Gamow-Teller transitions in the (^{7}Li,^{7}Be) reaction at 65*A* MeV

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We investigated the Gamow-Teller (GT) transitions in the (^{7}Li, ^{7}Be) reaction at 65*A* MeV on light nuclei of ^{6}Li, ^{12}C, and ^{28}Si. A one-step reaction process with a main contribution from the central force is dominant in the (^{7}Li, ^{7}Be) reaction at forward angles. The cross sections observed at $\theta_L=0°$ for the GT transitions were found to be proportional to the GT strengths deduced from the β decay. [S0556-2813(99)00210-1]

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The (^{7}Li,^{7}Be) reaction at an intermediate energy is expected to be a unique spin probe for studying the nuclear spin-isospin responses [1]. In this reaction, the ^{7}Be ejectile is populated in either the ground state ($\frac{3}{2}^-$;^{7}Be$_0$) or the first excited state ($\frac{1}{2}^-$,0.43 MeV;^{7}Be$_1$). Under the assumption of predominance of a one-step reaction process, the above two reaction channels have different spin selectivities: $\Delta S=0$, 1 for ^{7}Be$_0$ and $\Delta S=1$ for ^{7}Be$_1$. The cross sections for the transitions to the ^{7}Be$_0$ and ^{7}Be$_1$ reaction channels are described using the spin-nonflip $\sigma(\Delta S=0)$ and spin-flip $\sigma(\Delta S=1)$ cross sections in a target as follows:

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

$$\sigma(^7\mathrm{Be}_1)=B_1(\mathrm{GT},q)\sigma(\Delta S=1), \tag{2}$$

where q is the transferred linear momentum and the B values are reduced transition probabilities for the transition, ^{7}Li$\rightarrow$^{7}Be [2]. At $q=0$, the B values are obtained from the β decay of ^{7}Be [$B_0(\mathrm{F},0)=1.0$, $B_0(\mathrm{GT},0)=1.25$, and $B_1(\mathrm{GT},0)=1.11$] [3]. The ^{7}Be$_0$ and ^{7}Be$_1$ spectra are separated by measuring ^{7}Be-ejectiles in coincidence with the ^{7}Be 0.43-MeV γ ray [4,5]. We can separately derive the isovector $\Delta S=0$ and $\Delta S=1$ cross sections using Eqs. (1) and (2), under the same kinematics condition.

In the (^{7}Li, ^{7}Be) reaction, the total angular momentum transfer (ΔJ) is either 0, 1, 2, or 3 in the ^{7}Li($\frac{3}{2}^-$)$\rightarrow$^{7}Be$_0$($\frac{3}{2}^-$) transition or 1, 2 in the ^{7}Li($\frac{3}{2}^-$)$\rightarrow$^{7}Be$_1$($\frac{1}{2}^-$) transition [6]. Existence of large angular momentum transfers such as $\Delta J=2$ and/or 3 may distort the B values in Eqs. (1) and (2) from the values determined from the β-decay data of ^{7}Be, and make it difficult to accurately derive the $\Delta S=0$ and $\Delta S=1$ isovector excitations in the target. A further difficulty is that the $\Delta J=2$ transfer in ^{7}Li$\rightarrow$^{7}Be$_1$ allows the $\Delta S=0$ transition as well.

In a previous study of the (^{7}Li,^{7}Be) reaction at an incident energy of $E_L=21A$ MeV, the reaction proceeded predominantly via the one-step reaction process [7]. However, in this incident energy, a considerable contribution from the tensor force was observed at forward angles. In general, the tensor force enhances the large angular momentum transfers, $\Delta J=2$ and/or 3 in ^{7}Li$\rightarrow$^{7}Be. Distorted wave Born approximation (DWBA) calculation in the previous study [7] showed that the contribution from the tensor force decreased with increasing incident energy. Therefore, Eqs. (1) and (2) are expected to be applicable for intermediate incident energies.

