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High-resolution study of Gamow-Teller transitions in the $^{48}\text{Ti}(^3\text{He}, t)^{48}\text{V}$ reaction

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In this work we have studied $T_z = +2 \rightarrow +1$, Gamow-Teller (GT) transitions in the $^{48}\text{Ti}(^3\text{He}, t)^{48}\text{V}$ charge-exchange reaction at 140 MeV/nucleon and 0° at the Research Center for Nuclear Physics (RCNP), Osaka. Using the high resolution facility, consisting of a high dispersion beamline and the Grand Raiden spectrometer, the spectrum had an energy resolution of 21 keV, amongst the best achieved. Individual GT transitions were observed and GT strength was derived for each state populated up to an excitation energy of 12 MeV. The total sum of the $B(\text{GT})$ strength observed in discrete states was 4.0, which is 33% of the sum-rule-limit value of 12. The results were compared with the results of shell model calculations carried out with the GXPFIJ interaction. The measured $B(\text{GT})$ distribution was also compared with that obtained in the $(^3\text{He}, t)$ charge exchange reaction on ^{47}Ti . On the assumption of isospin symmetry the beta spectrum of the $T_z = -2$ nucleus ^{48}Fe was deduced from the observed spectrum in the $^{48}\text{Ti}(^3\text{He}, t)^{48}\text{V}$ reaction and this predicted spectrum was compared with the measured one.

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I. INTRODUCTION

The nucleus ^{48}V is located close to the middle of the $f_{7/2}$ shell. In the present work, we report the results of high resolution studies of the $^{48}\text{Ti}(^3\text{He}, t)^{48}\text{V}$ reaction

carried out at 140 MeV/nucleon. It is a part of systematic studies of $(^3\text{He}, t)$ reactions on the five stable titanium isotopes with masses $A = 46 - 50$. In turn this is part of a wider programme to examine how the Gamow-Teller (GT) strength distributions change as we move through the fp -shell in both N and Z .

Charge exchange (CE) reactions and β decay are complementary processes. The latter provides the most direct information on the Gamow-Teller (GT) transition strength, $B(\text{GT})$. The information obtained, however, is limited to transitions to states with excitation energies (E_x) in the daughter nucleus that are allowed by the β decay Q value. Moreover the feeding to higher excited states decreases rapidly because of the rapidly decreasing phase space factor. In CE reactions one can observe GT transitions to states at high excitation energies since there is no Q -value limitation (e.g., see Refs. [1–5]). In CE reactions at intermediate bombarding energies ~ 100 MeV/nucleon and forward angles close to 0° , there is a close proportionality for GT transitions between the dif-

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ferential cross-sections and the $B(\text{GT})$ values [6, 7],

$$\frac{d\sigma_{\text{GT}}}{d\Omega}(q, \omega) \simeq K(\omega) N_{\sigma\tau} |J_{\sigma\tau}(q)|^2 B(\text{GT}) \quad (1)$$

$$= \hat{\sigma}_{\text{GT}} F(q, \omega) B(\text{GT}), \quad (2)$$

where $J_{\sigma\tau}(q)$ is the volume integral of the effective interaction $V_{\sigma\tau}$, $K(\omega)$ is the kinematic factor, ω is the total energy transfer, and $N_{\sigma\tau}$ is a distortion factor. The value $\hat{\sigma}_{\text{GT}}$ is the “GT unit cross section” for a specific nuclear mass A at a given incoming energy and the value $F(q, \omega)$ gives the dependence of the GT cross-sections on the momentum and energy transfers. It has a value of unity at $q = \omega = 0$ and changes smoothly as a function of E_x . It can be reliably obtained from DWBA calculations.

In the 1980s, studies of (p, n) reactions at intermediate energies became possible and $B(\text{GT})$ distributions were studied for various nuclei [2]. It was found that broad resonance structures in GT strengths appear systematically at $E_x \approx 10$ MeV. In general these GT resonances (GTR) cannot be observed in beta decay because of the constraints imposed by the beta decay Q -value. Despite the success of these (p, n) reaction studies they were limited by the achievable energy resolutions, which were in excess of 300 keV. As a result it was difficult to resolve closely-lying, individual peaks in the spectra even if the level density was not very high. More recently this constraint was overcome by using other CE reactions such as the $(^3\text{He}, t)$ reaction at intermediate incident energies ≥ 100 MeV/nucleon [4]. Precise beam matching techniques [8] with the beamline and magnetic spectrometer system at the Research Center for Nuclear Physics (RCNP) [9], Osaka, routinely allow one to produce spectra with an energy resolution of ≤ 30 keV for incident beam energies of 140 MeV/nucleon at 0° . This allows one to observe discrete transitions to states not just at low excitation energies but also in the region of the GTR at ≈ 10 MeV [10–15].

The close proportionality given in Eq. (2) has been examined for the $(^3\text{He}, t)$ measurements by comparing the $B(\text{GT})$ values for analogous transitions in the CE reaction and the corresponding β decays of the mirror nuclei in the sd shell. In general, with some exceptions, the proportionality was good to within $\approx 5\%$ for transitions assigned $\Delta L = 0$ in studies of the mass $A = 23, 26, 27$ and 34 systems [4, 11–14]. These observations have now been followed by studies of the strengths of GT transitions in $(^3\text{He}, t)$ reactions on the $T_z = +1$, $f_{7/2}$ -shell nuclei ^{42}Ca , ^{46}Ti , ^{50}Cr and ^{54}Fe at RCNP, Osaka. The results were compared with the GT strengths measured in the beta decays of the equivalent $T_z = -1$ nuclei ^{42}Ti , ^{46}Cr , ^{50}Fe and ^{54}Ni [16]. The comparison of the $B(\text{GT})$ values obtained for the analogous GT transitions in CE and β decay in the $f_{7/2}$ -shell confirms the earlier observations that the proportionality in Eq. (2) holds for strong but not necessarily for weak transitions [17].

Recently these studies were extended to measurements of the GT transitions from the $T_z = +3/2$ nucleus ^{47}Ti to states in the $T_z = +1/2$ nucleus ^{47}V [15]. Here we

report on a further extension to measurements of the $(^3\text{He}, t)$ reaction on the $T_z = +2$ nucleus ^{48}Ti leading to states in $T_z = +1$ ^{48}V . The results obtained are compared with similar measurement for $^{47}\text{Ti}(^3\text{He}, t)^{47}\text{V}$ and with the results of shell model calculations.

II. EXPERIMENT

The $^{48}\text{Ti}(^3\text{He}, t)^{48}\text{V}$ reaction has been studied at RCNP, Osaka with the high resolution facility and a high quality beam of 140 MeV/nucleon from the K = 400 ring cyclotron [9]. This facility combines a high-dispersion beamline WS-course [18] with the Grand Raiden spectrometer [19]. The ^3He beam was stopped in a Faraday cup placed inside the first dipole magnet. The self-supporting ^{48}Ti target that was used has an enrichment of 99.1% and an areal density of 0.85 mg/cm². The beam current was typically 21 pA and the spectra were recorded over a period of an hour. The outgoing tritons were momentum analysed within the full acceptance of the spectrometer and detected at the focal plane with a system consisting of two multiwire drift chambers (MWDCs) that allow track reconstruction [20] and two plastic scintillators used both for the creation of triggers to start the data acquisition system and particle identification. The use of matching techniques [8] and the *faint beam method* [21, 22] resulted in a measured energy resolution of 21 keV. This meant that we were able to resolve individual states in ^{48}V up to $E_x = 12.5$ MeV. Figure 1-a shows the 0° spectrum from the ^{48}Ti target with scattering angles $\Theta \leq 0.5^\circ$, where Θ is defined by $\Theta_{\text{lab}} = \arctan \sqrt{\tan^2 \theta + \tan^2 \phi}$ at angles near 0° and (θ) and (ϕ) are the scattering angles in the x and y directions. It is important to determine the scattering angle Θ accurately near 0° , hence it is necessary to measure (θ) and (ϕ) equally well. Good θ resolution was achieved by using the *angular dispersion matching* technique [8], while good ϕ resolution was achieved by applying the *over-focus mode* of the Grand Raiden spectrometer [23]. A more detailed description of the experimental procedure can be found in Ref. [24].

The details of the spectrum can be seen better in Fig. 1(b) where the same spectrum is shown on an expanded scale. Here one can see the continuous background from quasi free scattering beginning at about the proton separation energy, $S_p \approx 6.83$ MeV [25].

