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High-resolution study of ^{11}B to ^{11}C Gamow-Teller strengths as a test case of *ab initio* shell-model calculations

Y. Fujita,[1,*] P. von Brentano,[2,†] T. Adachi,[1] G. P. A. Berg,[3] D. De Frenne,[4] K. Fujita,[5] K. Hatanaka,[5] E. Jacobs,[4] K. Nakanishi,[5] A. Negret,[4,‡] L. Popescu,[4,‡] Y. Sakemi,[5] Y. Shimbara,[1] Y. Shimizu,[5] Y. Tameshige,[5] A. Tamii,[5] M. Uchida,[6] M. Yosoi,[6] and K. O. Zell[2]

[1]*Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan*
[2]*Institut für Kernphysik, Universität zu Köln, 50937 Köln, Germany*
[3]*Kernfysisch Versneller Instituut, Zernikelaan 25, 9747 AA Groningen, The Netherlands*
[4]*Vakgroep Subatomaire en Stralingsfysica, Universiteit Gent, B-9000 Gent, Belgium*
[5]*Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan*
[6]*Department of Physics, Kyoto University, Sakyo, Kyoto 606-8502, Japan*

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A high energy-resolution ^{11}B(^{3}He$,t$)^{11}C experiment was performed at 0° and an intermediate incident energy of 140 MeV/nucleon for the study of precise Gamow-Teller (GT) transition strengths. Two doublet states at ≈4.5 and ≈8.4 MeV were clearly resolved with a resolution of 45 keV. The strengths are compared with a calculation using an *ab initio* no-core shell model, which became available for the $A=11$ system recently. It was found that a calculation including a three-nucleon interaction better reproduces the observed GT transition strengths.

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It has become possible to understand the structure of light nuclei from a very basic point of view by various schemes of *ab initio* calculations, e.g., Refs. [1–4]. In particular, *ab initio* no-core shell-model (NCSM) calculations starting from very light nuclei have become possible up to p-shell nuclei. Recently, Navrátil and Ormand extended the calculations to include a realistic three-nucleon interaction (TNI) [1]. It was suggested that the TNI can affect various structural properties, such as excitation energies and quadrupole as well as magnetic moments of the ground states (g.s.). It was also shown that the TNI has a relatively large effect on Gamow-Teller (GT) ($\Delta L=0,\Delta J^{\pi}=1^{+}$) transition strengths. In particular, a large effect was predicted for the GT transition strengths in the $A=11$ mirror nuclei ^{11}B and ^{11}C [1].

The most direct information on the GT transition strength B(GT) is obtained from β-decay studies, but the accessible range of excitation energy (E_x) is limited by the small Q value for the $A=11$ system ($Q_{\rm EC}=1.98$ MeV). In the β-decay study of ^{11}C, the B(GT) value can be obtained only for the g.s. to g.s. transition. Charge-exchange reactions, like the (p,n) reaction, can access analogous GT transitions without the Q-value limitation. In particular, those performed at angles around 0° and intermediate energies ($E_p>100$ MeV) were shown to be good probes of GT transition strengths owing to the relatively simple proportionality between the cross sections at 0° and the B(GT) values [5],

$$\frac{d\sigma_{\rm CE}}{d\Omega}(0^\circ) \simeq K N_{\sigma\tau}|J_{\sigma\tau}(0)|^2 B({\rm GT}) \quad (1)$$

$$=\hat{\sigma}_{\rm GT}(0^\circ)B({\rm GT}), \quad (2)$$

where $J_{\sigma\tau}(0)$ is the volume integral of the effective interaction $V_{\sigma\tau}$ at momentum transfer $q=0$, K is a kinematic factor, $N_{\sigma\tau}$ is a distortion factor, and $\hat{\sigma}_{\rm GT}(0^\circ)$ is a unit cross section for the GT transition at 0°.

The ^{11}B$(p,n)^{11}$C reactions were performed at various incident energies between $E_p=160$ and 795 MeV with resolutions of ≈700 keV, and several GT states were studied [6,7]. An improved resolution of about 300 keV was reported in a ^{11}B(^{3}He$,t$)^{11}C reaction at an incident energy of 150 MeV/nucleon [8]. We found, however, a better resolution was required to make a quantitative comparison with the states predicted by the NCSM calculation.

