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Gamow-Teller transitions from ^{58}Ni to discrete states of ^{58}Cu

The study of isospin symmetry in atomic nuclei

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Abstract. Under the assumption that isospin is a good quantum number, symmetry is expected for the transitions from the ground states of $T = 1, T_z = \pm 1$ nuclei to the common excited states of the $T_z = 0$ nucleus situated between the two nuclei. The symmetry can be studied by comparing the strengths of Gamow-Teller (GT) transitions obtained from a (p, n)-type charge-exchange reaction on a target nucleus with $T_z = 1$ with those from the β-decay of the $T_z = -1$ nucleus. The $A = 58$ system is the heaviest for which such a comparison is possible. As a part of the symmetry study, we measured the GT transitions from ^{58}Ni ($T_z = 1$) to ^{58}Cu ($T_z = 0$) by using the zero-degree (^{3}He$, t$) reaction at 150 MeV/nucleon. With the achieved resolution of 50 keV, many hitherto unresolved GT states have been identified. The GT transition strengths were obtained for states up to 8 MeV excitation, *i.e.*, near to the Q window limitation ($Q_{\rm EC} = 9.37$ MeV) of the β-decay from ^{58}Zn ($T_z = -1$) to ^{58}Cu. The strength distribution is compared with that from shell-model calculations.

PACS. 21.10.Hw Spin, parity and isobaric spin – 21.60.Cs Shell model – 25.55.Kr Charge-exchange reactions – 27.40.+z $39 \le A \le 58$

1 Introduction

Under the assumption that the nuclear interaction is charge symmetric, isospin is a good quantum number. A symmetric structure is expected for the mass A nuclei with $\pm T_z$, where T_z is the z component of the isospin defined by $(N - Z)/2$ (see *e.g.*, ref. [1]). The corresponding states in different T_z nuclei (isobars) are called isobaric analog states (or simply, analog states). Symmetry is also expected among transitions of which the initial and/or final states are replaced by analog states. Such "analogous transitions" agree in energies and strengths. Thus, the isospin symmetry of isobars can be investigated by comparing the energies and strengths of analogous transitions. Such a comparison becomes simple if one considers a transition which selects specific J^π values. It is also important that the transition is commonly observed.

The Gamow-Teller (GT) transitions, caused by the $\sigma\tau$ operator, are well suited for this purpose, because they can be studied in both β-decay and hadron charge-exchange (CE) reactions. The GT transition has the quantum-number selections $\Delta L = 0$, $\Delta S = 1$ and $\Delta T_z = \pm 1$, where L and S are the orbital and spin quantum numbers. The reduced GT transition strength B(GT) is an important physical quantity for the understanding of nuclear structures [2,3] as well as for the calculation of astrophysical processes [4]. The most direct information on B(GT) values is obtained from the studies of GT β-decay. In ad-

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dition, CE reactions, like (p, n) or $(^3\mathrm{He}, t)$, performed at intermediate energies (> 100 MeV/nucleon) can be used as a means to map the GT strengths over a wide range of excitation energy (E_x) [5]. For this purpose, one relies upon the approximate proportionality between the reaction cross-sections measured at the scattering angle $\theta = 0°$ and the $B(\mathrm{GT})$ values.

The simplest isospin symmetry is expected for the odd-mass mirror nuclei with $T_z = \pm 1/2$. For every state in the $T_z = +1/2$ nucleus, an analog state is expected in the $T_z = -1/2$ nucleus. Recently a good symmetry has been found for the ^{27}Al-^{27}Si pair up to the proton separation energy (S_p) of 8.3 MeV in ^{27}Al [6]. More interesting is the symmetry for larger T values. The $T_z = 1$ to $T_z = 0$ transitions can be studied in CE reactions, because they often start from stable nuclei in the region of sd- and fp-shell nuclei. On the other hand, the $T_z = -1$ to $T_z = 0$ transitions can be investigated by β-decay studies. The symmetry of these transitions, however, has been examined only for some light sd-shell nuclei, like the $A = 38$ system (^{38}Ar, ^{38}K and ^{38}Ca) [7], mainly because of the limited energy resolution of CE reactions. In addition, the studies are possible only for low-lying states due to small Q values of the relevant β-decays [8].