III. DATA ANALYSIS

A peak decomposition program SFIT [26] was used to determine the positions of the peaks and the number of counts they contained. In order to obtain the peak positions the shape of a well-defined isolated peak at 2.288 MeV was used as a reference and particular attention was paid to the tail of the peak to get a reliable response function.

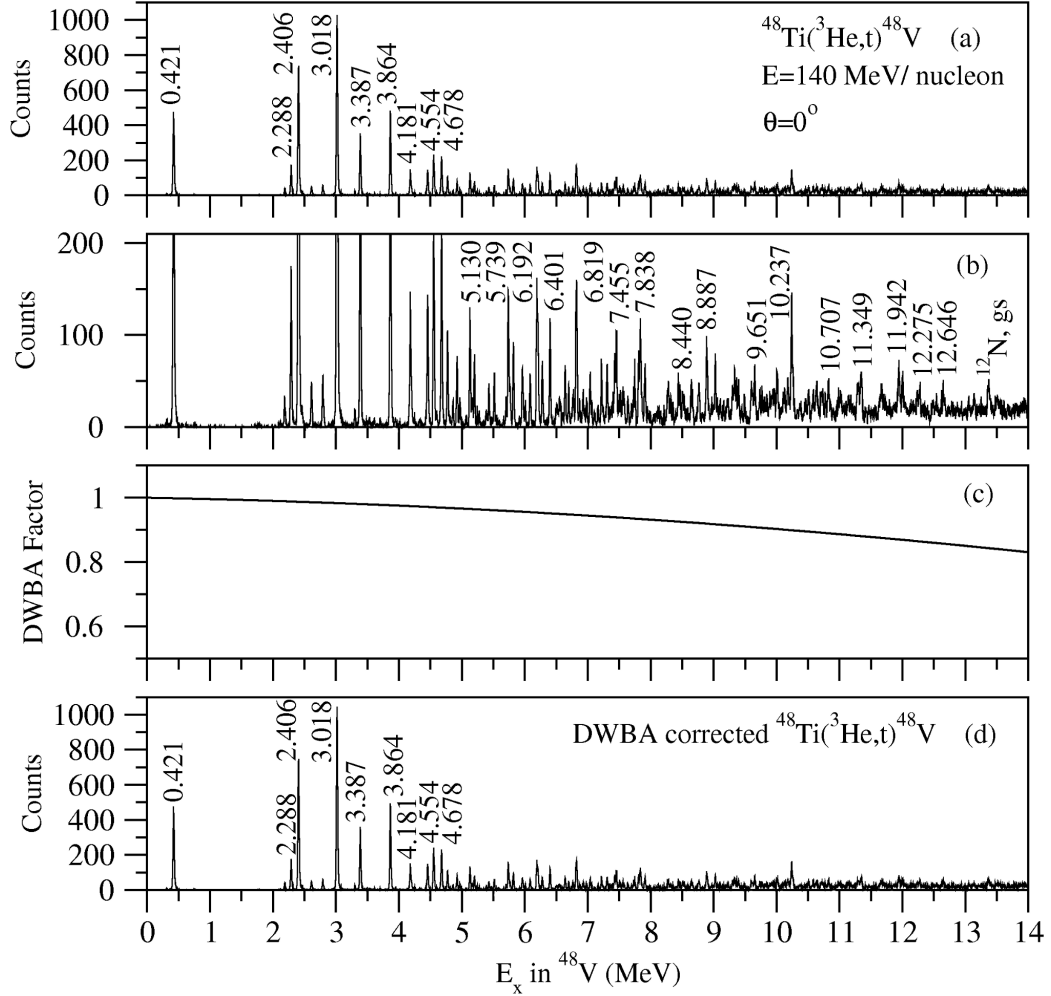


FIG. 1: a) The $^{48}\text{Ti}(^3\text{He}, t)^{48}\text{V}$ spectrum at 0° . Events with scattering angles $\Theta \leq 0.5^\circ$ are included. States prominently populated by $\Delta L = 0$ transitions are indicated by their excitation energies. b) The same spectrum is shown with the scale on the y axis expanded by a factor of ≈ 4.5 . c) The correction factor for the gradual decrease in $F(q, \omega)$ calculated using the results of DWBA calculations (see Section III) as a function of energy. d) The spectrum shown in panel a) corrected for the results of the DWBA calculations shown in panel c).

From the peak positions obtained, the E_x values of states in the higher excitation energy region were determined using the well known E_x values of states in ^{12}N , ^{13}N and ^{16}F as references using kinematical calculations. The states were observed in a spectrum from a thin Mylar target with an areal density of $\approx 1 \text{ mg/cm}^2$. The measurement was performed under the same conditions used with the ^{48}Ti target. The E_x values of the ^{48}V states could be determined by an interpolation process and they are listed in Tables I-IV. Prior to the present work the E_x values of only a few states were known [25] in ^{48}V . All of these states lie below 3.3 MeV and they are shown in Table I. In the present work most of these E_x values could be reproduced within a few keV. In addition the E_x value of the ^{12}N ground state (g.s), which appeared at $\approx 13.4 \text{ MeV}$ in the ^{48}V spectrum was reproduced with an error of 5 keV. Therefore, even if we take the uncertainty of the peak decomposition process into account, we estimate that the E_x values of the states listed in Ta-

bles I-IV have an accuracy better than 10 keV up to the region around 12 MeV. Due to the high isotopic abundance (99.1%) of ^{48}V in the target, peaks from other Ti isotopes were weak in our spectrum. Above the 12 MeV region, due to the high level density, the separation of peaks was difficult, even with the experimental energy resolution of 21 keV.

A continuous background was observed above the proton separation energy $S_p \approx 6.83 \text{ MeV}$. It increased with increasing excitation energy but it was essentially saturated at $E_x \approx 11.5 \text{ MeV}$. Accordingly, a smooth background was subtracted empirically in the peak fit analysis. In order to identify $\Delta L = 0$ transitions, the relative intensities of the peaks in the angle cuts $\theta = 0^\circ - 0.5^\circ$, $0.5^\circ - 0.8^\circ$, $0.8^\circ - 1.2^\circ$, $1.2^\circ - 1.6^\circ$, and $1.6^\circ - 2.0^\circ$ were examined. Figure 2 shows examples of the angular distributions, normalized to the counts at 0° , for some of the stronger transitions leading to states at low E_x . The transition to the state at 2.406 MeV was used as a stan-

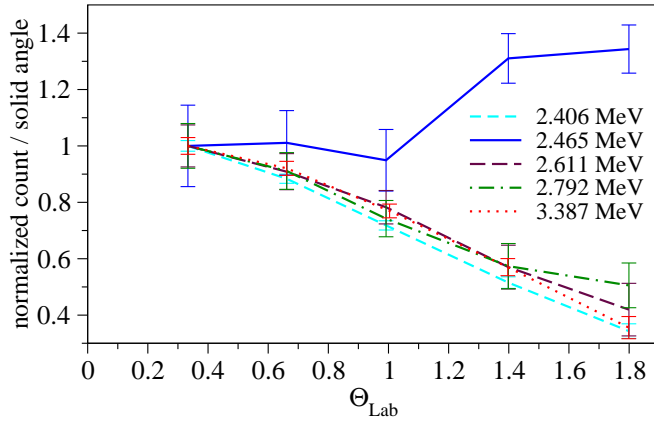


FIG. 2: (Color online) Angular distributions for selected transitions. They are labelled by the excitation energy of the level populated in the CE reaction. In this figure we have chosen a few weak transitions to show the power of the method to identify $\Delta L = 0$ transitions (see text). The counts at each angle are normalised to unity at $\Theta = 0^\circ - 0.5^\circ$ degrees.

dard $\Delta L = 0$ transition since the state populated has spin and parity 1^+ . With the exception of the transition to the 2.465 MeV state it is clear that there is no clear enhancement at the larger scattering angles. This confirms that all of the other transitions in the $0^\circ - 0.5^\circ$ degree cut shown in Fig. 2 have $\Delta L = 0$ character. More generally, in the low-lying region of excitation energy, where the transitions and the states are fairly well separated, the ΔL values were well determined. The comparison of the angular distributions of all of the transitions in Fig. 1 indicate that most of the strong transitions have $\Delta L = 0$ character. This is indicated in Tables I-IV. However, at higher excitation energies, where the level density is high, the determination of the ΔL values became difficult. A clear enhancement at larger angles was observed for some of the weaker transitions. This identifies them as having $\Delta L \geq 1$. When the determination is uncertain, the states are assigned $\Delta L = 0$ in brackets in the tables. Where the transitions have been assigned $\Delta L = 0$ character, we assume that they are GT transitions, except for the transition to the IAS [4]. For the details of the analysis of the angular distributions, see Ref [27, 28].

