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# $M1$ cross section for the photodisintegration of deuterium using the $^{2}$H($^{7}$Li,$^{7}$Be) reaction

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The ($^{7}$Li,$^{7}$Be) charge-exchange spin-flip reaction was for the first time used to deduce the distribution of the $B(M1)$ reduced matrix elements for the photodisintegration of deuteron from the analogous $B$(GT) distribution. The obtained distribution is in agreement with recent photodisintegration measurements and effective-field calculations.

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The neutron($n$)-proton($p$) radiative capture reaction ($n+p \rightarrow d+\gamma$) and its time-reversal reaction, photodisintegration of deuteron ($d$) ($\gamma+d \rightarrow n+p$), have been studied for a long time [1]. The cross sections for these reactions have been used to provide information on the nucleon-nucleon interaction and the wave function of the deuteron ground state [1]. Furthermore, the formation mechanism of the deuteron that is strongly relevant to the cross section near the threshold energy is of special interest in the determination of the primordial abundance of deuterium in the Big Bang (BB) [2,3]. In the threshold energy region, the contribution of the $M1$ capture process dominates over the $E1$ capture process. Accordingly, the cross section for the $n$-$p$ capture reaction deviates significantly from the $1/v$ law with increasing excitation energy [1]. The radiative $n$-$p$ capture cross sections have been measured at thermal energies and are given in the nuclear data compilation, at the energies of 275 keV in the center of mass (c.m.) and above [4–6]. In the BB energy region, i.e., the $n$-$p$ c.m. equivalent energies of 20−200 keV, measurements have not been performed because neutron beams with good energy resolution are not available.

The $n$-$p$ capture cross section may also be inferred via the "detailed balance" of the deuteron photodisintegration by using the $\gamma$-$d$ cross section. The $\gamma$-$d$ cross sections in the threshold energy region can then provide parameters used in evaluations of nucleosynthesis in the early universe. The $\gamma$-$d$ cross section has been measured using quasimonoenergetic $\gamma$-rays produced via laser-Compton backscattering [7–9]. Recently Tornow *et al.* measured the photodisintegration analyzing powers at $\theta_L = 90^\circ$ using linearly polarized $\gamma$ rays with $E_\gamma \geqslant 2.39$ MeV, corresponding to $E_{\mathrm{c.m.}} \geqslant 160$ keV in the $n$-$p$ exit channel, to determine the $M1$ and $E1$ strengths of the $\gamma$-$d$ cross sections [7]. The $M1$ contributions thus determined were in agreement with the effective-field theory calculations [10]. It is still challenging to measure the $M1$ $\gamma$-$d$ cross sections in greater detail in the BB-energy region with an energy resolution better than that currently obtainable using direct photodisintegration of the deuteron.

In this article we present a new method to deduce the $M1$ $\gamma$-$d$ cross section as a function of excitation energy in the deuteron by using the charge-exchange spin-flip (CESF) reaction. It is shown that the observed CESF spectrum provides the distribution of the $M1$ reduced matrix elements, $B(M1)$, relevant to the $M1$ $\gamma$-$d$ cross section over the excitation region from the threshold energy to the excitation energy of $E_x \approx 3$ MeV, where it is important to precisely determine the deuteron photodisintegration strengths. In the previous work [11], CESF reactions at intermediate energies have been used to study Gamow-Teller (GT) reduced matrix elements, $B$(GT), for nuclear discrete levels and nuclear resonances, including giant resonances. This article aims at extending the ($^{7}$Li,$^{7}$Be) reaction at 65 $A$ MeV [12] to studies of $M1$ photodisintegration strengths in the continuum region above the particle threshold energy. Knowledge of these strengths is extremely important in both astrophysics and neutrino physics [11].