Among the $|T_z| = 1 \to 0$ candidates, we find that analogous transitions in the $A = 58$ system, *i.e.*, ^{58}Ni ($T_z = 1$) to ^{58}Cu ($T_z = 0$) and ^{58}Zn ($T_z = -1$) to ^{58}Cu, are well suited for the accurate study of isospin symmetry. The former transitions can be probed in a CE reaction on a ^{58}Ni target, while the latter can be studied via the β-decay of ^{58}Zn. It should be noted that the $A = 58$ system is the heaviest for which such a study is possible, because ^{58}Ni is the heaviest stable $T_z = 1$ nucleus. Owing to the large A value, the β-decay of ^{58}Zn has a high Q_{EC} value of 9.37(5) MeV [9], which allows one to measure $B(\mathrm{GT})$ values up to high excitation energies of ^{58}Cu. It should be also noted that the $B(\mathrm{GT})$ values in the ^{58}Ni to ^{58}Cu transitions are determined independently of the ^{58}Zn β-decay study. Since the ground states of ^{58}Cu and ^{58}Ni have $J^\pi = 1^+$ and 0^+, respectively, the $B(\mathrm{GT})$ value of the transition between ground states, obtained from the β-decay of ^{58}Cu, can be used to calibrate the $B(\mathrm{GT})$ values from the CE reaction.

In a recent pioneering β-decay study of ^{58}Zn, the $B(\mathrm{GT})$ values were deduced for the transitions to the ground state and the 1.05 MeV state of ^{58}Cu [10], where it was found that the statistical accuracy was very important. On the other hand, in a CE reaction studying transitions from ^{58}Ni to ^{58}Cu, high energy resolution is important to obtain individual transition strengths. It is found that the $(^3\mathrm{He}, t)$ reaction is an excellent tool for this purpose. Indeed a good resolution $^{58}\mathrm{Ni}(^3\mathrm{He}, t)$ measurement [11] started to show significant fine structures of the GT resonance, which had been observed as a broad bump-like structure in an earlier (p, n) work [12].

As part of a series of experiments to explore the isospin symmetry of the $A = 58$ system, we performed a high-resolution $^{58}\mathrm{Ni}(^3\mathrm{He}, t)$ experiment at 0° in order to investigate the $T_z = 1 \to 0$ transitions to GT states in ^{58}Cu. The GT strengths were extracted from the measured cross-sections for states up to $E_x = 8$ MeV, which is in practice the highest excitation energy studied in the β-decay of ^{58}Zn.

2 Experiment and data evaluation

2.1 Characteristics of the $(^3\mathrm{He}, t)$ reaction

In intermediate-energy CE reactions, such as (p, n) or $(^3\mathrm{He}, t)$, the GT states become prominent at forward angles including $\theta = 0°$ because of their $L = 0$ nature and the dominance of the $\sigma\tau$ part of the effective nuclear interaction $V_{\sigma\tau}$ at small momentum transfer q [2,3,13]. The (p, n) reaction has been well established as a spectroscopic tool to study GT transitions. It was found that the cross-sections at 0° are proportional to the $B(\mathrm{GT})$ values obtained in GT β-decays, if the transitions are not too weak [5]. The proportionality is given by [5,14,15]

$$\frac{\mathrm{d}\sigma^{\mathrm{CE}}}{\mathrm{d}\Omega}(0°) \simeq K^{\mathrm{CE}} N_{\sigma\tau}^{\mathrm{CE}} |J_{\sigma\tau}(0)|^2 B(\mathrm{GT}), \qquad (1)$$

where $J_{\sigma\tau}(0)$ is the volume integral of the effective interaction $V_{\sigma\tau}$ at $q = 0$, K^{CE} the kinematic factor for the CE reaction, and $N_{\sigma\tau}^{\mathrm{CE}}$ the distortion factor. The product $K^{\mathrm{CE}} N_{\sigma\tau}^{\mathrm{CE}}$ gradually decreases as the E_x value of the final nucleus increases. The energy resolutions of the (p, n) reactions, however, were rather limited ($\Delta E \geq$ 200–300 keV) because of the difficulty of getting good resolutions in neutron time-of-flight systems [3].

