Relative Strength $(\Delta S=1)/[(\Delta S=0)+(\Delta S=1)]$ of Isovector Spin Excitations in the High-Lying Resonance Region of ^{12}C

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The relative strength $(\Delta S=1)/[(\Delta S=0)+(\Delta S=1)]$ of isovector spin excitations, $P_{\rm sf}$, in the high-lying resonance region of ^{12}C was investigated with the (^{7}Li,^{7}Be) reaction at $E_L=26$ MeV/nucleon and $\theta_L=0°$ by separately measuring the (^{7}Li,^{7}Be$_{\rm g.s.}$) and (^{7}Li,^{7}Be$_{0.43\,\rm MeV}$) reaction channels with the ^{7}Be-γ coincidence technique. The relative strength $P_{\rm sf}$ was derived up to an excitation energy of 18 MeV in ^{12}B and found to have a constant value of 0.4–0.5 for the continuum irrespective of excitation energy and 0.5 for the isovector dipole resonance centered at $E_x=7.6$ MeV.

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The relative strength $(\Delta S=1)/[(\Delta S=0)+(\Delta S=1)]$ of spin excitations, $P_{\rm sf}$, is defined as

$$P_{\rm sf}=\sigma(\Delta S=1)/[\sigma(\Delta S=0)+\sigma(\Delta S=1)]\,, \tag{1}$$

where $\sigma(\Delta S=0)$ and $\sigma(\Delta S=1)$ denote the cross sections resulting from $\Delta S=0$ and $\Delta S=1$ spin transfers in nuclei, respectively. Measurements of $P_{\rm sf}$ provide important information on the nuclear spin-isospin response function. So far, for isovector excitations, $P_{\rm sf}$ has been investigated with the spin-flip probability, S_{NN}, observed by using polarized protons, especially, in the $(\vec{p},\vec{n})$ reaction [1]. The relative strength $P_{\rm sf}$ is directly related to S_{NN} [2] as

$$P_{\rm sf}=S_{NN}/\alpha\,, \tag{2}$$

where α is the spin-flip probability for $\Delta S=1$ transitions and is expressed as a combination of Clebsch-Gordan coefficients [3,4]. Thus, the $(\vec{p},\vec{n})$ reaction has been an excellent spectroscopic tool with $\Delta T_z=-1$ for well-resolved states and isolated resonances. However, for excitations in a continuum where states excited via various values of ΔL, ΔJ, and ΔS coexist, a nuclear structure model is needed in order to derive $P_{\rm sf}$ from S_{NN}, because α in Eq. (2) depends on ΔL and ΔJ as well as ΔS [3]. Therefore, in order to provide definite information on $P_{\rm sf}$ for the continuum containing overlapping resonances, another tool is necessary, in which no nuclear structure model need be included.

The (^{7}Li,^{7}Be) reaction provides, independent of the nuclear structure model, the relative strength $P_{\rm sf}$ even for the continuum and overlapping resonances. In this reaction, ^{7}Be ejectiles are populated in either the ground state ($\frac{3}{2}^-$;^{7}Be$_0$) or the first excited state ($\frac{1}{2}^-$,$E_x=0.43$ MeV; ^{7}Be$_1$) (ejectile excitation). Under the assumption of dominance of a one-step reaction process, the (^{7}Li,^{7}Be$_0$) reaction proceeds through either $\Delta S=0$ or 1, and the (^{7}Li,^{7}Be$_1$) reaction proceeds predominantly through $\Delta S=1$ [5,6]. We have shown that these two reaction channels are separately measured by using a ^{7}Be-γ coincidence technique [7]. Magnitudes of the $\Delta S=0$ and $\Delta S=1$ excitations can be derived from transitions to a high-lying resonance region as well as discrete states by comparing the cross sections for the ^{7}Be$_0$ and ^{7}Be$_1$ reaction channels. Therefore, the (^{7}Li,^{7}Be) reaction is an unambiguous, $\Delta T_z=+1$, probe for obtaining $P_{\rm sf}$, with typically better energy resolution than the $(\vec{p},\vec{n})$ reaction because ^{7}Be ejectiles may be detected by a magnetic spectrograph.