Recently, precise beam matching techniques were applied to the (^{3}He$,t$) reaction at 0° and at intermediate incident energies [9]. A very good energy resolution ΔE of <50 keV was realized. Therefore, it was expected that doublet states unresolved in earlier measurements could be clearly resolved in a new ^{11}B(^{3}He$,t$) measurement. The validity of the approximate proportionality [Eq. (1)] in (^{3}He$,t$) reactions has been demonstrated for states with "$L=0$" nature and for values of $B({\rm GT})\geqslant 0.04$ by studying analogous GT transitions in the $A=27$ mirror nuclei, ^{27}Al and ^{27}Si [10], and the $A=26$ nuclei, ^{26}Mg, ^{26}Al, and ^{26}Si [11].

The ^{11}B(^{3}He$,t$)^{11}C experiment was performed at the high energy-resolution facility of RCNP, consisting of the "WS course" [12] and the Grand Raiden spectrometer [13] using a

*Email address: fujita@rcnp.osaka-u.ac.jp
†Email address: brentano@ikp.uni-koeln.de
‡Permanent address: NIPNE, Bucharest, Romania.

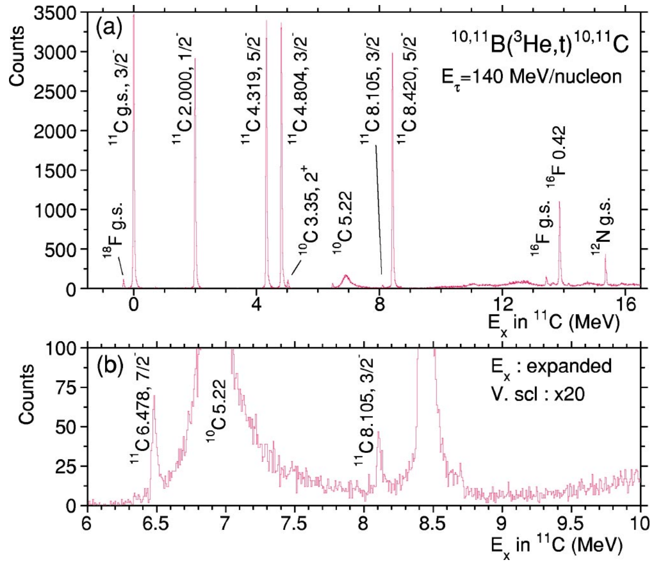

FIG. 1. (Color online) Spectra of the ^{11}B(^{3}He,t)^{11}C reaction of (a) the range up to the excitation energy of 16 MeV for scattering angles $\Theta \leqslant 0.5°$, and (b) expanded 6–10 MeV region. Excitation energies (in MeV) and J^{π} values are indicated.

140 MeV/nucleon ^{3}He beam from the K=400 Ring Cyclotron [14]. A self-supporting foil of boron oxide (B_2O_3) with a very thin carbon backing was used as a target. The thickness of the foil was $\approx$1.5 mg/cm^2. The natural abundances of ^{10}B and ^{11}B are 19.9% and 80.1%, respectively. The outgoing tritons were momentum analyzed within the full acceptance of the spectrometer placed at 0° and detected with a focal-plane detector system allowing for particle identification and track reconstruction in horizontal and vertical directions [15]. Good angle resolution of $<$8 mrad [full width at half-maximum (FWHM)] was achieved by applying the *angular dispersion matching* technique [16] and the "overfocus mode" of the spectrometer [17]. The acceptance of the spectrometer was subdivided in scattering-angle regions in the analysis using the track information.

An energy resolution of 45 keV (FWHM), which is better by more than a factor of 3 than the energy spread of the beam, was realized by applying *dispersion matching* and *focus matching* techniques [16]. For fast and efficient beam tuning, the "faint beam method" [18,19] was applied. Owing to the high energy-resolution, well separated states were observed up to E_x=8.4 MeV in the "0° spectrum" [Fig. 1(a)] showing events for scattering angles $\Theta \leqslant 0.5°$. By consulting Ref. [20], all of these prominent states could be identified as ^{11}C states with J^{π} values of either $1/2^-$, $3/2^-$, or $5/2^-$. No broadening of peak widths was observed for these states due to the high proton and neutron separation energies of 8.69 MeV and 13.12 MeV, respectively, in ^{11}C.