The deuteron bound state is predominantly a triplet $^{3}S$ ($T = 0$) configuration. No bound singlet $^{1}S$ ($T = 1$) resonance exists. Here the symbol denotes $^{2S+1}L$. The $\gamma+d \rightarrow p+n$ reaction near the threshold energy is expected to proceed dominantly via a spin-flip ($\Delta S = 1$) and isospin-flip ($\Delta T = 1$) $M1$ transition between the deuteron ground state ($^{3}S, T = 0;\ 1^{+}$) and the $p+n$ unbound system ($^{1}S, T = 1;\ 0^{+}$). This transition is the analog of the GT transition with $\Delta T = +1$ from the deuteron ground state with ($^{3}S, T = 0;\ 1^{+}$) to the $n+n$ state with ($^{1}S, T = 1;\ 0^{+}$). The $B$(GT) is obtained for the $\Delta S = 1$, $\Delta L = 0$ transition of $d\ (^{3}S) \rightarrow n+n$ ($^{1}S$) by using the CESF reaction. The $B(M1)$ for $d\ (^{3}S) \rightarrow p+n$ ($^{1}S$) is derived from the corresponding analogous $B$(GT) [13] by correcting for the difference between the two analogous

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${}^1S$ wave functions for the $p+n$ and $n+n$ systems [1]. Consequently the $M1$ $\gamma$-$d$ cross section over a wide excitation energy in the deuteron is obtained by using the $B(M1)$ distribution derived from the analogous $B(\mathrm{GT})$ distribution in the continuum region.

In the present work, the ($^7$Li,$^7$Be) reaction at 65$A$ MeV was used to deduce the $M1$ $\gamma$-$d$ cross section as a function of the deuteron excitation energy. The ($^7$Li,$^7$Be) charge-exchange reaction is a possible probe to measure the $B(\mathrm{GT})$ distribution [14] and can be used to evaluate the $M1$ cross sections in $\gamma+d \to p+n$. In the ($^7$Li,$^7$Be) reaction, the $^7$Be-scattered particles populate either the ground state ($3/2^-$; $^7\mathrm{Be}_0$) or the first excited state ($1/2^-$, 0.43 MeV; $^7\mathrm{Be}_1$) [15]. The $^7\mathrm{Be}_1$ state is produced when the reaction proceeds via a $\Delta S = 1$ transfer. The $^7\mathrm{Be}_1$ decays to the $^7\mathrm{Be}_0$ by emitting the 0.43-MeV $\gamma$ ray. The $\Delta S = 1$ spectrum can be identified by tagging the 0.43-MeV $\gamma$ ray of $^7$Be. The CESF cross sections observed at $\theta_L = 0^\circ$ were found to be proportional to the GT strengths deduced from the $\beta$ decay [12]. The $\Delta S = 1$ spectrum measured at $\theta_L = 0^\circ$ is expected to reflect the distribution of the GT transition strengths ($\Delta L = 0$). The $M1$ $\gamma$-$d$ cross sections thus deduced are compared with the photodisintegration measurements [7,8] and the effective-field theory calculations [10].

The proportionality between the $B(\mathrm{GT})$ and the CESF cross section has been found in various charge-exchange reactions at intermediate energies and at $\theta = 0^\circ$ [11,12,16] where the momentum transfer $q$ is nearly equal to zero. The proportionality is also realized over a wide excitation energy up to $E_x \approx 10$ MeV, where the kinematical condition of low momentum transfer, requisite for the dominance of GT strength, is satisfied. The $B(\mathrm{GT})$ distribution, $dB(\mathrm{GT})/dE$, is described as follows:

$$\frac{dB(\mathrm{GT})}{dE} = k \times \frac{d^2\sigma}{dEd\Omega}(0^\circ), \tag{1}$$

where the double differential cross section is given in a unit of mb/sr/MeV and $k$ is the proportionality coefficient. The $B(\mathrm{GT})$ is given in units where $B(\mathrm{GT}) = 3$ for the $\beta$ decay of a free neutron. The $B(M1)$ distribution, $dB(M1)/dE$, is derived from the analogous $dB(\mathrm{GT})/dE$ by taking into account the relevant nuclear interactions [13]. Here we assume pure ${}^3S \to {}^1S$ isovector transitions in the deuteron. Then the orbital contribution to the $M1$ $\gamma$ transition can be neglected. The $dB(M1)/dE$ is expressed in terms of the $dB(\mathrm{GT})/dE$ as follows:

$$\frac{dB(M1)}{dE} = \frac{3(\mu_p - \mu_n)^2}{8\pi}\frac{dB(\mathrm{GT})}{dE} = 2.64 \times \frac{dB(\mathrm{GT})}{dE}, \tag{2}$$

where $\mu_p$ and $\mu_n$ are the magnetic moments of a proton and a neutron in units of the nuclear magneton $\mu_N$, respectively. The $dB(M1)/dE$ is given in units of nuclear magnetons per mega-electron volts. The $dB(M1)/dE$ derived from the CESF cross section through Eqs. (1) and (2) provides the $M1$ component of the $\gamma$-$d$ cross section.