Transitions to individual states were observed up to 12.67 MeV in the $^{48}\text{Ti}(^3\text{He}, t)$ reaction. The relative $B(\text{GT})$ values for these transitions were derived by applying the proportionality given by Eq. (2) to the measured intensity of each peak. The gradual decrease in $F(q, \omega)$ as a function of excitation energy was corrected by using the results of Distorted Wave Born Approximation (DWBA) calculations. For this purpose, the DW81 code [29] was used where it was assumed that the transitions were between the $\nu f_{7/2} \rightarrow \pi f_{7/2}$ and $\nu f_{7/2} \rightarrow \pi f_{5/2}$ configurations. In the calculations we followed the procedure described in Refs. [30–32].

The optical potential parameters were taken from Ref. [33]. The DWBA calculation indicated that the GT

cross-section decreases with increasing excitation energy, and the decrease was $\approx 7\%$ from the g.s to $E_x = 8$ MeV.

In order to obtain absolute $B(\text{GT})$ values, we used the R^2 value defined by the ratio of the GT and Fermi unit cross-sections

$$R^2 = \frac{\hat{\sigma}_{\text{GT}}(0^\circ)}{\hat{\sigma}_{\text{F}}(0^\circ)} = \frac{\sigma_{\text{GT}}(0^\circ)}{B(\text{GT})} / \frac{\sigma_{\text{F}}(0^\circ)}{B(\text{F})}. \quad (3)$$

If the R^2 value is known for a mass A system, the $B(\text{GT})$ value of the transition to a given state can be deduced from the DWBA corrected 0° cross-sections of the state and the IAS where we assume that all of the Fermi transition strength is concentrated in the transition to the IAS at 3.018 MeV and that it takes the value of $B(\text{F}) = N - Z = 4$, the complete sum rule value. In addition we assume that R^2 is a smooth function of A . The A dependence of R^2 has been systematically studied and a smooth increase in R^2 was observed with increasing A [34, 35]. A value of $R^2 = 8.2(4)$ can be deduced for the $A = 48$ nuclei by quadratically interpolating the experimental R^2 values obtained for $A = 26$ [12], 34 [14], 46 [36], 54 [24], 64 [37], 78 [38], 118, and 120 [39]. The $B(\text{GT})$ values were derived for all states assigned to have $\Delta L=0$ and they are listed in Tables I-IV.

The $B(\text{GT})$ values of weakly excited states with $0.005 < B(\text{GT}) < 0.01$ are marked by the sign “S” and those with $B(\text{GT}) \leq 0.005$ as “SS” in Tables I-IV.

The uncertainties in the $B(\text{GT})$ values given in Tables I-IV include the statistical uncertainties in the experimental data, the quality of the peak-fit analysis, and also the uncertainty in R^2 . However, the uncertainties associated with the background subtraction were not included. Therefore, the $B(\text{GT})$ values of the transitions to the states in the region at higher energy, where the background counts were larger, can have larger uncertainties.

For the states assigned to have $\Delta L \geq 1$, counts in $\Theta \leq 0.5^\circ$ are listed to show the intensities.

IV. RESULTS AND DISCUSSION

A. $B(\text{GT})$ distribution in ^{48}V

The $B(\text{GT})$ distribution obtained for the $^{48}\text{Ti}(^3\text{He}, t)^{48}\text{V}$ reaction is shown in Fig. 3(a). Note that the $B(\text{GT})$ distribution is shown up to 12 MeV in the figures although the states in Table IV are listed up to 12.7 MeV.

The $B(\text{GT})$ distribution shows that the GT strength is highly fragmented and distributed over many discrete states. However, no compact structure corresponding to the GT resonance (GTR) was observed.

Shell Model (SM) calculations were performed using the GXPF1J interaction [40, 41]. The model space was restricted to the pf -shell and an inert ^{40}Ca core was assumed. The theoretical $B(\text{GT})$ values for this reaction include the average normalisation factor (the so-called “quenching factor”) of $(0.74)^2$ [42]. The results of the

TABLE I: States observed in the $^{48}\text{Ti}(^3\text{He}, t)^{48}\text{V}$ reaction up to $E_x = 6.5$ MeV. The $B(\text{GT})$ values for weakly populated states with $\Delta L = 0$ are listed in two categories marked by S and SS, where S indicates $0.005 < B(\text{GT}) < 0.01$ and SS indicates $B(\text{GT}) \leq 0.005$. For these states the numbers of counts observed in the $\Theta \leq 0.5^\circ$ spectrum are listed.

Evaluated values ^a		$(^3\text{He}, t)^b$			
E_x^c (MeV)	J^π	E_x (MeV)	ΔL	Counts	$B(\text{GT})^d$
0.421	1^+	0.421	0	3410 (81)	0.224 (13)
		2.186	0	197 (19)	0.013 (1)
2.289	1^+	2.288	0	1140 (47)	0.076 (5)
2.408 (7)	1^+	2.406	0	5260 (100)	0.351 (19)
		2.465	≥ 1	137 (20)	
		2.611	0	333 (25)	0.022 (2)
		2.792	0	356 (28)	0.024 (2)
3.019	$(0)^+$	3.018 ^e	0	7260 (117)	
		3.387	0	2180 (65)	0.147 (9)
3.866	1^+	3.864	0	3140 (76)	0.213 (12)
		3.945	0	64 (12)	SS
		4.181	0	821 (59)	0.056 (5)
		4.201	(0)	201 (43)	0.014 (3)
		4.245	0	53 (11)	SS
		4.456	0	1030 (44)	0.070 (5)
		4.554	0	1480 (52)	0.101 (6)
		4.595	0	80 (14)	SS
		4.678	0	1560 (55)	0.107 (7)
		4.773	0	694 (36)	0.048 (3)
		4.857	0	172 (18)	0.012 (1)
		4.924	0	471 (30)	0.032 (3)
		4.971	0	195 (20)	0.013 (2)
		5.067	0	64 (12)	SS
		5.130	0	830 (42)	0.057 (4)
		5.164	0	166 (27)	0.011 (2)
		5.199	0	436 (31)	0.030 (3)
		5.246	(0)	61 (15)	SS
		5.277	0	80 (15)	S
		5.388	0	117 (16)	S
		5.430	0	273 (24)	0.019 (2)
		5.477	≥ 1	43 (12)	
		5.516	≥ 1	312 (24)	
		5.567	0	50 (11)	SS
		5.702	0	125 (20)	S
		5.739	0	956 (52)	0.067 (5)
		5.766	0	226 (33)	0.016 (2)
		5.820	0	597 (33)	0.042 (3)
		5.913	≥ 1	54 (11)	
		5.965	0	474 (31)	0.033 (3)
		6.005	0	125 (16)	S
		6.085	≥ 1	387 (27)	
		6.192	0	911 (80)	0.064 (7)
		6.208	0	574 (70)	0.040 (5)
		6.280	0	456 (29)	0.032 (3)
		6.401	0	847 (40)	0.060 (4)
		6.464	0	45 (11)	SS
		6.501	0	134 (50)	S
		6.516	(0)	114 (49)	S
		6.548	0	192 (39)	0.014 (3)
		6.568	(0)	127 (32)	S

^aTaken from the compilation in Ref. [25].

^bPresent work.

^cEnergy uncertainties of < 1 keV are not indicated.

^dFrom R^2 evaluation.

^eThe IAS.

TABLE II: States observed in the $^{48}\text{Ti}(^3\text{He}, t)^{48}\text{V}$ reaction between $E_x = 6.5$ and 8.5 MeV. For details, see the caption to Table I.