In the earlier (p,n) experiments [7], one broad peak was observed at 4.5 MeV. This peak was resolved into two sharp states at 4.319 and 4.804 MeV with nearly equal strengths. A previously unresolved peak at 8.4 MeV was also resolved into 8.105 and 8.420 MeV states in agreement with Ref. [20]. It was found that there was almost no strength in the transition to the $J^{\pi}=3/2^-$, 8.105 MeV state, although the transition from the ^{11}B g.s. with $J^{\pi}=3/2^-$ is allowed by the J^{π} selection rule. Several positive-parity states are known below E_x=9 MeV [20], but none of them is seen in this "0° spectrum."

The excitation energies and J^{π} values of ^{11}C states given in Fig. 1(a) and Table I are taken from Ref. [20]. The yields of the five major states were compared in the spectra with angle cuts $\Theta=0°-0.5°$, $0.5°-1.0°$, and $1.0°-1.5°$. All of these states showed 0° peaked angular distributions, suggesting the L=0 nature. For all states below 8.5 MeV, the given errors of excitation energies are smaller than 2 keV [20]. The energies are in agreement within an error of 5 keV with our results. For details of our energy calibration, see Ref. [21].

The broad peak at $E_x \approx 7$ MeV was assigned as the 5.22 MeV state in ^{10}C with a probable J^{π} value of 2$^+$ on the basis of the Q-value difference (1.67 MeV) of the (^{3}He,t) reactions on ^{10}B and ^{11}B nuclei. This state corresponds to the largest peak in the ^{10}B$(p,n)^{10}$C spectrum at 0° [22]. In addition, the excitation of the $J^{\pi}=2^+$, 3.35 MeV state is re-

TABLE I. The $J^{\pi}=1/2^-$, $3/2^-$, and $5/2^-$ states in ^{11}C and their B(GT) strengths. The results from charge-exchange reactions and NCSM calculations with and without a TNI are compared.

Experiment				NCSM			
			B(GT)	With TNI		Without TNI	
E_x (MeV)	$2J^{\pi}$	(p,n)[a]	(^{3}He,t)	E_x (MeV)	B(GT)	E_x (MeV)	B(GT)
0.0	3^-	0.345(8)[b]	0.345(8)[b]	0.0	0.315	0.0	0.765
2.000	1^-	0.399(32)	0.440(22)	0.525	0.591	−0.197	0.909
4.319	5^-	0.961(60)[c]	0.526(27)	3.584	0.517	2.656	0.353
4.804	3^-		0.525(27)	3.852	0.741	2.498	0.531
8.105	3^-	0.444(10)[d]	0.005(2)[e]				
8.420	5^-		0.461(23)	8.943	0.625	7.978	0.197

[a]From Ref. [7].
[b]B(GT) value from β-decay measurement [20].
[c]Unresolved doublet, E_x=4.32+4.80 MeV, approximately equal strength.
[d]Unresolved doublet, E_x=8.10+8.42 MeV, most strength in the 8.42-MeV transition.
[e]The proportionality between the cross section at 0° and B(GT) [see Eq. (2)] may not hold for this weak transition.

ported in the ^{10}B(p,n) reaction. With the help of kinematic calculations, this state was identified as a sharp but weak state on the right side of the 4.804 MeV state of ^{11}C. It was also found that the continuous yields above 10 MeV excitation energies originates from the ^{10}B isotope. The ^{11}B$(p,n)^{11}$C experiment shows two broad bump structures at E_x=12.5 and 15 MeV [7]. These structures, however, were overlapping with the continuous yield originating from the ^{10}B isotope.