The situation can be drastically improved by using the $(^3\mathrm{He}, t)$ reaction at intermediate energies. The momenta of the outgoing tritons are precisely analyzed by a magnetic spectrometer, and thus a higher energy resolution is achieved. At the QQDD-type Grand Raiden spectrometer [16] at RCNP, Osaka, tritons up to an energy of 150 MeV/nucleon can be analyzed. At this beam energy it has been shown, from the study of mirror GT transitions in $^{27}\mathrm{Al}(^3\mathrm{He}, t)^{27}\mathrm{Si}$ and $^{27}\mathrm{Si} \to {}^{27}\mathrm{Al}$ β-decay [6], that the proportionality given by eq. (1) is valid if the $B(\mathrm{GT})$ values are larger than 0.04.

2.2 Procedure of the $(^3\mathrm{He}, t)$ experiment

The $^{58}\mathrm{Ni}(^3\mathrm{He}, t)$ experiment was performed by using a 150 MeV/nucleon ^{3}He beam from the RCNP Ring Cyclotron. The $^3\mathrm{He}^{2+}$ beam with a typical current of 5 nA was transported on a 1.5 mg/cm^2 thick ^{58}Ni target and stopped in a Faraday cup inside the first dipole magnet of the spectrometer which was set at 0°. The ejectile tritons were accepted with the full acceptance of the spectrometer (about ±30 mr in vertical (y) direction and about ±20 mr in horizontal (x) direction). After momentum analysis, tritons were detected in the focal plane by a multi-wire drift-chamber system capable of determining x-y positions and angles of each ray [17]. The track reconstruction of each

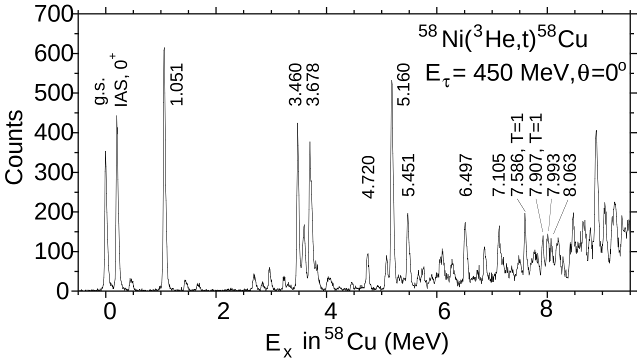

Fig. 1. High-resolution ^{58}Ni(^{3}He, t)^{58}Cu spectrum measured at 0°. Major states with $L = 0$ character are indicated by their excitation energies.

ray made it possible to subdivide the acceptance angle of the spectrometer by a software.

Figure 1 shows the spectrum obtained around $\theta = 0°$ for the angular range ±12 mr in the x-direction (no cut is made in the y-direction). Precise *dispersion matching* and *angular dispersion matching* were realized by using the newly commissioned WS beam line [18,19]. Owing to the development of a new diagnostic method for the realization of matching conditions [20,21], a resolution of 50 keV (FWHM) has been realized.

The experimental knowledge on 0^+ and 1^+ states in ^{58}Cu is scarce [22]. The ground state and the 1.052 MeV level are assigned to be 1^+, $T = 0$, whereas 0^+, $T = 1$ is proposed for the 0.203 MeV level.

The excitation energies of newly observed states were calibrated using well-known low-lying discrete states of ^{12}N and ^{13}N [23] observed in the $^{\rm nat}$C(^{3}He, t) spectrum as reference. Owing to the small Q value of the (^{3}He, t) reaction on ^{13}C and the large Q value on ^{12}C, the excitation energies of ^{58}Cu states were determined by interpolation. We estimate an error of ±10 keV in the region up to $E_x = 5$ MeV and ±20 keV in the 8 MeV region. The excitation energies of low-lying states from ref. [22] and those of the states determined in the present work are listed in table 1.