In this Letter, we report on a measurement of the relative strength of isovector spin excitations in the continuum and giant resonance regions of ^{12}C by using the ^{7}Be-γ coincidence technique. The relative strength of spin excitations was measured up to an excitation energy of 18 MeV in ^{12}B. In this excitation energy region, the isovector dipole resonance containing the giant dipole resonance (GDR; $\Delta S=0$, $\Delta L=1$) and the spin dipole resonance (SDR; $\Delta S=1$, $\Delta L=1$) has been observed by measuring the excitation functions in the (p,n) reaction [8].

A 26-MeV/nucleon ^{7}Li^{3+} beam was provided by the AVF cyclotron of the Research Center for Nuclear Physics, Osaka University. The target used was a self-supporting $^{\rm nat}$C (^{12}C; 98.9%) foil with a thickness of 0.46 mg/cm^2. A typical beam intensity was about 0.2 nA.

The ^{7}Be particles emitted at $\theta_L=0°$ were analyzed using the magnetic spectrograph RAIDEN [9]. The excitation energy range accepted by RAIDEN was about 14 MeV. The accepted solid angle was 6 msr ($\pm1.7° \times \pm2.9°$) at $\theta_L=0°$. The ^{7}Li^{3+} beam passing through the target was stopped at the wall of the chamber located midway between the $D1$ and $D2$ dipole magnets of RAIDEN, about 3 m downstream from the target. The observed energy resolution was about 200 keV which was mainly due to the target thickness and the reaction kinematics.

The ejectile excitation in the (^{7}Li,^{7}Be) reaction was measured with the particle-γ coincidence technique [7]. The 0.43-MeV γ ray emitted from the $^7\mathrm{Be}_1$ was detected using four 2 in. diam×3 in. NaI(Tl) scintillators surrounding the target chamber. These small scintillators were optimal for detecting the low-energy γ ray in the presence of an intense high-energy γ-ray background. The scintillators were located at mean scattering angles of $\theta_L = \pm 55°$ and $\pm 125°$. The solid angle of each scintillator was about 8% of 4π. The absolute photopeak efficiency of the 0.43-MeV γ ray for four NaI(Tl) scintillators was about 0.1. Details of the experimental setup are described elsewhere [7].

The energy spectra of $^7\mathrm{Be}_0$ and $^7\mathrm{Be}_1$ (without and with ^{7}Be–0.43-MeV-γ coincidence) are shown in Figs. 1(a) and 1(b), respectively. The observed discrete states in ^{12}B correspond to previously observed states in the data compilation of Ref. [10]. The observed low-lying states in ^{12}B are different in the $^7\mathrm{Be}_0$ and $^7\mathrm{Be}_1$ spectra due to the different spin selectivities for the (^{7}Li,$^7\mathrm{Be}_0$) and (^{7}Li,$^7\mathrm{Be}_1$) reaction channels. The spin-flip transitions to low-lying unnatural-parity states show up in the $^7\mathrm{Be}_1$ spectrum. The $^7\mathrm{Be}_1$ spectrum is consistent with the data obtained for the (^{12}C,^{12}N) reaction at 70 MeV/nucleon [11] which also has a spin selectivity of $\Delta S = 1$. Indeed, the known 2^- component of the SDR [8,12,13] is clearly seen at $E_x = 4.37$ MeV in the $^7\mathrm{Be}_1$ spectrum. It is very interesting to note that broad structures are observed at $E_x = 7.6$ MeV in both the $^7\mathrm{Be}_0$ and $^7\mathrm{Be}_1$ spectra which have been assigned as the isovector dipole resonances [5,8,14].