$(^3\text{He}, t)^a$			
E_x (MeV)	ΔL	Counts	$B(\text{GT})$
6.603	(0)	79 (16)	S
6.641	0	438 (29)	0.031 (3)
6.697	0	305 (25)	0.022 (2)
6.748	≥ 1	81 (40)	
6.770	0	248 (42)	0.018 (3)
6.819	0	1310 (52)	0.093 (6)
6.874	0	169 (21)	0.012 (2)
6.924	0	263 (28)	0.019 (2)
6.950	0	73 (21)	SS
6.982	0	195 (23)	0.014 (2)
7.038	0	347 (32)	0.025 (3)
7.061	0	98 (21)	S
7.106	0	101 (16)	S
7.163	0	131 (18)	S
7.219	0	420 (33)	0.030 (3)
7.247	≥ 1	72 (20)	
7.308	0	458 (32)	0.033 (3)
7.350	(≥ 1)	85 (27)	
7.374	0	99 (37)	S
7.398	0	149 (37)	0.011 (3)
7.428	0	435 (45)	0.031 (4)
7.455	0	696 (46)	0.050 (4)
7.496	0	144 (32)	0.010 (2)
7.520	0	214 (30)	0.015 (2)
7.558	0	241 (35)	0.017 (3)
7.580	0	155 (30)	0.011 (2)
7.639	0	207 (22)	0.015 (2)
7.693	0	117 (21)	S
7.728	0	203 (44)	0.015 (3)
7.749	0	260 (44)	0.019 (3)
7.810	0	514 (43)	0.037 (4)
7.838	0	727 (66)	0.052 (5)
7.862	≥ 1	85 (40)	
7.909	0	475 (34)	0.034 (3)
7.955	(≥ 1)	100 (19)	
7.990	(0)	77 (16)	S
8.049	0	65 (16)	SS
8.086	0	85 (19)	S
8.119	(0)	132 (22)	0.010 (2)
8.161	0	72 (16)	SS
8.216	(0)	80 (16)	S
8.262	0	137 (47)	0.010 (3)
8.279	0	297 (49)	0.022 (4)
8.316	0	176 (25)	0.013 (2)
8.353	0	99 (19)	S
8.401	(0)	82 (18)	S
8.440	0	317 (37)	0.023 (3)
8.465	0	188 (33)	0.014 (2)
8.505	0	211 (32)	0.015 (2)
8.530	(0)	189 (31)	0.014 (2)
8.572	(0)	91 (21)	S
8.600	(0)	55 (19)	SS

^aPresent work.

TABLE III: States observed in the $^{48}\text{Ti}(^3\text{He}, t)^{48}\text{V}$ reaction between $E_x = 8.5$ and 10.5 MeV. For details, see the caption to Table I.

$(^3\text{He}, t)^a$			
E_x (MeV)	ΔL	Counts	$B(\text{GT})$
8.645	0	304 (42)	0.022 (3)
8.666	(0)	129 (35)	S
8.744	(0)	106 (29)	S
8.767	0	312 (36)	0.023 (3)
8.821	≥ 1	73 (17)	
8.887	0	543 (80)	0.040 (6)
8.904	(0)	227 (73)	0.017 (5)
8.967	0	142 (26)	0.010 (2)
8.998	(0)	120 (29)	S
9.027	0	429 (37)	0.032 (3)
9.061	0	132 (24)	0.010 (2)
9.105	0	171 (24)	0.013 (2)
9.157	(0)	111 (58)	S
9.198	(0)	74 (36)	S
9.220	0	115 (73)	S
9.232	0	103 (63)	S
9.268	(≥ 1)	52 (19)	
9.301	0	287 (34)	0.021 (3)
9.333	0	378 (39)	0.028 (3)
9.362	≥ 1	261 (34)	
9.397	0	286 (30)	0.021 (3)
9.446	0	98 (20)	S
9.492	0	183 (21)	0.014 (2)
9.606	0	340 (32)	0.025 (3)
9.651	(0)	440 (34)	0.033 (3)
9.699	≥ 1	52 (18)	
9.732	0	223 (27)	0.017 (2)
9.770	0	212 (28)	0.016 (2)
9.808	0	149 (26)	0.011 (2)
9.846	0	188 (25)	0.014 (2)
9.891	0	200 (27)	0.015 (2)
9.930	0	244 (32)	0.018 (3)
9.962	0	252 (31)	0.019 (3)
10.008	0	431 (38)	0.033 (3)
10.038	≥ 1	64 (22)	
10.073	(0)	86 (21)	S
10.107	0	183 (33)	0.014 (3)
10.133	0	222 (35)	0.017 (3)
10.179	≥ 1	366 (33)	
10.237	0	834 (56)	0.063 (5)
10.258	(0)	287 (48)	0.022 (4)
10.286	≥ 1	58 (25)	
10.334	0	91 (21)	S
10.373	0	136 (24)	0.010 (2)
10.446	(0)	91 (31)	S
10.470	0	129 (32)	0.010 (2)
10.509	0	227 (28)	0.017 (2)
10.564	0	108 (36)	S
10.585	0	198 (39)	0.015 (3)
10.626	0	252 (39)	0.019 (3)
10.653	≥ 1	140 (35)	
10.707	0	238 (33)	0.018 (3)

^aPresent work.

TABLE IV: States observed in the $^{48}\text{Ti}(^3\text{He}, t)^{48}\text{V}$ reaction between $E_x = 10.5$ and 12.0 MeV. For details, see the caption to Table I.

$(^3\text{He}, t)^a$			
E_x (MeV)	ΔL	Counts	$B(\text{GT})$
10.735	0	183 (31)	0.014 (3)
10.777	0	156 (25)	0.012 (2)
10.823	0	293 (33)	0.023 (3)
10.856	≥ 1	117 (26)	
10.901	≥ 1	61 (19)	
10.955	≥ 1	77 (20)	
10.984	(0)	171 (29)	0.013 (2)
11.017	0	215 (29)	0.017 (2)
11.061	(0)	103 (23)	S
11.102	(0)	97 (23)	S
11.139	0	177 (28)	0.014 (2)
11.174	0	161 (27)	0.013 (2)
11.207	≥ 1	94 (23)	
11.280	(0)	206 (37)	0.016 (3)
11.302	0	238 (41)	0.019 (3)
11.335	0	198 (69)	0.015 (5)
11.349	0	297 (65)	0.023 (5)
11.419	≥ 1	65 (20)	
11.466	≥ 1	79 (21)	
11.512	≥ 1	57 (20)	
11.565	≥ 1	58 (20)	
11.636	0	151 (28)	0.012 (2)
11.669	0	258 (33)	0.020 (3)
11.707	≥ 1	143 (26)	
11.768	≥ 1	72 (25)	
11.794	≥ 1	72 (24)	
11.858	≥ 1	78 (25)	
11.883	≥ 1	62 (27)	
11.942	0	684 (70)	0.054 (6)
11.991	(0)	136 (56)	0.011 (4)
12.008	(0)	216 (55)	0.017 (4)
12.046	(0)	107 (25)	S
12.133	(0)	93 (24)	S
12.169	(0)	101 (24)	S
12.233	(0)	226 (30)	0.018 (3)
12.275	0	254 (30)	0.020 (3)
12.321	≥ 1	53 (24)	
12.346	0	63 (24)	SS
12.398	(0)	54 (21)	SS
12.482	0	121 (26)	0.010 (2)
12.538	0	106 (32)	S
12.618	≥ 1	102 (31)	
12.646	(0)	220 (41)	0.018 (3)
12.675	≥ 1	90 (29)	

^aPresent work.

SM calculations are shown in Fig. 3(b). They are in reasonable agreement with the observed $B(\text{GT})$ strength in the region up to ~ 5 MeV. Moreover, the building up of the GTR can be seen around 9 MeV.

The difference between the measured and calculated strengths is clearly seen in Fig. 4 where the accumulated $B(\text{GT})$ strength is plotted as a function of excitation energy in ^{48}V up to 12 MeV. As mentioned above up to ~ 5

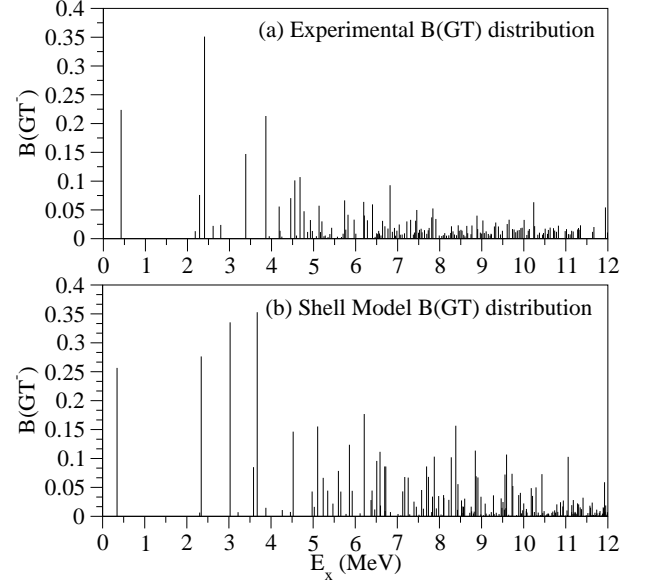


FIG. 3: A comparison of a) the measured $B(\text{GT})$ strength distribution and b) Shell model calculations with the GXPF1J interaction of the $B(\text{GT})$ strength distribution for the $^{48}\text{Ti}(^3\text{He}, t)^{48}\text{V}$ reaction (see text).