As the scattering angle θ increases beyond 0°, the cross-sections of $L = 0$ states decrease, whereas those of $L = 1$ and higher multipoles increase. The spectra at three different angle cuts ($\theta \leq 0.25°$, $\theta = 0.25° - 0.5°$ and $\theta = 0.5° - 0.75°$) were compared. The ^{58}Cu states with a relative decrease in strength similar to that of the known 1^+ state at 1.052 MeV were assigned to be $L = 0$ GT states. For these states, GT transition strengths are listed in table 1. It was found that almost all prominent peaks, except for the peak seen between the 3.460 and 3.678 MeV states, showed the similar relative decrease. The $L = 0$ assignment was less certain for the three states above $E_x = 8.1$ MeV.

Table 1. Discrete states in ^{58}Cu and B(GT) values deduced from ^{58}Ni(^{3}He, t) measurements. The E_x values are in units of MeV. The literature E_x values are accurate within less than 1 keV. The B(GT) values are given to the states assigned to have $L = 0$ character. For details of the derivation of E_x values and B(GT) values, see text. Isospin value $T = 0$ is assigned to all the $L = 0$ states unless $T = 1$ is indicated.

Nucl. data sheets$^{(a)}$		(^{3}He, t)		
E_x	J^π	E_x	B(GT)	Isospin
0.0	1^+	0.0	0.155(1)$^{(b)}$	
0.203	0^+	0.204	–	$T=1$
0.444	(3^+)	0.444	–	
1.051	(1^+)	1.051	0.265(13)	
1.428	2^+	1.427	–	
1.652	2^+	1.651	–	
		2.949	0.025(3)	
		3.460	0.173(11)	
		3.678	0.155(10)	
		3.717	0.050(5)	
		4.720	0.042(4)	
		5.065	0.040(4)	
		5.160	0.250(14)	
		5.451	0.082(7)	
		5.645	0.016(3)	
		6.038	0.029(4)	
		6.086	0.033(4)	
		6.497	0.061(7)	
		6.844	0.044(5)	
		7.105	0.057(6)	
		7.143	0.014(4)	
		7.586	0.073(7)	$T=1$
		7.700	0.021(4)	
		7.752	0.028(5)	
		7.907	0.052(5)	$T=1$
		7.993	0.049(5)	
		8.063	0.035(5)	$(T=1)^{(c)}$
		8.159$^{(d)}$	0.037(5)	
		8.199$^{(d)}$	0.033(4)	
		8.282$^{(d)}$	0.016(4)	

$^{(a)}$ From ref. [22].
$^{(b)}$ Value from β-decay measurement, which is used as a B(GT) standard.
$^{(c)}$ See text for the discussion of T assignment.
$^{(d)}$ $L = 0$ assignment is less certain.

2.3 Experimental determination of the GT strength

The S_p value of ^{58}Cu is 2.873(3) MeV [9]. Above this energy, a gradual increase of the underlying continuum is observed in the spectrum shown in fig. 1 because of the three body kinematics. In order to determine the intensities for the "structure part", the continuum part should be removed. Since there is no established theory for reliably calculating the cross-section of continuum, a smooth line connecting the "valleys between the peaks" was subtracted in the analysis. Because of the good energy resolution of 50 keV, there is almost no ambiguity in drawing the line of the continuum in the energy region $E_x \leq 8$ MeV in which we are interested. The intensities of individual peaks were obtained by employing a peak decomposition program using the peak shape of the well-separated peak at 1.05 MeV as reference.

In order to calculate $B(\mathrm{GT})$ values from the experimental peak intensities by applying the proportionality given by eq. (1), a standard $B(\mathrm{GT})$ value is needed. For that purpose, we used the $B(\mathrm{GT})$ value from the β-decay connecting the ground states of $^{58}\mathrm{Cu}$ ($J^\pi = 1^+$) and $^{58}\mathrm{Ni}$ ($J^\pi = 0^+$). In the GT β-decay, the relationship among the $B(\mathrm{GT})$ value, the phase space factor f and the partial half-life t is given by [24]

$$f(1+\delta_\mathrm{R})t = \frac{6145 \pm 4}{(g_\mathrm{A}/g_\mathrm{V})^2\, B(\mathrm{GT})}, \tag{2}$$