The $M1$ component of the $\gamma$-$d$ cross section is obtained from the $M1$ $\gamma$-transition probability in the breakup of $d$ to the $p+n$ continuum. The $M1$ $\gamma$-transition probability may be expressed in terms of the $M1$ reduced matrix element $B(M1)$ [1]. The $M1$ $\gamma$ width, $\Gamma(M1)$, is written in terms of the $B(M1)$ as follows:

$$\Gamma(M1) = \frac{16\pi}{9}\bar{\lambda}^{-3}\mu_N^2 B(M1), \tag{3}$$

where $\bar{\lambda} = \hbar c/E_\gamma$ is the $\gamma$-ray wavelength, $E_\gamma$ is the $\gamma$-ray energy that is equal to the deuteron excitation energy, and $B(M1) = (2J_i+1)^{-1}|\langle\|M1\|\rangle|^2$ is given in units of nuclear magnetons. Here $J_i$ is an angular momentum of the initial state. In the present case of the transition to the $p+n$ (${}^1S$) continuum, the $\Gamma(M1)$ per unit energy interval, $\Gamma(E_\gamma)$, is expressed in terms of the $B(M1)$ per unit energy interval, namely, $dB(M1)/dE$. It is noted that in case of a single state in the unit energy interval, the $\Gamma(E_\gamma)$ and $dB(M1)/dE$ correspond to the $\Gamma(M1)$ and $B(M1)$ for the discrete state in Eq. (3), respectively. Therefore the $\Gamma(E_\gamma)$ for the continuum region can be written as:

$$\Gamma(E_\gamma, 1^+ \to 0^+) = \frac{16\pi}{9}\bar{\lambda}^{-3}\mu_N^2\frac{dB(M1)}{dE_\gamma}. \tag{4}$$

This relation is used for the $\gamma$ absorption as well as $\gamma$ emission. Then the $M1$ photoabsorption cross section for the continuum region, $\sigma_{M1}(E_\gamma)$, is expressed in terms of the $\Gamma(E_\gamma)$ [1] as follows:

$$\sigma_{M1}(E_\gamma, 1^+ \to 0^+) = \pi^2\bar{\lambda}^{-2}\Gamma(E_\gamma, 1^+ \to 0^+). \tag{5}$$

Substitution of Eq. (4) into Eq. (5) yields

$$\sigma_{M1}(E_\gamma, 1^+ \to 0^+) = 0.044 \times E_\gamma\frac{dB(M1)}{dE_\gamma}, \tag{6}$$

where the cross section and $E_\gamma$ are given in units of millibarns and mega-electron volts, respectively. Using the proportionality relation as given in Eq. (1), one gets

$$\sigma_{M1}(E_\gamma, 1^+ \to 0^+) = 0.12k \times E_\gamma\frac{d^2\sigma}{dEd\Omega}(0^\circ). \tag{7}$$

The proportionality coefficient $k$ can be determined by normalizing the CESF cross section to the data of the $M1$ deuteron photodisintegration measured at $E_\gamma \approx 3$ MeV. The typical energy spreads of incident beams used for these CESF reactions are about 500 keV and sufficiently small to enable the determination of the deuteron excitation energy above threshold energy. The difference between the two ${}^1S$ wave functions in the $n+n$ and $n+p$ systems is corrected for by taking into account their scattering lengths [1]. The scattering lengths of $n+n$ and $n+p$ systems in the ${}^1S$ state have been measured to be $-18.7 \pm 0.6$ fm and $-23.5 \pm 0.8$ fm, respectively [17]. The $\sigma_{M1}(E_\gamma)$ thus derived from the CESF reactions provides the $M1$ $\gamma$-$d$ cross section over a wide range of deuteron excitation energies.