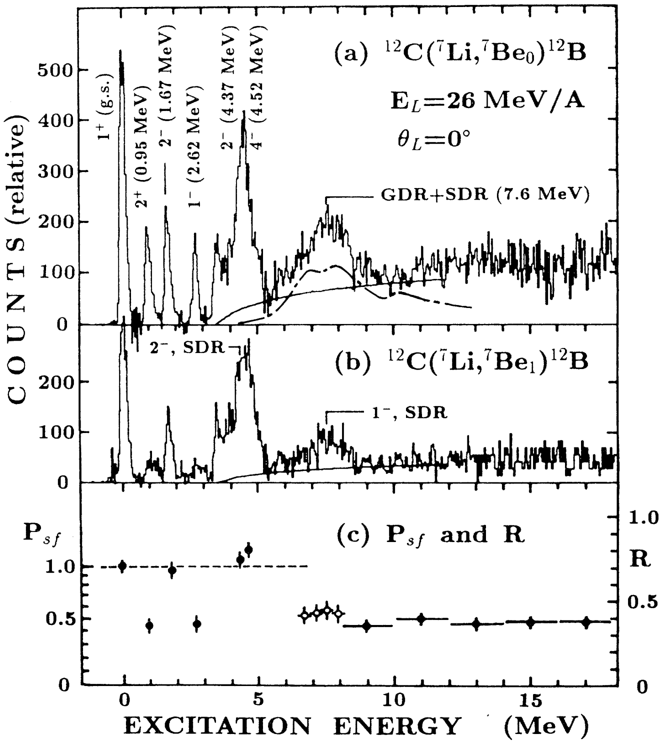

FIG. 1. Energy spectra for (a) (^{7}Li,$^7\mathrm{Be}_0$) and (b) (^{7}Li,$^7\mathrm{Be}_1$) reaction channels on ^{12}C at $\theta_L = 0°$ and $E_L = 26$ MeV/nucleon, and (c) the relative strength of spin excitations, P_{sf}, and the cross-section ratio R. The relationship between P_{sf} and R is given by Eq. (6). The dot-dashed curve in (a) is the arbitrarily normalized energy spectrum from the photonuclear reaction on ^{12}C [14]. Smooth lines are assumed underlying continua for the isovector dipole resonance region. In (c), the dashed line is the average value for the ratio R observed for the transitions to the 1^+ (g.s.) and 2^- (1.67 MeV) states, and solid and open circles in the region of $E_x \geq 6$ MeV denote P_{sf} and R for the continuum and the isovector dipole resonance, respectively.

The relative strength of spin excitations, P_{sf}, is derived from the cross sections observed for the $^7\mathrm{Be}_0$ and $^7\mathrm{Be}_1$ reaction channels. Employing microscopic distorted-wave Born approximation (DWBA) calculations [15] at forward-scattering angles, it is shown that cross sections are expressed in a good approximation as an incoherent sum of $\Delta S = 0$ and $\Delta S = 1$ cross sections for the $^7\mathrm{Be}_0$ reaction channel, and only $\Delta S = 1$ cross section for the $^7\mathrm{Be}_1$ reaction channel. It should be noted that the DWBA calculations have well reproduced the excitation functions and the cross-section ratios, $\sigma(^7\mathrm{Be}_1)/\sigma(^7\mathrm{Be}_0)$, observed for low-lying discrete states in ^{12}B at $\theta_L = 0°$ and $E_L \geq 21$ MeV/nucleon, as reported in our previous work [15]. Therefore, the cross sections $\sigma(^7\mathrm{Be}_0)$ and $\sigma(^7\mathrm{Be}_1)$ are approximated as

$$\sigma(^7\mathrm{Be}_0) \approx B_0(\mathrm{F},q)\sigma(\Delta S = 0) + B_0(\mathrm{GT},q)\sigma(\Delta S = 1)\,, \tag{3}$$

$$\sigma(^7\mathrm{Be}_1) \approx B_1(\mathrm{GT},q)\sigma(\Delta S = 1)\,, \tag{4}$$

where q is the linear momentum transfer, $B_0(\mathrm{F},q)$ and $B_0(\mathrm{GT},q)$ are the nuclear structure factors for non-spin-flip and spin-flip transitions in $^7\mathrm{Li} \rightarrow {}^7\mathrm{Be}_0$, respectively, and $B_1(\mathrm{GT},q)$ is the nuclear structure factor for spin-flip transition in $^7\mathrm{Li} \rightarrow {}^7\mathrm{Be}_1$. These factors [$B_0(\mathrm{F},0)$, $B_0(\mathrm{GT},0)$, and $B_1(\mathrm{GT},0)$] in the limit of $q = 0$ become the Fermi [$B_0^\beta(\mathrm{F})$] and Gamow-Teller [$B_0^\beta(\mathrm{GT})$] reduced transition probabilities in the β decay for the $^7\mathrm{Be}(\frac{3}{2}^-) \rightarrow {}^7\mathrm{Li}(\frac{3}{2}^-)$ transition and the Gamow-Teller [$B_1^\beta(\mathrm{GT})$] reduced transition probability in the β decay for the $^7\mathrm{Be}(\frac{3}{2}^-) \rightarrow {}^7\mathrm{Li}(\frac{1}{2}^-)$ transition, respectively.