The (^{7}Li,^{7}Be) reaction at an intermediate incident energy, 65*A* MeV, was investigated for studying the spin-nonflip and spin-flip excitations. The Gamow-Teller (GT) transitions in light nuclei have been studied in detail in order to test the reaction mechanism [8]. We measured cross sections of the GT transitions and their angular distributions for the (^{7}Li,^{7}Be) reactions on ^{6}Li, ^{12}C, and ^{28}Si for which B_{GT} values have been well established. The angular distributions of the differential cross sections for ^{12}C were compared with the DWBA calculations. We calculated the cross sections with three interactions; a full effective nuclear interaction, its central part only and its tensor part only. In this paper, we report that a one-step reaction process with a dominant contribution from the central force proceeds in the (^{7}Li,^{7}Be) reaction at 65*A* MeV and at forward angles. The cross sections observed at $\theta_L=0°$ for the GT transitions were found to be proportional to the GT strengths deduced from the β decay. Thus, we established that the $\Delta S=0$ and $\Delta S=1$ isovector excitation modes in target could be derived from the ^{7}Be$_0$ and ^{7}Be$_1$ spectra using Eqs. (1) and (2).

A 65*A*-MeV ^{7}Li^{3+} beam was provided from the Ring cyclotron of the Research Center for Nuclear Physics, Osaka University. Targets used were self-supporting foils of a separated ^{6}Li isotope (96.5%), ^{nat}C (^{12}C;98.9%), and

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$^{\mathrm{nat}}$Si (^{28}Si; 92.2%) with their thicknesses of 2.5, 1.0, and 1.4 mg/cm^2, respectively. A typical beam intensity was about 1 nA. The ^{7}Be ejectiles were analyzed using the ''Grand RAIDEN'' spectrograph [9] set at $\theta_L = 0.3°$. For ^{12}C, the ^{7}Be ejectiles were also measured at $\theta_L = 1°$. The typical energy resolution was about 500 keV which was mainly due to beam energy spreading. The ^{7}Li^{3+} beam passing through the target was stopped at a Faraday cup inside the first dipole magnet of the Grand RAIDEN. Background from the Faraday cup was negligible. The aperture of the entrance slit of the Grand RAIDEN was set to be ± 25 mr horizontally (θ) and ± 15 mr vertically (ϕ). The scattering angles for the ^{7}Be ejectiles were determined by tracing back their positions and incident angles at the focal plane of the Grand RAIDEN. The angular resolution in θ was about 2 mr, but in ϕ was only about 10 mr. Angular distributions of the differential cross section were obtained by gating with a width of 10 mr in the θ direction.

The ^{7}Be 0.43-MeV γ ray was measured using a GSO γ-detector system NYMPHS [5]. The ^{7}Be γ ray was clearly observed as a prominent peak. The total absolute detection efficiency of the NYMPHS was measured to be about 0.2.

Figure 1 shows the ^{7}Be$_0$ and ^{7}Be$_1$ spectra in the (^{7}Li, ^{7}Be) reactions on ^{6}Li, ^{12}C, and ^{28}Si. For all the spectra, a hydrogen contamination in the target was observed. The hydrogen contamination provides a calibration for separation between the ^{7}Be$_0$ and ^{7}Be$_1$ spectra, as well as for the incident angle 0° of the ^{7}Li beam. The transition strengths for the H(^{7}Li, ^{7}Be$_0$) and H(^{7}Li, ^{7}Be$_1$) reactions are taken by using $B_{\mathrm{F}} = 1$ and $B_{\mathrm{GT}} = 3$ in the β decay of neutron [10]. The ratio $|V_{\sigma\tau}/V_\tau|^2$ of the isovector spin-flip and spin-nonflip effective nuclear interactions was fairly well investigated by using the (p,n) reaction between 50 and 200 MeV [11]. From the empirical relationship of ($|V_{\sigma\tau}/V_\tau|^2 = |E_L(A\ \mathrm{MeV})/55|^2/3$), the cross section ratio of $\sigma(\mathrm{Be}_0)/\sigma(\mathrm{Be}_1)$ is estimated to be 1.77 for the H(^{7}Li, ^{7}Be) reaction at 65*A* MeV by using Eqs. (1) and (2). Here, we assumed the same distortion factor for the cross sections in the $\Delta S = 0$ and $\Delta S = 1$ transitions. The GT transitions were clearly observed for all the targets. In ^{6}Li and ^{12}C, the GT transition was observed as the ground-state transition. In ^{28}Si, one prominent peak was observed at $E_x = 2.2$ MeV and corresponds to the main GT-transition strength. All the GT transitions showed a similar angular distribution with a sharp increase towards $\theta_L = 0°$.