The CESF spectrum in the ($^7$Li,$^7$Be) reaction was measured by using the 65-$A$ MeV $^7\mathrm{Li}^{3+}$ beam from the ring cyclotron at the Research Center for Nuclear Physics, Osaka University. The targets used were foils of $\mathrm{CD}_2$ and $^{\mathrm{nat}}$C ($^{12}$C; 98.9%) with thicknesses of 1.5 and 1.0 mg/cm$^2$, respectively. A typical beam intensity was about 1 nA. The $^7$Be scattered particles were analyzed using the "Grand RAIDEN" spectrograph [18] set at $\theta_L = 0.3^\circ$. The $^7\mathrm{Li}^{3+}$ beam passing through the target was stopped at the 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 $\pm 20$ mr horizontally ($\theta$) and $\pm 15$ mr vertically ($\phi$). The angular resolution was about 2 mr in $\theta$ and about 15 mr in $\phi$. The scattering angle for the $^7$Be was limited within $\pm 15$ mr horizontally and vertically with respect to $\theta_L = 0^\circ$ by tracing back their positions and incident angles at the focal plane of the Grand RAIDEN. The $^7$Be 0.43-MeV $\gamma$ ray was measured using a $Gd_2SiO_5$(Ce) $\gamma$-detector system "NYMPHS" [19]. The $^7$Be $\gamma$ ray was clearly observed as a prominent peak. The total detection efficiency of the NYMPHS was about 0.2. The $^7Be_1$ spectrum was measured in coincidence with the $^7$Be 0.43-MeV $\gamma$ rays, and the $^7Be_0$ spectrum was obtained by subtracting the $^7Be_1$ spectrum from the $^7$Be singles spectrum that were renormalized to account for the detection efficiency of the NYMPHS. Details of the procedure for separation of the spin-flip ($\Delta S = 1$) and spin-nonflip ($\Delta S = 0$) spectra from the $^7Be_0$ and $^7Be_1$ spectra thus obtained are described in Ref. [19].

The $\Delta S = 1$ and $\Delta S = 0$ spectra for the $CD_2(^7Li,^7Be)$ reaction at $E_L = 65$ $A$ MeV and at $\theta_L < 1^\circ$ are shown in Fig. 1. These two spectra show a remarkable contrast in the low excitation energy region. The $\Delta S = 1$ ($^7Be_1$) spectrum shows that the $\Delta S = 1$ strength is distributed above 2 MeV excitation, which is around the threshold energy for $d \rightarrow p+n$. This indicates a dominant contribution from the $\Delta S = 1$ transition in $d \rightarrow n+n$. Conversely, as shown by the closed circles in Fig. 1, the flat distribution of the experimentally determined $\Delta S = 0$ spectrum is the signature expected for $\Delta S = 0$ transitions with $\Delta L \neq 0$. Above $E_x \approx 10$ MeV the contributions from the $\Delta S = 0$ and $\Delta S = 1$ transitions are comparable.

In fact the $^7Be_1$ spectrum is not pure-GT $\Delta S = 1$ process, but includes non-GT processes as well. They arise mainly from the $\Delta L = 2$ transitions because of the tensor interaction. The cross sections with $\Delta L = 2$ for the $^2H(^7Li,^7Be)$ reaction at 65 $A$ MeV and at $\theta_L < 1^\circ$ were estimated by using microscopic distorted wave Born approximation

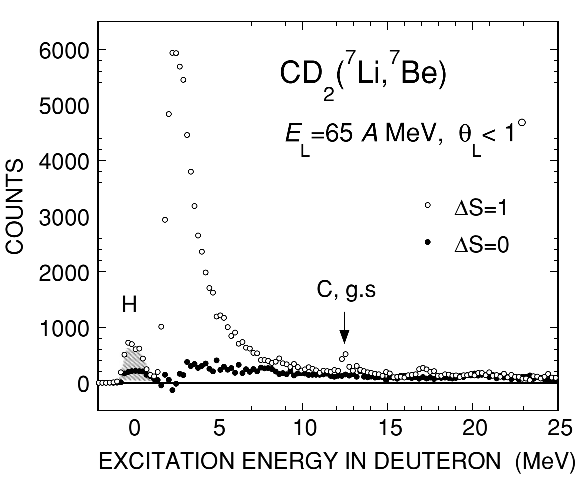


FIG. 1. Spin-flip and spin-nonflip spectra for the $CD_2(^7Li,^7Be)$ reaction at $E_L = 65$ $A$ MeV and $\theta_L < 1^\circ$. The symbols of H and C denote peaks because of the hydrogen and carbon contaminations in the target, respectively.