Inserting $\sigma(\Delta S = 0)$ and $\sigma(\Delta S = 1)$ obtained from Eqs. (3) and (4) into Eq. (1), and assuming that the ratios of the B factors in Eqs. (3) and (4) are given by the corresponding values from the β decay, we get

$$P_{\mathrm{sf}} = N \frac{R}{B_1^\beta(\mathrm{GT})/B_0^\beta(\mathrm{F}) + R[1 - B_0^\beta(\mathrm{GT})/B_0^\beta(\mathrm{F})]}\,, \tag{5}$$

where R is the cross-section ratio $\sigma(^7\mathrm{Be}_1)/\sigma(^7\mathrm{Be}_0)$, and N is a renormalization factor which should be equal to unity in the limit of $q = 0$. The ratios of $B_0^\beta(\mathrm{GT})/B_0^\beta(\mathrm{F})$ and $B_1^\beta(\mathrm{GT})/B_0^\beta(\mathrm{F})$ are estimated to be 1.25 and 1.11, respectively, from the β-decay data [16]. Here N is experimentally obtained by normalizing P_{sf} using R values observed for well-established unnatural-parity transitions, for which P_{sf} should be equal to unity. The average value of 0.72 for the ratios R observed for these transitions to the 1^+ (g.s.) and 2^- (1.67 MeV) states gives $N \approx 1.3$. This deviation from unity might be caused mainly from the nonzero linear momentum transfer q which is about 0.3 fm^{-1}, which means that there are additional contributions from nonzero angular momentum transfer in ^{7}Li $\rightarrow$ ^{7}Be and from the tensor force in the effective nuclear interaction [5]. Since a linear momentum transfer q varies only from 0.3 to 0.7 fm^{-1} as an excitation energy increases and only ratios of B factors are involved in Eq. (5), the q dependence of N may not be a problem. As an empirical relationship between P_{sf} and R, we then get

$$P_{sf} = \frac{R}{0.83 - 0.19R} . \qquad (6)$$

Applying this result, the relative strength P_{sf} is derived for excitations in the continuum and isovector dipole resonance regions. Values of P_{sf} thus derived for these regions as well as low-lying discrete states are shown as solid circles in Fig. 1(c). The relative strength P_{sf} is found to be almost a constant value of 0.4–0.5 for the continuum irrespective of excitation energy. This fact suggests that the $\Delta S = 0$ and $\Delta S = 1$ isovector excitations have similar magnitudes in the continuum up to an excitation energy of 18 MeV. The present result seems to be in a striking contrast to the $(\vec{p},\vec{p}')$ result on ^{40}Ca [2] in which spin excitations have been shown to appear relatively suppressed at low excitation energies but surprisingly enhanced at higher excitation energies, at a similar linear momentum transfer to our case. Three explanations may be possible: (1) dominance of isospin interaction (V_τ) in the (^{7}Li,^{7}Be) reaction, (2) isoscalar excitations in the $(\vec{p},\vec{p}')$ reaction, and (3) three-body reaction processes in the (^{7}Li,^{7}Be) reaction. The first explanation may not be reasonable. The transitions to low-lying states in ^{12}B show that a dominance of V_τ in the (^{7}Li,^{7}Be) reaction is not needed, because the observed cross sections have been well reproduced by the DWBA calculations using the effective nucleon-nucleon interactions [5,15]. The second explanation may be rather reasonable. Recently, using the $(\vec{d},\vec{d}')$ reaction on ^{12}C, Morlet *et al.* [17] have shown a considerable isoscalar spin strength in the continuum above $E_x = 20$ MeV in ^{12}C which corresponds to an excitation energy of 5 MeV in ^{12}B. This may indicate that an enhancement of spin excitations in the $(\vec{p},\vec{p}')$ reaction is due to contributions from isoscalar excitations. On the other hand, the last explanation is not excluded. We expect that in this excitation energy region, there may exist a large contribution from three-body reaction processes independent of elementary isovector excitations. Though the present result may provide important information on the continuum in the (^{7}Li,^{7}Be) reaction, this topic is beyond the present scope.