In order to identify the states coming from carbon isotopes ^{12}C and ^{13}C (natural abundance 98.9% and 1.1%, respectively) and oxygen isotopes ^{16}O and ^{18}O (natural abundance 99.8% and 0.2%, respectively), a spectrum from a thin film of polyvinylalcohol (PVA) ($[C_2H_4O]_n$) was measured under the same condition as for the boron target. By a comparison of these spectra, the small peak at ≈15.4 MeV was identified as the g.s. of ^{12}N ($J^\pi=1^+$) originating from the reaction on ^{12}C in the carbon backing of the target. The g.s. and the 3.50 MeV states of ^{13}N are expected just on the right side of the g.s. of ^{11}C and at $E_x\approx 3.6$ MeV, respectively, but no evidence of any peak was observed. The g.s. and the 0.42 MeV states of ^{16}F originating from ^{16}O were observed at ≈13.4 and 13.9 MeV, respectively. It was also found that the small peak on the left side of the g.s. of ^{11}C was the g.s. of ^{18}F ($J^\pi=1^+$).

In order to derive B(GT) values from Eq. (2), a standard B(GT) value, preferably from a β-decay measurement, is needed. The only available β-decay measurement is for the g.s. to g.s. transition in this A=11 mirror system [20]. The transition, however, contains both GT and Fermi components, because the transition can be caused by both $\boldsymbol{\sigma\tau}$ and $\boldsymbol{\tau}$ operators. In order to extract the cross section for the GT component, we used the fact that the ratio of GT and Fermi unit cross sections denoted as R^2 [5] and defined by

$$R^2 = \frac{\hat{\sigma}_{\rm GT}(0\,°)}{\hat{\sigma}_{\rm F}(0\,°)} = \frac{\sigma_{\rm GT}(0\,°)}{B({\rm GT})} \Big/ \frac{\sigma_{\rm F}(0\,°)}{B({\rm F})} \qquad (3)$$

is only weakly dependent on the mass number A and can be deduced to be 5.1(7) for the A=11 nuclei by an interpolation from separately determined R^2 values of 4.7(7), 5.8(5), 6.6(4), and 10.5(5) for A=7, 18, 26, and 58 nuclei [11,23,24], respectively. In deriving these values, $B(F)=N-Z$ was assumed. The unit GT intensity for the 0° spectrum was calculated by using this R^2 value, the B(GT) value of 0.345(8) from the β-decay measurement [20], and B(F)=1 for the g.s. to g.s. transition. Here we use a unit system that gives a value of B(GT)=3 for the β decay of the free neutron. The B(GT) values for other excited states were calculated from their peak intensities, corrected for excitation energy using the results of distorted-wave Born approximation (DWBA) calculations and assuming the proportionality of Eq. (2) (for details, see Ref. [21]). The correction was small and only about 2% at 8.4 MeV. The deduced B(GT) values are listed in column 4 of Table I.

The B(GT) values from (p,n) experiments [7] are given in column 3 of Table I. These values agree within errors with the (^{3}H,t) values, but the total B(GT) value of 2.15 summed