MeV they are in reasonable agreement. From ~ 5 MeV the SM predicts greater strength than is observed.

In both experiment and the SM, there is a jump in the accumulated $B(\text{GT})$ strength just above 2 MeV. Below this energy, the states expected are essentially due to the coupling of the odd neutron and proton in the $f_{7/2}$ orbitals.

B. Comparison of the $B(\text{GT})$ distributions in ^{47}V and ^{48}V

It is interesting to compare the $B(\text{GT})$ distribution from the $^{48}\text{Ti}(^3\text{He}, t)^{48}\text{V}$ reaction with that observed in the $^{47}\text{Ti}(^3\text{He}, t)^{47}\text{V}$ reaction [15]. Figure 4 shows the accumulated strengths as a function of excitation energy for the two reactions from both experiment and the SM. Comparing the $A=47$ and $A=48$ cases we see very similar behaviour. The main difference is that the jump in the accumulated $B(\text{GT})$, seen both in theory and experiment, is delayed in energy by ≈ 2 MeV in the case of the odd nucleus ^{47}V . This can be explained in terms of the diagrams shown in Figs. 5(a), 5(b) and 5(c), where we are concerned with the particles and interactions between them in ^{47}V and ^{48}V . In the case of ^{48}Ti , we start with even numbers of protons and neutrons. In a GT transition one of the neutrons in a pair in the $f_{7/2}$ orbital is transformed into a proton in the ^{48}V final nucleus, hence we populate proton-neutron excitations which are the lowest possible excitations in the odd-odd nucleus ^{48}V .

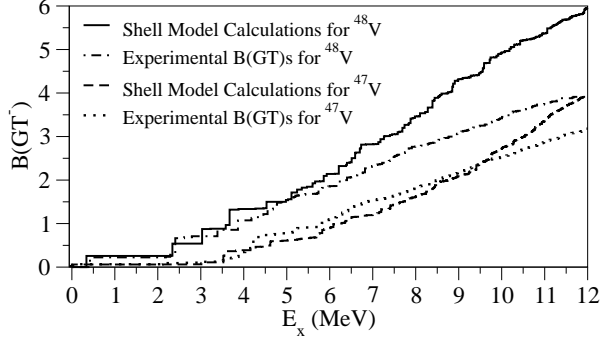


FIG. 4: A comparison of the accumulated experimental and theoretical (Shell Model) $B(GT)$ distributions for both the $^{48}\text{Ti}(^3\text{He}, t)^{48}\text{V}$ reaction measured in the present work and the $^{47}\text{Ti}(^3\text{He}, t)^{47}\text{V}$ reaction measured earlier [15].

There are two possibilities for such GT transitions, Fig. 5(c): i) $\nu f_{7/2} \rightarrow \pi f_{7/2}$ which should populate states lying at low energy and ii) $\nu f_{7/2} \rightarrow \pi f_{5/2}$, which should populate states in ^{48}V at higher energy. Let us now turn to the $A=47$ case. Initially we have a valence neutron in the $\nu f_{7/2}$ orbital in ^{47}Ti . This neutron can proceed by GT transition to the $\pi f_{7/2}$ orbital, which should populate a level at very low energy close to the g.s., or to the $\pi f_{5/2}$ orbital and populate a state at higher excitation energy. Additionally in the ^{47}V case, if we think of GT transitions involving a neutron from the $(\nu f_{7/2})^2$ pair, we have to break the pair first which typically costs ≈ 2 MeV and in the same way as in the $A=48$ case the GT transitions lead us to the transformation of one of the neutrons from the pair into the proton in the $\pi f_{7/2}$ or the $\pi f_{5/2}$ orbitals, see Fig. 5(b). The states populated in the second case should be similar to those in the $A=48$ case adding the extra odd neutron in ^{47}V but shifted the pairing energy of ≈ 2 MeV, which is what we see in Fig. 4. Since in the ^{47}V case there are 4 paired neutrons and one odd neutron and in the ^{48}V case there are 6 paired neutrons, the accumulated strength of ^{47}V up to 12 MeV should be similar to the accumulated strength in ^{48}V up to 10 MeV, to take into account the energy shift, corrected by the number of neutron pairs and the odd neutron in the $f_{7/2}$ orbital, namely $3.5 \times 5/6 = 2.9$ which is close to the value of 3.2 observed (See Fig. 4). In order to verify if this effect is reproduced by the calculations, we have shifted the energy of the shell model calculations for $^{48}\text{Ti} \rightarrow ^{48}\text{V}$ by 2 MeV, scaled by a factor of $5/6=0.833$ and compared with Shell Model calculations for $^{47}\text{Ti} \rightarrow ^{47}\text{V}$. The result is shown in Fig. 6(a). In the same way we have shifted the experimental accumulated strength distribution, scaled by 0.833 and by 2 MeV and compared it with the ^{47}V distribution in Fig. 6(b). The agreement is remarkable in both cases, which gives us some confidence in our interpretation.

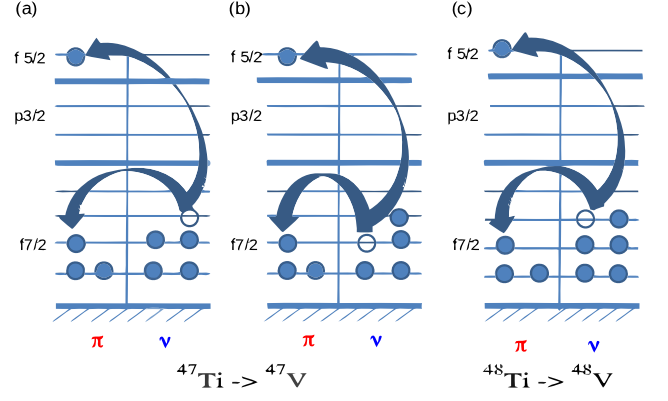


FIG. 5: (Color online) A schematic picture of the transitions involved in the CE reactions on ^{47}Ti and ^{48}Ti . Full circles represent the particles in the final nucleus above $N=20$ and $Z=20$. Empty circles show the original position of the neutron before it is transformed into a proton. It provides a simple explanation of the differences in the accumulated $B(GT)$ distributions seen in Fig.4(see text).

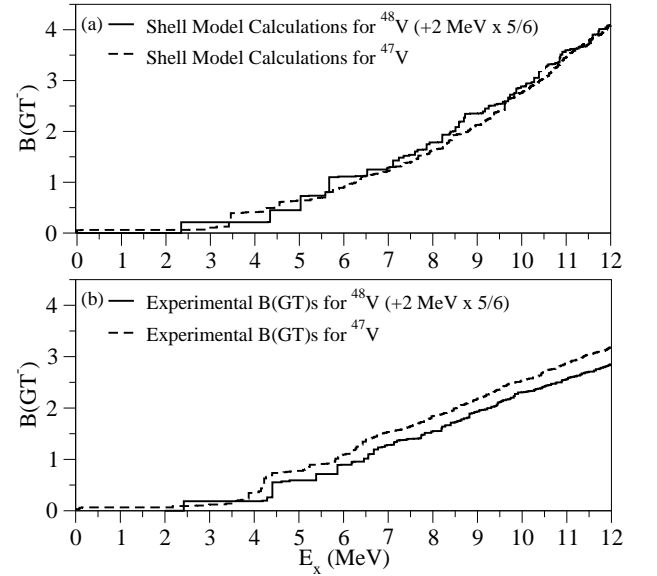


FIG. 6: (a) A comparison of the accumulated theoretical (Shell Model) $B(GT)$ distributions for ^{47}V and ^{48}V shifted by 2 MeV and scaled by a factor of $5/6=0.833$. (b) A comparison of the accumulated experimental $B(GT)$ distributions for ^{47}V and ^{48}V obtained in the same way as in (a).

C. Total $B(GT)$ strength

The total sum of the $B(GT)$ strength observed in the discrete states in ^{48}V up to 12 MeV was 4.0. We suggest that this $B(GT)$ value is the minimum of the total sum in the entire region up to 12 MeV due to background ambiguities (see discussion below). One can see that this value is only 33% of the sum-rule-limit value of $3(N-Z)$ even if the negative contribution from the GT strengths

in the β^+ direction is ignored. It should be noted that the SM predicts the sum of the $B(\text{GT})$ strength to be 5.95 up to 12 MeV.