Values of P_{sf} for the region around the isovector dipole resonance observed at $E_x = 7.6$ MeV were derived by subtracting the underlying continuum as a background. The background is assumed to be linear around $E_x = 10$–12 MeV and smoothly extended to an excitation energy equal to the neutron separation energy ($E_x = 3.37$ MeV). The assumed shape of the background is identical for both the ^{7}Be$_0$ and ^{7}Be$_1$ spectra (smooth curves in Fig. 1) because P_{sf} is approximately independent of excitation energy throughout the continuum region as mentioned above. Thus obtained P_{sf} is found to be a constant value of about 0.5 over the resonance [open circles in Fig. 1(c)]. The resonance in the ^{7}Be$_0$ spectrum is observed at about $E_x = 7.6$ MeV with a full width at half maximum (FWHM) of about 2.2 MeV. It should be noted that the FWHM is very dependent on the shape of the continuum background. The currently observed structure corresponds to the shape and position of the GDR ($E_x = 7.8$ MeV, FWHM = 3.2 MeV) excited via the photonuclear reaction [14] which is shown as the arbitrarily normalized dot-dashed curve in Fig. 1(a). There is little difference from the observed FWHM. This may be due to the assumed continuum background shape. On the other hand, the resonance in the ^{7}Be$_1$ spectrum is observed at $E_x = 7.6$ MeV with the FWHM of about 2.1 MeV. Its shape is more similar to that observed in the (p,n) reaction at $E_L = 120$–200 MeV [8], in which the 1^-, SDR is predominantly excited. Therefore, both the GDR and the 1^-, SDR are excited at $E_x = 7.6$ MeV by the (^{7}Li,^{7}Be) reaction via the spin selectivities of $\Delta S = 0$ and $\Delta S = 1$, respectively. Since the observed P_{sf} has a constant value of about 0.5 over the entire resonance width, we conclude that not only the magnitudes but also the shapes of the 1^-, SDR and the GDR are similar.

A prominent peak is observed at $E_x = 4.5$ MeV. This peak has been reported to include the transitions to the 2^- (4.37 MeV) and 4^- (4.52 MeV) states [15,18]. The former state has been assigned as the 2^- component of the SDR [8,12,13]. Observed P_{sf} for the peak at $E_x = 4.5$ MeV was found to be almost unity, from which we confirm that the peak consists predominantly of spin-flip transitions to the 2^- (4.37 MeV) and 4^- (4.52 MeV) states. The SDR distribution for the 1^- and 2^- components deduced from the ^{7}Be$_1$ spectrum is in a good agreement with the shell-model calculation for the SDR [8]. Though another component of the SDR, 0^- is expected around $E_x = 10$ MeV [13], we could not clearly identify the peak corresponding to the 0^-, SDR by the ^{12}C(^{7}Li,^{7}Be)^{12}B reaction at $E_L = 26$ MeV/nucleon. A similar situation has also been reported in the (^{3}He,t) study at about the same energy per nucleon [19]. In both cases, the 0^- component may be buried in the continuum.

In summary, the relative strength of isovector spin excitations, P_{sf}, in the ^{12}C(^{7}Li,^{7}Be)^{12}B reaction at $E_L = 26$ MeV/nucleon was investigated by separately measuring the (^{7}Li,^{7}Be$_0$) and (^{7}Li,^{7}Be$_1$) reaction channels with the ^{7}Be-γ coincidence technique. The relative strength P_{sf} in the continuum and isovector dipole resonance regions was obtained to be almost a constant value of 0.4–0.5, which shows that there are comparable contributions from $\Delta S=0$ and $\Delta S=1$ excitations in the high-lying resonance region. It is especially noticed that the GDR and the 1^-, SDR in ^{12}C have similar distributions centered at $E_x=7.6$ MeV.

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