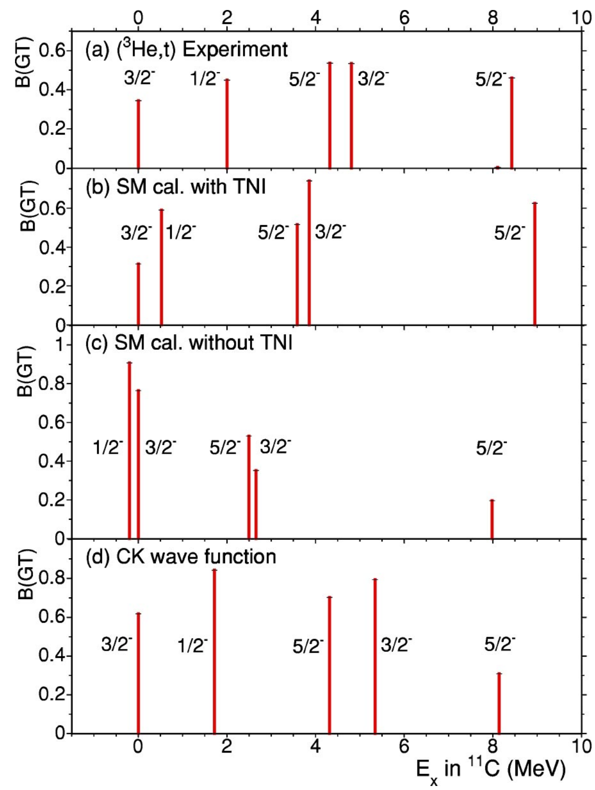

FIG. 2. (Color online) Experimental and shell-model B(GT) distributions. The J^π values of states are indicated. The B(GT) distributions are shown (a) for the present ^{11}B(^{3}He,t)^{11}C experiment, (b) for a NCSM calculation by Navrátil and Ormand including the TNI [1], (c) for a NCSM calculation without a TNI [1], and (d) for a shell-model calculation obtained by using the Cohen-Kurath interaction (from Ref. [7]). Note the change in size of the panels.

up to E_x=8.4 MeV was smaller by about 7% than the (^{3}H,t) value of 2.30.

The B(GT) values determined here are plotted in Fig. 2(a). The results from the NCSM calculations [1] are shown in Figs. 2(b) and 2(c) for the results with and without the TNI, respectively, and tabulated in Table I. In these calculations, the Argonne V8' nucleon-nucleon potential [25] and the Tucson-Melbourne TM'(99) TNI [26] were used. It is seen that the inclusion of the TNI significantly improves the agreement with the experimental results. The excitation energies as well as the strengths of five strongly excited states are reasonably reproduced. On the other hand, in the calculation without the TNI, the strengths are more or less shifted to the lower-lying states, and in addition the order of the g.s. and the first excited state is reversed. This suggests that it is essential to include the TNI in NCSM calculations. The total B(GT) value of 2.79 in the NCSM calculation with the TNI was larger than the experimental value of 2.30, but they differ by only 20%.

The effective interaction by Cohen-Kurath (CK) [27] is well accepted for the study of p-shell nuclei. The B(GT) distribution was studied in Ref. [7] using the CK interaction and the result is shown in Fig. 2(d). The agreement between the calculated and experimental excitation energies is excellent, and the relative strengths of four states below 6 MeV are in good agreement. However, the strengths of these states are about 60% larger than the experimental values. On the other hand, the $B(\mathrm{GT})$ value of the 8.1 MeV state, corresponding to the state at 8.420 MeV in the experiment, is about 30% smaller. As a result, the total calculated strength is about 40% larger than the experimental one. An improved shell-model interaction for *p*-shell nuclei has been proposed recently [28].

Compared to the other J^π allowed states ($1/2^-$, $3/2^-$, $5/2^-$ states) listed in Table I, the $B(\mathrm{GT})$ value of the $J^\pi=3/2^-$, 8.105 MeV state is surprisingly weak, as seen from Fig. 1(b). The strength is only about 1% of the others. Similarly, no indication is seen for the 9.650, $J^\pi=(3/2^-)$ state and the 9.780, $J^\pi=(5/2^-)$ state [20], although we should mention that our sensitivity for these states with the widths of about 200 keV [20] is not as high as for a sharp state, because the peak heights of these states are suppressed in our high-resolution measurement. One might consider that the strong reductions are due to an unknown selection rule. It is interesting to note that no appreciable GT transition strength to these weakly excited states is shown in any of the three shell-model calculations. This suggests a completely different structure for these states compared to the strongly excited other states.

In summary, we performed a high-resolution $^{11}\mathrm{B}(^3\mathrm{He},t)^{11}\mathrm{C}$ experiment at 0° and an intermediate incident energy of 140 MeV/nucleon for studying GT transitions. With a resolution of 45 keV, the two doublet states at ≈4.5 and ≈8.4 MeV were clearly resolved. Furthermore, the $B(\mathrm{GT})$ values were deduced for five major transitions. As a result, the one-to-one correspondence of GT transition strengths could be studied between the experiment and theoretical calculations. A comparison with calculations using the *ab initio* no-core shell model, which became recently available for the $A=11$ system, showed that the observed GT transition strengths were significantly better reproduced by including a realistic three-nucleon interaction. The total sum of the $B(\mathrm{GT})$ values was also reproduced with a difference of only 20% without introducing any quenching factor. Surprisingly weak transition strengths to the J^π allowed states at 8.105, 9.650, and 9.780 MeV were observed and need further study.

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