The continuum from quasifree scattering (QFS) [43, 44] is expected to be observed above the proton separation energy of $S_p = 6.83$ MeV. Since there is no theory for reliably calculating the cross section of the QFS continuum, a background described by a smooth line was subtracted in our analysis, as mentioned earlier. Under the extreme assumption that the background counts are all due to GT transitions, this would add a value of 0.67 to the summed $B(\text{GT})$ value in the region up to 12 MeV. Therefore, our results show that the total sum of the $B(\text{GT})$ located in the energy region from 0 to 12 MeV is $\approx 33\%$, but can never be larger than 39% of the sum-rule-limit value.

D. The Mirror Beta Decay

In principle one can normalise the measured $B(\text{GT})$ values from CE using the measured $B(\text{GT})$ values from the complementary β decay of the mirror nucleus assuming isospin symmetry. In the present case this is not possible because too little is known of the decay of the $T_z = -2$ mirror nucleus ^{48}Fe . However we can use our measured relative $B(\text{GT})$ values in the $^{48}\text{Ti}(^3\text{He}, t)^{48}\text{V}$ CE reaction, normalized using R^2 as explained in Section III, to predict the β decay spectrum of $^{48}\text{Fe} \rightarrow ^{48}\text{Mn}$, on the assumption of isospin symmetry, which would mean that $T_z = \pm 2 \rightarrow \pm 1$ mirror GT transitions have the same values of $B(\text{GT})$. Firstly, the phase space (f) factor of β decay [45] for each transition was calculated using the Q_β [46] of the ^{48}Fe β decay and the $^{48}\text{Ti}(^3\text{He}, t)^{48}\text{V}$ spectrum was multiplied by the f factor. Since the f factor is proportional to $(Q_\beta - E_x)^5$ [47] it decreases rapidly with E_x as shown in Fig. 7(b). In the ^{48}V nucleus the 3.018 MeV state is the IAS populated with the strength $B(F)=4$ by a Fermi transition. The coupling constants for Fermi and GT transitions (governed by σ and $\sigma\tau$ operators respectively) are different in the $^{48}\text{Ti}(^3\text{He}, t)^{48}\text{V}$ reaction and ^{48}Fe β decay. Thus in predicting the β -decay spectrum the intensity of the IAS peak in the Fig 7(c) has to be increased by a factor of R^2/λ^2 , that is ≈ 5.1 . Here λ is the ratio between the axial-vector coupling constant and the vector coupling constant, $g_A/g_V = -1.270(3)$ [48]. Figure 7(d) shows the resulting β decay spectrum expected to be observed in ^{48}Fe β decay. A detailed explanation of this procedure is given in Ref. [49]. This spectrum has recently been measured at LISE-GANIL [50]. It turns out that the measured spectrum is similar to that predicted in Fig 7(d) but there are some discrepancies. In particular the 3864 keV 1^+ state populated in the CE experiment appears to correspond to three separate states when seen in β decay. The reasons for the differences are not yet understood and will be the subject of further study. The states corresponding to those at 2288 and 2406 keV ly-

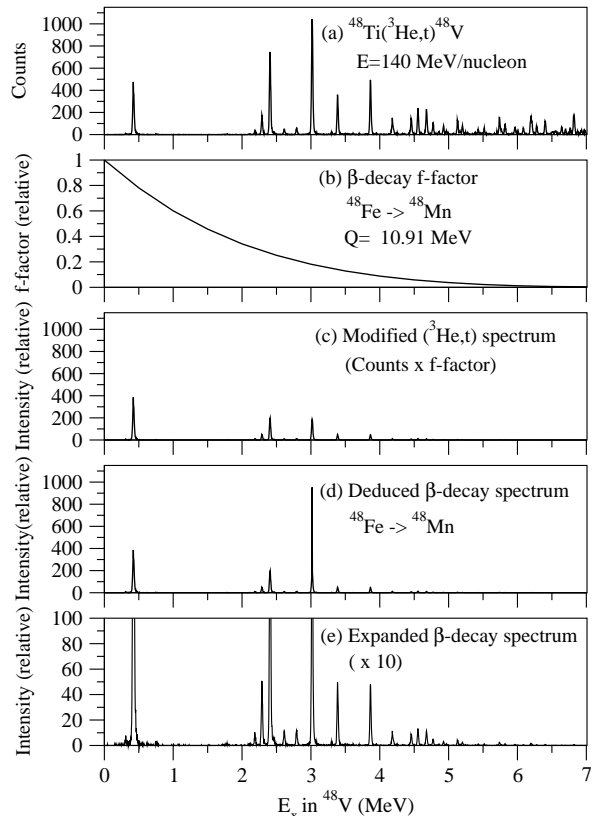


FIG. 7: Color online) (a) $^{48}\text{Ti}(^3\text{He}, t)^{48}\text{V}$ DWBA corrected spectrum up to 7 MeV for $\Theta \leq 0.5^\circ$, (b) The f-factor for the ^{48}Fe β decay normalized to unity at $E_x = 0$ MeV. (c) The modified $^{48}\text{Ti}(^3\text{He}, t)^{48}\text{V}$ spectrum obtained by multiplying the spectrum in panel (a) with the f-factor in panel (b), (d) The deduced β -decay spectrum ^{48}Mn after correcting for the IAS strength (see text) and (e) The same spectrum is shown on an expanded scale expanded by a factor of 10.

ing below the IAS and populated in the CE reaction were not seen in the β decay of ^{48}Fe , presumably because of the background of beta particles at lower energy in the spectrum.

V. SUMMARY

The $T_z = +2 \rightarrow +1$, GT transitions were studied in the $^{48}\text{Ti}(^3\text{He}, t)^{48}\text{V}$ reaction at the intermediate beam energy of 140 MeV/nucleon and 0° scattering angle. An energy resolution of 21 keV was achieved. This was among the best energy resolutions that has ever been achieved at this incoming beam energy of 420 MeV. Owing to this excellent energy resolution many discrete states, including those weakly populated, could be studied up to 12.7 MeV. From the analysis of the angular distributions of the outgoing tritons it was possible to identify $\Delta L = 0$ transitions from their characteristic, forward-peaked an-

gular distributions. The GT strength was found to be highly fragmented amongst many transitions. No strong concentration of the strength in the form of a GT resonance was observed. In addition, judging from the increasing trend of the accumulated sum of the $B(\text{GT})$ strength, it seems that strength still exists even in the region above 12 MeV.

Shell model calculations were performed using the GXPF1J interaction. It was shown that the calculations reproduce the observed $B(\text{GT})$ strength reasonably well in the region up to 5 MeV but above this energy they exceed the measured values. It should be stressed that the study of GT transition strengths starting from an exotic nucleus, such as ^{48}Fe , contributes to the understanding of weak processes that are important in astrophysics and have not been well studied previously. The measured $B(\text{GT})$ distribution for the $^{48}\text{Ti}(^3\text{He},t)^{48}\text{V}$ reaction was compared with the corresponding measured distribution for the $^{47}\text{Ti}(^3\text{He},t)^{47}\text{V}$ reaction. The distributions follow roughly the same pattern but the latter is shifted to higher energies by about 2 MeV. A qualitative explanation is given in terms of the interactions of the particles involved and more specifically in terms of the transformation of the paired and unpaired valence par-

ticles. This explanation is corroborated by theory. On the assumption of isospin symmetry it is possible to use the measured $B(\text{GT})$ distribution in the $^{48}\text{Ti}(^3\text{He},t)^{48}\text{V}$ reaction to predict the distribution of $B(\text{GT})$ strength in the analogous beta decay of the $T_z = -2$ nucleus ^{48}Fe .