where $(1 + \delta_\mathrm{R})$ is the radiative-correction term. The $B(\mathrm{GT})$ value is given in units where $B(\mathrm{GT}) = 3$ for the β-decay of the free neutron. The partial half-life of the ground-state β-decay was obtained by using the known half-life $t = 3.204(7)$ s [22,25] and the branching ratio of 81.2(5)%, which was accurately measured with the total absorption spectrometer at GSI Darmstadt [26]. A very similar value is reported from γ-ray measurements using an IGISOL (Ion Guide Isotope Separator On-Line) facility [27]. The $f(1 + \delta_\mathrm{R})$ value was calculated from the decay energy $Q_\mathrm{EC} = 8563(2)$ keV [9] by using the tables of Wilkinson and Macefield [28]. The $\log f(1 + \delta_\mathrm{R})t$ value for the above-mentioned $^{58}\mathrm{Cu}$ ground state $\to$ $^{58}\mathrm{Ni}$ ground state was determined to be 4.870(3). By using the ratio $(g_\mathrm{A}/g_\mathrm{V}) = -1.266(4)$ [29], the corresponding $B(\mathrm{GT})$ value of the decay was deduced as 0.0517(4). Correcting for the $2J + 1$ factors of the initial and final states, we determine that the $B(\mathrm{GT})$ value is 0.155(1) for the transition $^{58}\mathrm{Ni}$ ground state $\to$ $^{58}\mathrm{Cu}$ ground state.

The $B(\mathrm{GT})$ values of transitions to the excited GT states can be obtained by using the proportionality given by eq. (1). Care should be taken that the product of K^CE and $N^\mathrm{CE}_{\sigma\tau}$ changes gradually as a function of excitation energy. To estimate this effect, a DWBA calculation was performed by using the code DW81 [30] and assuming various particle-hole (p-h) configurations for the 1^+ states in the fp-shell region. The optical potential parameters for $^3\mathrm{He}$ were taken from ref. [31]. For the outgoing tritons, following the arguments given in ref. [32], we multiplied the well depths by a factor of 0.85 without changing the geometrical parameters of the optical potential. The form of the effective projectile-target interaction for the composite particle $^3\mathrm{He}$ used here was derived by Schaeffer [33] through the folding procedure. The interaction strengths at 150 MeV/nucleon are not well studied. Therefore, we tentatively used the strength $V_{\sigma\tau} = -3.0$ MeV and the range $R = 1.415$ fm derived by an extrapolation of the values determined at 67 MeV/nucleon [34]. It was found that the calculated 0° cross-section for a p-h configuration decreases by about 10% at $E_x = 8$ MeV, whereas the decrease is almost independent of the assumed configuration. The resulting experimental $B(\mathrm{GT})$ strengths are listed in table 1 and shown in fig. 2a).

The uncertainties of these $B(\mathrm{GT})$ values were estimated by taking into account the statistics of peak counts, ambiguities in the peak decomposition and the uncertainty of the $B(\mathrm{GT})$ value in the β-decay measurement. The uncertainties due to the subtraction of the continuum were neglected. Since the proportionality is not well established for weak transitions with $B(\mathrm{GT}) < 0.04$, as mentioned before, the uncertainties for them may be underestimated.

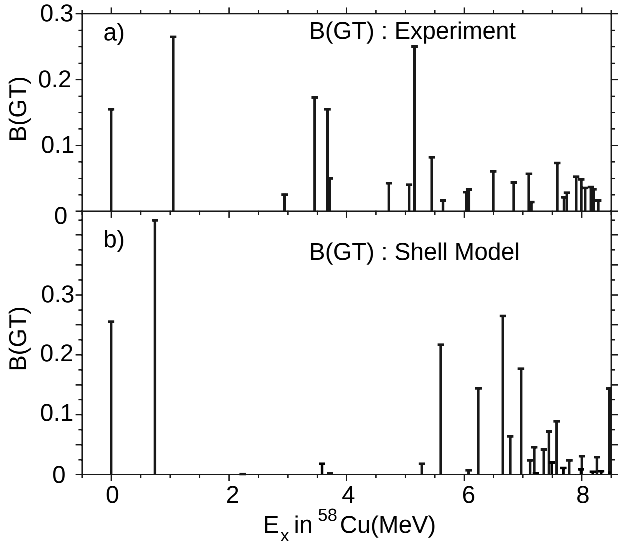

Fig. 2. The $B(\mathrm{GT})$ distributions a) from the experiment, and b) from the shell-model calculation.