The distorted wave Born approximation (DWBA) calculations were performed for the (^{7}Li, ^{7}Be) reaction at 65*A* MeV. The effective *NN* interaction at 65*A* MeV was deduced from those between 50 and 400 *A* MeV given by Love and Franey [12]. Details of the calculation were given in Ref. [13]. The total angular momentum transfers (ΔJ) of 0 and 1 were found to be dominant in the $^7\mathrm{Li}(\frac{3}{2}^-) \rightarrow {}^7\mathrm{Be}_0(\frac{3}{2}^-)$ transition. The $\Delta J = 1$ was dominant in the $^7\mathrm{Li}(\frac{3}{2}^-) \rightarrow {}^7\mathrm{Be}_1(\frac{1}{2}^-)$ transition. The contribution from the large angular momentum transfers was only small at forward scattering angles, about 5% or less for $\Delta J = 2$ and 3 in the (^{7}Li, ^{7}Be$_0$) reaction and a few % for $\Delta J = 2$ in the (^{7}Li, ^{7}Be$_1$) reaction. Further in the (^{7}Li, ^{7}Be$_1$) reaction, the cross section with $\Delta S = 0$ was found to be negligible. It should be noted that, for the $\Delta S = 0$ transitions, the calculated angular distributions are dominated by the central *NN* interaction and the tensor contribution is about two orders of magnitude smaller or even less. For the $\Delta S = 1$ transitions, on the other hand, the tensor contribution is large even at forward scattering angles.

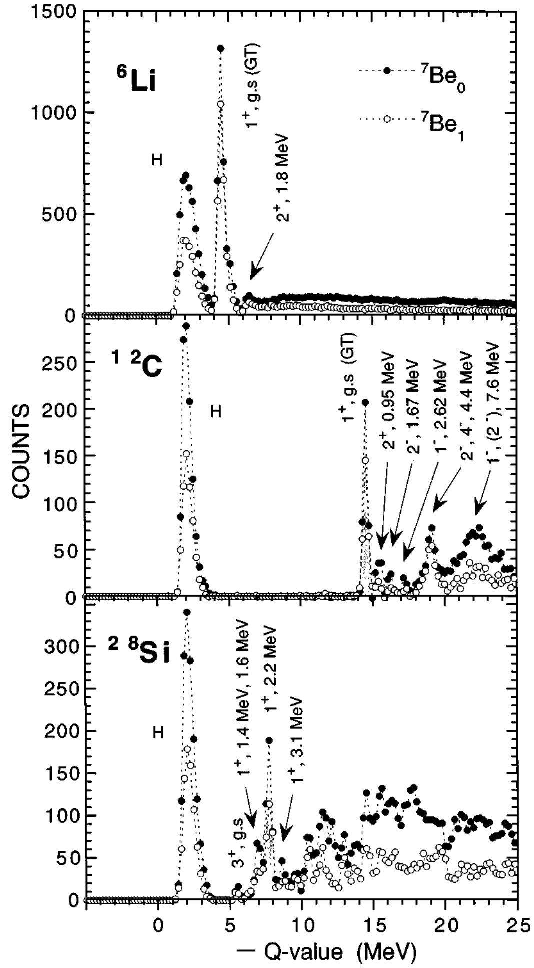

FIG. 1. Energy spectra in the (^{7}Li, ^{7}Be) reactions on ^{6}Li, ^{12}C, and ^{28}Si at 65*A* MeV and $\theta_L = 0°$. Closed and open circles correspond to the (^{7}Li, ^{7}Be$_0$) and (^{7}Li, ^{7}Be$_1$) reactions separated with the ^{7}Be-γ coincident method, respectively. Shaded peaks are the GT transitions presently interested. Symbols of H denote a contamination of hydrogen in target.

Figure 2 shows the angular distribution of the differential cross sections $\sigma(^7\mathrm{Be}_0)$ for the GT transition to the 1^+ ground state in ^{12}B. Error bars indicated are only from statistics. Absolute errors in the cross section were evaluated to be about 20% due to uncertainties in the target thickness, the accumulated beam-current and the procedure to separate the ^{7}Be$_0$ and ^{7}Be$_1$ spectra. Three DWBA calculations with the full effective *NN* interaction, with its central part only and with its tensor part only are shown by the solid, dashed, and dotted curves in Fig. 2, respectively. Here the calculated cross sections were averaged over a solid angle of $10 \times 30\,(\mathrm{mr})^2$ used in sorting data. The angular distribution observed at forward angles was found to be reproduced by the DWBA calculation. The calculated angular distribution at

