or multistep reaction processes, and to consider that no resonancelike structure exists in the underlying continuum of the $\Delta S=0$ spectrum. Accordingly, we assume that the shapes of the underlying continuum due to quasifree scattering and/or multistep reaction processes for the $\Delta S=0$ spectra of ^{12}C and ^{28}Si are similar to the $\Delta S=1$ energy spectra above the SDR. Below the SDR, they are smoothly extended to the excitation energy region of the neutron separation energy (solid lines in Figs. 1 and 2).

The background of the $\Delta S=0$ spectrum is determined by combining these two sources of background in order to reproduce the $\Delta S=0$ spectrum around the GDR. This is shown by the dotted line in the $\Delta S=0$ spectrum. The spectra around the GDR for both ^{12}C and ^{28}Si are found to be fairly well fitted with the renormalized strength function observed in the photonuclear reaction and the assumed underlying continuum due to quasifree scattering and/or multistep reaction processes. In the insets to Figs. 1 and 2 the $\Delta S=0$ spectra are shown in the continuum region of these spectra after subtraction of the background thus determined. The background subtracted spectra show clearly the presence of a resonance structure around $E_x=30$ MeV in target nuclei beyond the limits of errors. It is very interesting to note that this structure seems to be composed of two parts. In particular, these two components are separately distributed in the case of ^{12}C. So far, in this excitation energy region, the isovector giant monopole (IVGMR) and quadrupole (IVGQR) resonances with $\Delta S=0$ have been reported; the $(\pi^{\pm},\pi^{0})$ reaction [17] has provided evidence for the IVGMR, and the $(\vec{p},\gamma_0)$ reaction [18] and electron scattering [3] have provided evidence for the IVGQR. Though the IVGMR and IVGQR have been theoretically predicted in this excitation energy region [19], no single probe provides definitive evidence for both IVGMR and IVGQR. Moreover, extracted values of their excitation energies and widths are not consistent among the previous results obtained using various probes. The structures presently observed seem to correspond to these resonances.

After subtracting the assumed background from the $\Delta S=0$ spectrum, the remaining spectrum is fitted with two Gaussian shapes (GR1 and GR2). The values extracted for the excitation energies and widths of these resonances are tabulated in Table I together with those of the GDR. For the GR1, fitting errors for both the excitation energy and width are about 1.5 MeV or more, due

TABLE I. Excitation energies and widths of isovector giant resonances.

Nucleus	GR1		GR2		GDR		
	E_x[a] (MeV)	Γ (MeV)	E_x[a] (MeV)	Γ (MeV)	E_x[a] (MeV)	Γ (MeV)	
^{12}C	33±1.5	3.5±1.5	28±0.5	3.5±0.5	23±0.5	4.0±0.5	present work
	39[b]	10∼15[c]	27[d]	4[d]	23[e]	4[e]	other works
^{28}Si	31±1.5	4.0±1.5	27±0.5	3.5±0.5	20±0.5	4.0±0.5	present work
	34[b]	10∼15[c]	22∼40[f]		20[e]	4[e]	other works

[a] Excitation energy in target nucleus.

[b] Estimated using $E_x=59.2/A^{1/6}$ MeV taken from the $(\pi^{\pm},\pi^{0})$ reaction (Ref. [17]).

[c] Width taken from the $(\pi^{\pm},\pi^{0})$ reaction on medium and heavy nuclei.

[d] Taken from the $(\vec{p},\gamma)$ reaction (Ref. [18]).

[e] Taken from the (γ,n) reaction (Ref. [14]).

[f] Taken from the ^{28}Si(e,e') reaction (Ref. [20]).

partly to the fact that this structure extends beyond the energy acceptance for the spectrograph. For the GR2, errors are about 0.5 MeV. The excitation energies for the GR1 are very close to those obtained from the excitation energy of $E_x = 59.2/A^{1/6}$ MeV for the IVGMR observed in the $(\pi^{\pm},\pi^0)$ reaction, taking into account that the location of the giant resonance shifts to lower excitation energy in light mass nuclei than that expected for medium and heavy mass nuclei. The width presently observed is much narrower than that observed in the $(\pi^{\pm},\pi^0)$ data (see Table I). Since, in the $(\pi^{\pm},\pi^0)$ reaction, the resonance has been observed around the centroid of the quasifree scattering, it may be therefore very difficult to derive its strength distribution. As a matter of fact, in the (^{13}C, ^{13}N) reactions [1], a resonance with a narrower width has been reported to be excited close to the excitation energy of the IVGMR observed in the $(\pi^{\pm},\pi^0)$ reaction.

On the other hand, the GR2 seems to correspond to the $(\vec{p},\gamma_0)$ data in light nuclei [18]. The resonance presently observed at $E_x = 28$ MeV in ^{12}C is nearly consistent with the $(\vec{p},\gamma_0)$ result, with respect to both the excitation energy and width. However, in the case of ^{28}Si, the IVGQR reported by the electron scattering [20] was about five times wider and has an excitation energy range including both the GR1 and GR2 of the data presently observed. It should be noted that, in the electron scattering, it is very difficult to distinguish between $E0$ and $E2$ modes, as indicated in previous work which identified the isoscalar $E0$ and $E2$ modes [3]. Both the IVGMR and IVGQR may be excited in the electron scattering.

In summary, two electric isovector giant resonances at $2\hbar\omega$ in ^{12}C and ^{28}Si were identified by distinguishing them from the underlying continuum. The shape of the underlying continuum was determined from the comparison of the $\Delta S = 0$ and $\Delta S = 1$ energy spectra employing the ^{7}Be-γ coincidence method in the (^{7}Li,^{7}Be) reaction at $E_L = 26$ MeV/nucleon and $\theta_L = 0°$. We suggest that the resonances observed at $E_x = 33$ MeV in ^{12}C and $E_x = 31$ MeV in ^{28}Si correspond to the IVGMR, and those at $E_x = 28$ MeV in ^{12}C and $E_x = 27$ MeV in ^{28}Si to the IVGQR.

One of the authors (S.N.) would like to dedicate this work to the late Mrs. Noriko Nakayama. This experiment was performed at the Research Center for Nuclear Physics, Osaka University, under program numbers 30A19 and 31A06.

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