3 Discussion

3.1 GT strengths and isospin values

In the $^{58}\mathrm{Zn} \to {}^{58}\mathrm{Cu}$ β-decay measurement, a $B(\mathrm{GT})$ value of 0.34(16) is reported for the transition to the 1.052 MeV state in $^{58}\mathrm{Cu}$ [10]. For the analogous transition to the same 1.052 MeV state, a $B(\mathrm{GT})$ value of 0.265(13) is obtained in the present analysis. Both results are in agreement, although more accuracy is needed for the β-decay measurement in order to discuss the symmetry of the transitions.

Due to its $\Delta T = 1$ selection rule, the $(^3\mathrm{He}, t)$ reaction excites $J^\pi = 1^+$ states with $T = 0$, 1 and 2 in $^{58}\mathrm{Cu}$ starting from the $T_0 = 1$ ground state of $^{58}\mathrm{Ni}$. On the other hand, only the $T = 1$ or 2 parts of the excited 1^+ states are observed as analog states in $^{58}\mathrm{Ni}$, which are called $M1$ states. The 0.203 MeV state in $^{58}\mathrm{Cu}$ is the isobaric analog state of the $J^\pi = 0^+, T = 1$ ground state of $^{58}\mathrm{Ni}$ [22]. It is, therefore, expected that analog GT states in $^{58}\mathrm{Cu}$ have about 200 keV higher E_x values than the parent $M1$ states in $^{58}\mathrm{Ni}$. The $J^\pi = 1^+, T = 2$ $M1$ states are reported above $E_x = 9.85$ MeV in $^{58}\mathrm{Ni}$ [35], and their analog GT states above 10.03 MeV in $^{58}\mathrm{Cu}$ [36]. Consequently the GT states in $^{58}\mathrm{Cu}$ should have either $T = 0$ or 1 in the region examined here.

By using the nuclear resonance fluorescence (NRF) method and linearly polarized bremsstrahlung photons [37], a clear 1^+ identification was made for the 5.905, 7.389 and 7.710 MeV states in $^{58}\mathrm{Ni}$ in the region up to $E_x = 8$ MeV, and $M1$ transition strengths $B(M1)\!\uparrow$ (the strength from the ground state to the excited state) are obtained for these states (see columns 1, 2 and 3 of table 2).

Table 2. Candidates for $J^\pi = 1^+$, $T = 1$ states in the energy region up to $E_x = 8$ MeV in ^{58}Cu and ^{58}Ni. The ^{58}Ni E_x values are accurate within less than 1 keV except for 7.877 MeV state (2.6 keV uncertainty). The $B(M1)$ values are in units of μ_N^2. For the definition of $B^R(M1)$ and R_{BB}, see text.

States in ^{58}Ni$^{(a)}$				States in ^{58}Cu$^{(b)}$			
E_x	J^π	$B(M1)\uparrow$	$B^{\rm R}(M1)$	E_x	B(GT)	ΔE_x	$R_{BB}^{(c)}$
5.905	1^+	0.023(4)	0.009(2)	–	–		
6.027	1	0.516(14)$^{(d)}$	0.195(5)				
7.272	1	0.308(30)$^{(d)}$	0.116(11)				
7.389	1^+	0.294(16)	0.111(6)	7.586	0.073(7)	0.200	1.2
7.710	1^+	0.358(13)	0.135(5)	7.907	0.052(5)	0.197	2.1
7.877	1	0.181(38)$^{(d)}$	0.068(14)	8.063	0.035(5)	0.176	1.6

$^{(a)}$ From ref. [37].
$^{(b)}$ From present (^{3}He,t) experiment.
$^{(c)}$ Assuming $R_{\rm MEC} = 1.25$.
$^{(d)}$ Tentative value obtained by assuming $J^\pi = 1^+$.