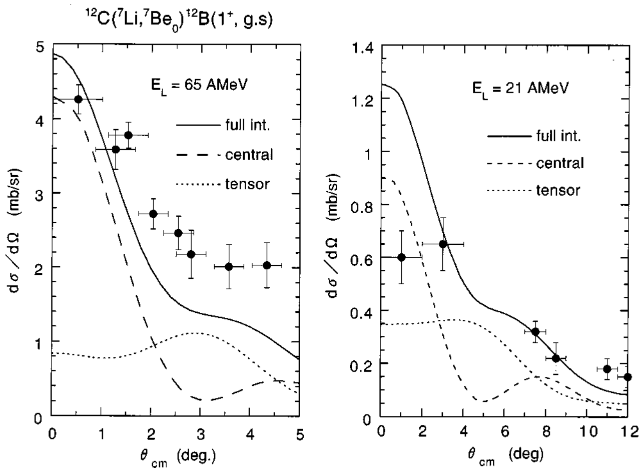

FIG. 2. Angular distributions of the (^{7}Li,^{7}Be$_0$) reaction at 65*A* MeV for the GT transition to the 1^+ ground state of ^{12}B (left side). Solid, dashed and dotted curves correspond to the DWBA calculations with the full effective *NN* interaction, with its central part and with its tensor part only, respectively. For the comparison, the previous result at 21*A* MeV [13] is shown on the right-hand side of the figure.

$\theta_{\rm c.m.}\sim 0°$ is dominated by the central *NN* interaction. Around $\theta_{\rm c.m.}\sim 3°$, on the other hand, the tensor contributions is dominant. The observed angular distribution $\theta_{\rm c.m.}\sim 3°$ shows that the tensor interaction is stronger than that deduced from the *NN* interaction and/or there are additional contributions from two-step reaction processes. The previous result at 21*A* MeV [13] is also shown in Fig. 2 in comparison with the present result. The tensor contribution at 21*A* MeV was much larger than in the present case and the observed GT cross section was not forward peaked, which meant that the tensor contribution at 21*A* MeV was large even at $\theta_{\rm c.m.} = 0°$.

The GT cross sections observed at $\theta_L = 0°$ were investigated in comparison with the $B_{\rm GT}$ values obtained by the β decay. For this purpose, the cross sections σ were obtained by gating with ± 10 mr in the θ direction. The $\sigma/(\mu^2 N_D)$ observed in ^{6}Li, ^{12}C, and ^{28}Si nuclei were compared with the $B_{\rm GT}$ values obtained from the β decay [10]. Here, μ and N_D are the reduced mass and distortion factor, respectively. The cross sections observed are largely affected by the distortion in the wave functions of the projectile. The N_D is expressed as $N_D \propto \exp(-bA^{1/3})$. The N_D value in the (^{7}Li, ^{7}Be) reaction was assumed to be equal to those obtained in the (*n,p*) reaction at 60 MeV [14]. The results are shown in Fig. 3. The indicated errors in the cross sections included systematic uncertainties in the target thickness and accumulated beam-current. In this figure, the observed cross section of the transition to the first excited state (2^+) in ^{6}He is also plotted. The transition has only a small GT strength estimated to be 0.006 by the shell-model calculation [15]. Figure 3 shows that though the distortion effect is a little bit large as compared with the (*n,p*) case, there is a proportionality between $\sigma/(\mu^2 N_D)$ and $B_{\rm GT}$ in the (^{7}Li,^{7}Be) reaction at 65*A* MeV. Dominance of the central interaction at $\theta_L = 0°$ enables the observation of the proportionality between cross sections and the $B_{\rm GT}$ values.

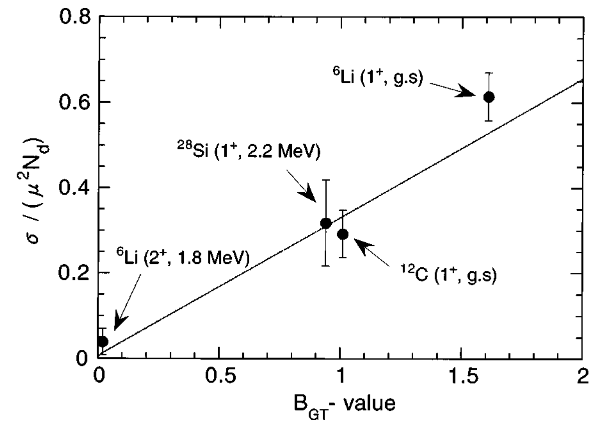

FIG. 3. Comparison of cross sections $\sigma/(\mu^2 N_D)$ observed for GT transitions in the (^{7}Li,^{7}Be) reaction at 65*A* MeV and $\theta_L = 0°$ with Gamow-Teller $B_{\rm GT}$ values. The μ and N_D are the reduced mass and distortion factor, respectively. The N_D was obtained in the (*n,p*) reaction at 60 MeV [14]. A solid line is to guide the eye.