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- [1] F. Osterfeld, *Rev. Mod. Phys.* **64**, 491 (1992), and references therein.
 - [2] J. Rapaport and E. Sugarbaker, *Annu. Rev. Nucl. Part. Sci.* **44**, 109 (1994).
 - [3] D. Frekers, *Prog. Part. Nucl. Phys.* **57**, 217 (2006).
 - [4] Y. Fujita, B. Rubio, and W. Gelletly, *Prog. Part. Nucl. Phys.* **66**, 549 (2011).
 - [5] A.L. Cole, H. Akimune, Sam M. Austin, D. Bazin, A. M. van den Berg, G. P. A. Berg, J. Brown, I. Daito, Y. Fujita, M. Fujiwara, S. Gupta, K. Hara, M. N. Harakeh, J. Jänecke, T. Kawabata, T. Nakamura, D. A. Roberts, B. M. Sherrill, M. Steiner, H. Ueno, and R. G. T. Zegers, *Phys. Rev. C* **74**, 034333 (2006).
 - [6] T.N. Taddeucci, C.A. Goulding, T.A. Carey, R.C. Byrd, C.D. Goodman, C. Gaarde, J. Larsen, D. Horen, J. Rapaport, and E. Sugarbaker, *Nucl. Phys.* **A469**, 125 (1987), and references therein.
 - [7] W.G. Love, K. Nakayama, and M.A. Franey, *Phys. Rev. Lett.* **59**, 1401 (1987).
 - [8] Y. Fujita, K. Hatanaka, G.P.A. Berg, K. Hosono, N. Matsuoka, S. Morinobu, T. Noro, M. Sato, K. Tamura, and H. Ueno, *Nucl. Instrum. Meth. Phys. Res. B* **126**, 274 (1997), and references therein.
 - [9] <http://www.rcnp.osaka-u.ac.jp>.
 - [10] H. Fujita, Y. Fujita, T. Adachi, A. D. Bacher, G. P. A. Berg, T. Black, E. Caurier, C. C. Foster, H. Fujimura, K. Hara, K. Harada, K. Hatanaka, J. Jänecke, J. Kamiya, Y. Kanzaki, K. Katori, T. Kawabata, K. Langanke, G. Martínez-Pinedo, T. Noro, D. A. Roberts, H. Sakaguchi, Y. Shimbara, T. Shinada, E.J. Stephenson, H. Ueno, T. Yamanaka, M. Yoshifuku, and M. Yosoi, *Phys. Rev. C* **75**, 034310 (2007).
 - [11] Y. Fujita, Y. Shimbara, I. Hamamoto, T. Adachi, G. P. A. Berg, H. Fujimura, H. Fujita, J. Görres, K. Hara, K. Hatanaka, J. Kamiya, T. Kawabata, Y. Kitamura, Y. Shimizu, M. Uchida, H. P. Yoshida, M. Yoshifuku, and M. Yosoi, *Phys. Rev. C* **66**, 044313 (2002).
 - [12] Y. Fujita, Y. Shimbara, A.F. Lisetskiy, T. Adachi, G.P.A. Berg, P. von Brentano, H. Fujimura, H. Fujita, K. Hatanaka, J. Kamiya, T. Kawabata, H. Nakada, K. Nakanishi, Y. Shimizu, M. Uchida, and M. Yosoi, *Phys. Rev. C* **67**, 064312 (2003).
 - [13] Y. Fujita, H. Akimune, I. Daito, H. Fujimura, M. Fujiwara, M. N. Harakeh, T. Inomata, J. Jänecke, K. Katori, A. Tamii, M. Tanaka, H. Ueno, and M. Yosoi, *Phys. Rev. C* **59**, 90 (1999).
 - [14] Y. Fujita, R. Neveling, H. Fujita, T. Adachi, N. T. Botha, K. Hatanaka, T. Kaneda, H. Matsubara, K. Nakanishi, Y. Sakemi, Y. Shimizu, F. D. Smit, A. Tamii, and M. Yosoi, *Phys. Rev. C* **75**, 057305 (2007).
 - [15] E. Ganioglu, H. Fujita, Y. Fujita, T. Adachi, A. Algora, M. Csatlós, J. M. Deaven, E. Estevez-Aguado, C. J. Guess, J. Gulyás, K. Hatanaka, K. Hirota, M. Honma, D. Ishikawa, A. Krasznahorkay, H. Matsubara, R. Meharchand, F. Molina, H. Okamura, H. J. Ong, T. Otsuka, G. Perdikakis, B. Rubio, C. Scholl, Y. Shimbara, G. Susoy, T. Suzuki, A. Tamii, J. H. Thies, R. G. T. Zegers, and J. Zenihiro *Phys. Rev. C* **87**, 014321 (2013).
 - [16] F. Molina, B. Rubio, Y. Fujita, W. Gelletly, J. Agramunt, A. Algora, J. Benlliure, P. Boutachkov, L. Caceres, R. B. Cakirli, E. Casarejos, C. Domingo-Pardo, P. Doornenbal, A. Gadea, E. Ganioglu, M. Gascon, H. Geissel, J. Gerl, M. Gorska, J. Grebosz, R. Hoischen, R. Kumar, N. Kurz, I. Kojouharov, L. A. Susam, H. Matsubara, A. I. Morales, Y. Oktem, D. Pauwels, D. Perez-