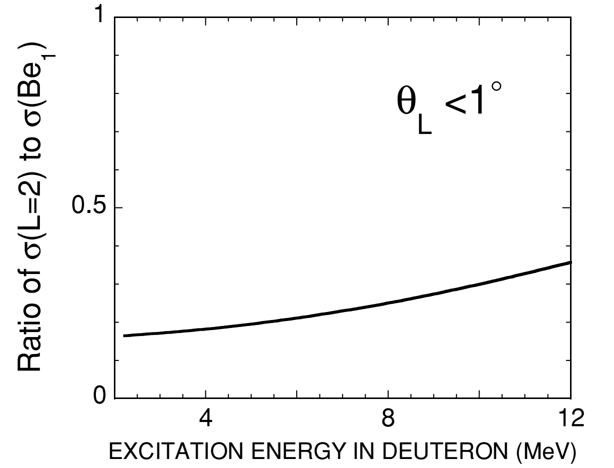


FIG. 2. Ratio of non-GT cross section to the $^7Be_1$ cross section for the transition of $d(1^+) \rightarrow n+n(0^+)$. The ratio was estimated using the DWBA calculations as a function of the deuteron excitation energy.

(DWBA) calculations with effective nucleon-nucleon isovector interactions, including tensor interactions. Because we have not determined the optical parameters for $^2$H and $^7$Li at 65 MeV and because, as discussed below, the relevant cross sections are relatively insensitive to optical parameters, we instead used the optical parameters for $^{12}C + ^7Li$ at 19 $A$ MeV. Details of the calculation were given in Ref. [20]. We assumed particle-hole configurations of $s_{1/2} \otimes s_{1/2}^{-1}$ and $d_{3/2} \otimes s_{1/2}^{-1}$ in the transition for $d(1^+) \rightarrow n+n(0^+)$. The former cross section was calculated to be more than one order of magnitude larger than the latter one. The ratio of non-GT cross section to the the $^7Be_1$ cross section, which is thus predominantly because of a $\Delta L = 2$ transition from the $s_{1/2} \otimes s_{1/2}^{-1}$ configuration, is shown in Fig. 2. The contribution from the $\Delta L = 2$ transitions was estimated to be $17 \sim 35\%$ of the $^7Be_1$ cross sections in the excitation energy region from $E_x = 2$ MeV to 12 MeV, depending smoothly on the excitation energy. We checked whether the present result is dependent on the optical potentials in the DWBA calculations. We performed the DWBA calculations with quite different optical potential parameters for $^6Li + ^7Li$ at 50 $A$ MeV [21]. The estimated cross sections were different by $3 \sim 4\%$, but the difference in cross-section ratios was less than 0.5% in the relevant excitation energy region. The results are identical within the solid line in Fig. 2.

The CESF cross sections were estimated by subtracting the non-GT cross sections from the observed $^7Be_1$ cross sections. The experimental error in the absolute CESF cross section is about 15% which is mainly because of the combined uncertainties in the integrated beam current and the target thickness. The distribution of the CESF cross sections as a function of excitation energy is found to be little influenced by the sizable contribution from the non-GT cross sections that are smooth in the relevant region of excitation energy.

The proportionality coefficient $k$ in Eq. (7) was determined to be $0.42 \pm 0.07$ by normalizing the CESF cross section to the data of the $M1$ cross section of deuteron photodisintegration measured at $E_x \approx 3$ MeV [7]. The error in the obtained $k$ value is because of the uncertainty of the absolute cross sections.