Lastly, we discuss on the cross section ratio $\sigma(^7{\rm Be}_1)/\sigma(^7{\rm Be}_0)$. For the pure $\Delta S = 1$ transitions, the ratio is expressed as $\sigma(^7{\rm Be}_1)/\sigma(^7{\rm Be}_0) = B_1({\rm GT},q)/B_0({\rm GT},q)$. Therefore, with the condition that the ratio $B_1({\rm GT},q)/B_0({\rm GT},q)$ is constant, we can separate the $\Delta S = 0$ and $\Delta S = 1$ transitions using Eqs. (1) and (2). However, the ratio may be dependent upon the tensor contribution. Figure 4 shows the scattering angle dependence of the ratio $\sigma(^7{\rm Be}_1)/\sigma(^7{\rm Be}_0)$ for the GT transition to the 1^+ ground state of ^{12}B in the (^{7}Li,^{7}Be) reaction at 65*A* MeV. The hatched area in Fig. 4 is the mean value of 0.80 ± 0.05. Though the central and tensor contributions seemed to be dominant at $\theta_{\rm c.m.} = 0°$ and 3°, respectively, as shown in Fig. 3, it is found that the cross section ratio is independent of scattering angle. Furthermore, within errors, we obtained the same cross section ratio for the spin-flip transitions to the 2^- and 4^- states at the excitation energy of 4.4 MeV of ^{12}B in which the contribution from the tensor force was expected to be dominant. The ratio

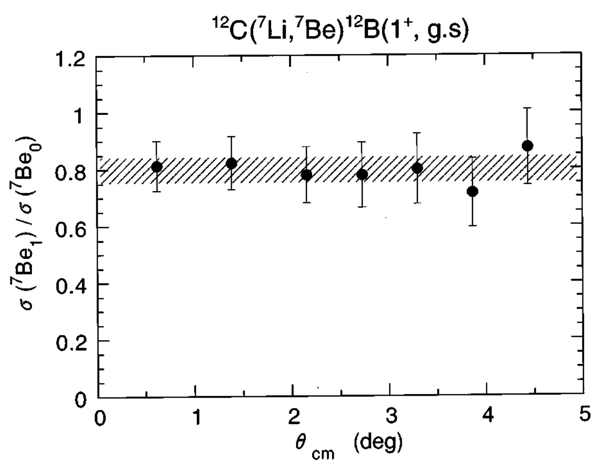

FIG. 4. Angular dependence of the ratio $\sigma(^7{\rm Be}_1)/\sigma(^7{\rm Be}_0)$ in the (^{7}Li,^{7}Be) reaction at 65*A* MeV for the GT transition to the 1^+ ground state of ^{12}B. A hatched area is the value accepted presently.

$B_1(\mathrm{GT},q)/B_0(\mathrm{GT},q)$ was found to be independent of the tensor contribution. For the GT transitions in ^{6}Li and ^{28}Si, the ratio was observed to be 0.83 ± 0.05 and 0.8 ± 0.1, respectively. The mean $\sigma(^7\mathrm{Be}_1)/\sigma(^7\mathrm{Be}_0)$ ratio for the targets measured was 0.81 ± 0.05. On the other hand, the ratio is estimated to be 0.89 from the β decay of ^{7}Be [3]. This slight difference may be due to the nonzero linear momentum transfer. The separation between the $\Delta S=0$ and $\Delta S=1$ cross sections can be performed using the empirical value for $\sigma(^7\mathrm{Be}_1)/\sigma(^7\mathrm{Be}_0)$ in the GT transition.

In summary, we conclude the (^{7}Li,^{7}Be) reaction at 65*A* MeV was found to be a good spin-probe for the isovector excitations. The (^{7}Li,^{7}Be) reaction at 65*A* MeV was found to predominantly proceed via one-step reaction process and dominated by the central force at forward angles. The cross sections observed at $\theta_L=0°$ for the GT transitions were found to be proportional to the GT strengths deduced from the β decay.

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