- Loureiro, S. Pietri, Zs. Podolyak, W. Prokopowicz, D. Rudolph, H. Schaffner, S. J. Steer, J. L. Tain, A. Tamii, S. Tashenov, J. J. Valiente-Dobon, S. Verma, and H.-J. Wollersheim, *Phys. Rev. C* **91**, 014301 (2015).
- [17] R. G. T. Zegers, H. Akimune, Sam M. Austin, D. Bazin, A.M. van den Berg, G.P.A. Berg, B. A. Brown, J. Brown, A. L. Cole, I. Daito, Y. Fujita, M. Fujiwara, S. Galès, M. N. Harakeh, H. Hashimoto, R. Hayami, G. W. Hitt, M. E. Howard, M. Itoh, J. Jänecke, T. Kawabata, K. Kawase, M. Kinoshita, T. Nakamura, K. Nakanishi, S. Nakayama, S. Okumura, W. A. Richter, D. A. Roberts, B. M. Sherrill, Y. Shimbara, M. Steiner, M. Uchida, H. Ueno, T. Yamagata, and M. Yosoi, *Phys. Rev. C* **74**, 024309 (2006).
- [18] T. Wakasa, K. Hatanaka, Y. Fujita, G.P.A. Berg, H. Fujimura, H. Fujita, M. Itoh, J. Kamiya, T. Kawabata, K. Nagayama, T. Noro, H. Sakaguchi, Y. Shimbara, H. Takeda, K. Tamura, H. Ueno, M. Uchida, M. Uraki, and M. Yosoi, *Nucl. Instrum. Meth. Phys. Res. A* **482**, 79 (2002).
- [19] M. Fujiwara, H. Akimune, I. Daito, H. Fujimura, Y. Fujita, K. Hatanaka, H. Ikegami, I. Katayama, K. Nagayama, N. Matsuoka, S. Morinobu, T. Noro, M. Yoshimura, H. Sakaguchi, Y. Sakemi, A. Tamii, and M. Yosoi, *Nucl. Instrum. Meth. Phys. Res. A* **422**, 484 (1999).
- [20] T. Noro *et al.*, RCNP (Osaka University), Annual Report, 1991, p. 177.
- [21] H. Fujita, Y. Fujita, G. P. A. Berg, A. D. Bacher, C. C. Foster, K. Hara, K. Hatanaka, T. Kawabata, T. Noro, H. Sakaguchi, Y. Shimbara, T. Shinada, E. J. Stephenson, H. Ueno, and M. Yosoi, *Nucl. Instrum. Meth. Phys. Res. A* **484**, 17 (2002).
- [22] Y. Fujita, H. Fujita, G. P. A. Berg, K. Harada, K. Hatanaka, T. Kawabata, T. Noro, H. Sakaguchi, T. Shinada, Y. Shimbara, T. Taki, H. Ueno, and M. Yosoi, *J. Mass Spectrom. Soc. Jpn.* **48**(5), 306 (2000).
- [23] H. Fujita, G. P. A. Berg, Y. Fujita, K. Hatanaka, T. Noro, E. J. Stephenson, C. C. Foster, H. Sakaguchi, M. Itoh, T. Taki, K. Tamura, and H. Ueno, *Nucl. Instrum. Meth. Phys. Res. A* **469**, 55 (2001).
- [24] T. Adachi, Y. Fujita, A. D. Bacher, G. P. A. Berg, T. Black, D. De Frenne, C. C. Foster, H. Fujita, K. Fujita, K. Hatanaka, M. Honma, E. Jacobs, J. Jänecke, K. Kanazaki, K. Katori, K. Nakanishi, A. Negret, T. Otsuka, L. Popescu, D. A. Roberts, Y. Sakemi, Y. Shimbara, Y. Shimizu, E. J. Stephenson, Y. Tameshige, A. Tamii, M. Uchida, H. Ueno, T. Yamanaka, M. Yosoi, and K. O. Zell, *Phys. Rev. C* **85**, 024308 (2012).
- [25] T.W. Burrows, *Nuclear Data Sheets*, **107**, 1747-1922 (2006).
- [26] A computer program SFIT, H. Fujita *et al.*, RCNP (Osaka University), Annual Report, 2010, p. 3.
- [27] Y. Fujita, H. Fujita, T. Adachi, C. L. Bai, A. Algora, G. P. A. Berg, P. von Brentano, G. Colò, M. Csatlós, J. M. Deaven, E. Estevez-Aguado, C. Fransen, D. De Frenne, K. Fujita, E. Ganioglu, C. J. Guess, J. Gulyás, K. Hatanaka, K. Hirota, M. Honma, D. Ishikawa, E. Jacobs, A. Krasznahorkay, H. Matsubara, K. Matsuyanagi, R. Meharchand, F. Molina, K. Muto, K. Nakanishi, A. Negret, H. Okamura, H. J. Ong, T. Otsuka, N. Pietralla, G. Perdikakis, L. Popescu, B. Rubio, H. Sagawa, P. Sarriguren, C. Scholl, Y. Shimbara, Y. Shimizu, G. Susoy, T. Suzuki, Y. Tameshige, A. Tamii, J. H. Thies, M. Uchida, T. Wakasa, M. Yosoi, R. G. T. Zegers, K. O. Zell, and J. Zenihiro, *Phys. Rev. Lett.* **112**, 112502 (2014).
- [28] Y. Fujita, H. Fujita, T. Adachi, G. Susoy, A. Algora, C. L. Bai, G. Colò, M. Csatlós, J. M. Deaven, E. Estevez-Aguado, C. J. Guess, J. Gulyás, K. Hatanaka, K. Hirota, M. Honma, D. Ishikawa, A. Krasznahorkay, H. Matsubara, R. Meharchand, F. Molina, H. Nakada, H. Okamura, H. J. Ong, T. Otsuka, G. Perdikakis, B. Rubio, H. Sagawa, P. Sarriguren, C. Scholl, Y. Shimbara, E. J. Stephenson, T. Suzuki, A. Tamii, J. H. Thies, K. Yoshida, R. G. T. Zegers, and J. Zenihiro, *Phys. Rev. C* **91**, 064316 (2015).
- [29] DW81, a DWBA computer code by J. R. Comfort (1981) used in an updated version (1986), an extended version of DWBA70 by R. Schaeffer and J. Raynal (1970).
- [30] S.Y. van der Werf, S. Brandenburg, P. Grasdijk, W.A. Sterrenburg, M.N. Harakeh, M.B. Greenfield, B.A. Brown, and M. Fujiwara, *Nucl. Phys. A* **496**, 305 (1989).
- [31] R. Schaeffer, *Nucl. Phys. A* **164**, 145 (1971).
- [32] R.G.T. Zegers, H. Abend, H. Akimune, A.M. van den Berg, H. Fujimura, H. Fujita, Y. Fujita, M. Fujiwara, S. Galès, K. Hara, M.N. Harakeh, T. Ishikawa, T. Kawabata, K. Kawase, T. Mibe, K. Nakanishi, S. Nakayama, H. Toyokawa, M. Uchida, T. Yamagata, K. Yamasaki, and M. Yosoi, *Phys. Rev. Lett.* **90**, 202501 (2003).
- [33] J. Kamiya, K. Hatanaka, T. Adachi, K. Fujita, K. Hara, T. Kawabata, T. Noro, H. Sakaguchi, N. Sakamoto, Y. Sakemi, Y. Shimbara, Y. Shimizu, S. Terashima, M. Uchida, T. Wakasa, Y. Yasuda, H. P. Yoshida, and M. Yosoi, *Phys. Rev. C* **67**, 064612 (2003).
- [34] Y. Fujita, *Journal of Physics, Conference Series* **20**, 107 (2005).
- [35] T. Adachi, Y. Fujita, P. von Brentano, G.P.A. Berg, C. Fransen, D. De Frenne, H. Fujita, K. Fujita, K. Hatanaka, M. Honma, E. Jacobs, J. Kamiya, K. Kawase, T. Mizusaki, K. Nakanishi, A. Negret, T. Otsuka, N. Pietralla, L. Popescu, Y. Sakemi, Y. Shimbara, Y. Shimizu, Y. Tameshige, A. Tamii, M. Uchida, T. Wakasa, M. Yosoi, and K.O. Zell, *Nucl. Phys. A* **788**, 70c (2007).
- [36] T. Adachi, Y. Fujita, P. von Brentano, A. F. Lisetskiy, G. P. A. Berg, C. Fransen, D. De Frenne, H. Fujita, K. Fujita, K. Hatanaka, M. Honma, E. Jacobs, J. Kamiya, K. Kawase, T. Mizusaki, K. Nakanishi, A. Negret, T. Otsuka, N. Pietralla, L. Popescu, Y. Sakemi, Y. Shimbara, Y. Shimizu, Y. Tameshige, A. Tamii, M. Uchida, T. Wakasa, M. Yosoi, and K.O. Zell, *Phys. Rev. C* **73**, 024311 (2006).
- [37] L. Popescu, T. Adachi, G.P.A. Berg, P. von Brentano, D. Frekers, D. De Frenne, K. Fujita, Y. Fujita, E.-W. Grewe, M.N. Harakeh, K. Hatanaka, E. Jacobs, K. Nakanishi, A. Negret, Y. Sakemi, Y. Shimbara, Y. Shimizu, Y. Tameshige, A. Tamii, M. Uchida, H. J. Wörtche, and M. Yosoi, *Phys. Rev. C* **79**, 064312 (2009).
- [38] Y. Fujita *et al.*, RCNP (Osaka University), Annual Report, 2010, p. 1.
- [39] Y. Fujita *et al.*, RCNP (Osaka University), Annual Report, 2010, p. 2.
- [40] M. Honma, T. Otsuka, B.A. Brown, and T. Mizusaki, *Phys. Rev. C* **69**, 034335 (2004).
- [41] M. Honma, T. Otsuka, T. Mizusaki, M. Hjorth-Jensen,

- and B. A. Brown, Journal of Physics, Conference Series **20**, 7 (2005).
- [42] G. Martínez-Pinedo, A. Poves, E. Caurier, and A.P. Zuker, Phys. Rev. C **53**, R2602 (1996).
 - [43] J. Jänecke, K. Pham, D.A. Roberts, D. Stewart, M.N. Harakeh, G.P.A. Berg, C.C. Foster, J.E. Lisantti, R. Sawafu, E.J. Stephenson, A.M. van den Berg, S.Y. van der Werf, S.E. Muraviev, and M.H. Urin, Phys. Rev. C **48**, 2828 (1993).
 - [44] Y. Shimbara, Y. Fujita, T. Adachi, G.P.A. Berg, H. Fujimura, H. Fujita, K. Fujita, K. Hara, K.Y. Hara, K. Hatanaka, J. Kamiya, K. Katori, T. Kawabata, K. Nakanishi, G. Martínez-Pinedo, N. Sakamoto, Y. Sakemi, Y. Shimizu, Y. Tameshige, M. Uchida, M. Yoshifuku, and M. Yosoi, Phys. Rev. C **86**, 024312 (2012).
 - [45] N. B. Gove and M. J. Martin, Nuclear Data Tables **A10**, 246 (1971).
 - [46] M. Wang, G. Audi, A. H. Wapstra, F. G. Kondev, M. MacCormick, X. Xu, B. Pfeiffer, Chin.Phys.C**36**, 1603 (2012).
 - [47] D. H. Wilkinson and B. E. F. Macefield, Nucl. Phys. **A232**, 58 (1974).
 - [48] J.C. Hardy, I. S. Towner, Nucl. Phys. News **16**, 11 (2006).
 - [49] Y. Fujita, T. Adachi, H. Fujita, A. Algora, B. Blank, M. Csatlós, J. M. Deaven, E. Estevez-Aguado, E. Ganioglu, C. J. Guess, J. Gulyás, K. Hatanaka, K. Hirota, M. Honma, D. Ishikawa, A. Krasznahorkay, H. Matsubara, R. Meharchand, F. Molina, H. Okamura, H. J. Ong, T. Otsuka, G. Perdikakis, B. Rubio, C. Scholl, Y. Shimbara, E. J. Stephenson, G. Susoy, T. Suzuki, A. Tamii, J. H. Thies, R. G. T. Zegers, and J. Zenihiro, Phys. Rev. C **88**, 014308 (2013).
 - [50] S. E. A. Orrigo, B. Rubio, Y. Fujita, W. Gelletly, J. Agramunt, A. Algora, P. Ascher, B. Bilgier, B. Blank, L. Caceres, R. B. Cakirli, E. Ganioglu, M. Gerbaux, J. Giovinazzo, S. Grevy, O. Kamalou, H. C. Kozer, L. Kucuk, T. Kurtukian-Nieto, F. Molina, L. Popescu, A. M. Rogers, G. Susoy, C. Stodel, T. Suzuki, A. Tamii, and J. C. Thomas, Phys. Rev. C **93**, 044336 (2016).