This is in accord with the value of $0.50 \pm 0.05$ from the CESF cross sections on $^{6}$Li and $^{12}$C [12]. The $\sigma_{M1}(E_\gamma)$ derived from the ($^{7}$Li,$^{7}$Be) reaction at 65 *A* MeV is given as follows:

$$\sigma_{M1}(E_\gamma, 1^+ \rightarrow 0^+) = 0.050 \times E_\gamma \frac{d^2\sigma}{dEd\Omega}(0^\circ). \qquad (8)$$

The results for $\sigma_{M1}(E_\gamma)$ are shown by the open circles in Fig. 3. These results for $\sigma_{M1}(E_\gamma)$ change much more slowly as a function of energy in the threshold energy region than the results obtained from photodisintegration measurements [7]. This is because of the experimental energy resolution ($\Delta E_s$) composed of the energy spread of the incident beam and a kinematical energy spread because of angular acceptance of $\theta_L < 1^\circ$. The full width at half maximum (FWHM) of $\Delta E_s$ was determined to be $800 \pm 50$ keV by fitting the $\sigma_{M1}(E_\gamma)$ deduced from the $^{2}$H($^{7}$Li,$^{7}$Be) reaction, which gradually increases as $E_x$ increases in the excitation energy region of $E_x = 1.5-3.0$ MeV.

To establish the validity of the present approach, the $\sigma_{M1}(E_\gamma)$ cross sections obtained via the $^{2}$H($^{7}$Li,$^{7}$Be) reaction should be reproducible via calculations for the *M*1 $\gamma$-*d* cross sections folded over $\Delta E_s$. The solid curve in Fig. 3 is a calculation for the *M*1 $\gamma$-*d* cross section performed using the effective-field theory [10]. This calculation in the energy region up to $E_x = 5$ MeV, folded over $\Delta E_s$ with an assumed Gaussian shape of 800 keV FWHM, is shown by the closed circles in Fig. 3. The folded *M*1 cross sections near threshold well reproduce the $\sigma_{M1}(E_\gamma)$ cross sections obtained via the $^{2}$H($^{7}$Li,$^{7}$Be) reaction at $\theta_L < 1^\circ$. It should be noted that agreement of the calculation above $E_x > 3$ MeV with the data demonstrates the feasibility of the present method for deducing the *M*1 $\gamma$-*d* cross section.

One can determine the relative *M*1 $\gamma$-*d* cross sections over a wide excitation energy of the deuteron more precisely by normalizing the $\sigma_{M1}(E_\gamma)$ obtained via the $^{2}$H($^{7}$Li,$^{7}$Be) reaction to that obtained via the deuteron photodisintegration measured around $E_\gamma \approx 3$ MeV. Here the 15% uncertainty in the absolute cross section is implicitly included in the normalization constant. If the CESF reaction with energy resolution less than 100 keV could be performed, this method would enable a more detailed and precise determination of the *M*1 $\gamma$-*d* cross sections near threshold than those obtainable by other means. Measurements using a high-resolution $^{7}$Li beam and an acceptance angle limited to about 2 mr [22] for the $^{7}$Be scattered particle may quite feasibly be used for this purpose.

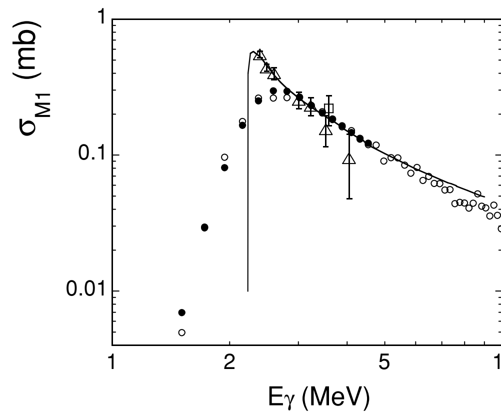


FIG. 3. *M*1 cross sections (open circles) evaluated by using Eq. (8) in the text. The relative uncertainties are smaller than the symbol size. The solid curve is a recent calculation for the *M*1 $\gamma$-*d* cross section in Ref. [10]. The open triangles [7] and squares [8] denote the recent data in the *M*1 deuteron photodisintegration. The closed circles are the *M*1 cross sections obtained by folding the calculation with $\Delta E_s = 800$ keV. See the text.

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