The $M1$ assignment was also made for the strongly excited 7.389 and 7.710 MeV states in the (e, e') reaction [35].

To these electro-magnetic $M1$ transitions, not only the IV spin ($\sigma\tau$) term, but also the isoscalar (IS) term and the isovector (IV) orbital ($\ell\tau$) term of the $M1$ operator can make contributions [38,39]. Since the contribution of the orbital term is expected to be small due to the small nuclear deformation in the nickel region [40], the contribution of the IV spin term is expected to be the largest. The $B(M1)\uparrow$ values, therefore, become roughly proportional to the B(GT) values of the analogous GT transitions, which are caused by the IV spin-type ($\sigma\tau$-type) GT operator. The proportionality is given by [6]

$$B(M1)\uparrow \approx \frac{3}{8\pi}\,(\mu_p - \mu_n)^2\,\frac{C_{M1}^2}{C_{\rm GT}^2}\,R_{\rm MEC}\,B({\rm GT}), \qquad (3)$$

where C_{M1} is the isospin Clebsch-Gordan (CG) coefficient $(T_iT_{zi}10|T_fT_{zf})$ with $T_{zf} = T_{zi}$, and $C_{\rm GT}$ is $(T_iT_{zi}1 \pm 1|T_fT_{zf})$ with $T_{zf} = T_{zi} \pm 1$. The so-called meson exchange currents (MEC) affect $M1$ and GT transitions differently [41]. This is expressed by the parameter $R_{\rm MEC}$. An average value of 1.25 was obtained for sd-shell nuclei [39] by comparing experimental $B(M1)$ and B(GT) values with those from shell-model calculations. We tentatively use this value, although there is a suggestion that $R_{\rm MEC}$ may be smaller for fp-shell nuclei [42]. The numerical factor is $2.643\mu_N^2$ if the magnetic moments of free nucleons are used. The ratio of the squared CG coefficients is unity for transitions from the ground state of ^{58}Ni to excited $M1$ and GT states with $T = 1$.

The GT states which are analogous to the $M1$ states in ^{58}Ni are identified from the correspondence of both excitation energies and transition strengths. It was found that the 7.586 and 7.907 MeV GT states correspond to the well-assigned $M1$ states at 7.389 and 7.710 MeV [35, 37], respectively. As listed in table 2, the differences of E_x values for each pair of GT and $M1$ states are 0.200 and 0.197 MeV, respectively. They are in good agreement with the expected value. From eq. (3), it is noticed that, except for the IS and IV orbital contributions, a value directly comparable with the B(GT) value is obtained if the $B(M1)\uparrow$ value is divided by the coefficient $2.643\mu_N^2$ and the ratio of the squared CG coefficients, which is unity. We call the modified $B(M1)\uparrow$ values to be compared to the B(GT) values "renormalized" $B(M1)\uparrow$ values, and use the notation $B^{\rm R}(M1)$. The calculated $B^{\rm R}(M1)$ values are listed in column 4 of table 2. The correspondence of strengths is examined by the ratio

$$R_{BB} = B^{\rm R}(M1)/[R_{\rm MEC}\,B({\rm GT})]. \qquad (4)$$

For the states with good $M1$ and GT correspondence, R_{BB} values roughly close to unity are expected. By using the $B^{\rm R}(M1)$ and B(GT) values of table 2, we obtain R_{BB} values of 1.2 and 2.1 for these two pairs of states.

Several states in ^{58}Ni are given $J = 1$, but no parity is assigned in the NRF experiment [37]. The possibility of these states being $J^\pi = 1^+$ has been examined based again on the correspondence of both excitation energies and transition strengths. It is found that the 7.877 MeV state corresponds energywise to the 8.063 MeV state in ^{58}Cu (see table 2). The R_{BB} value of 1.6 supports a good correspondence. However, it is mentioned in ref. [37] that the existence of the 7.877 MeV state depends on the assumption made for the γ-decay scheme. In addition the 7.877 MeV state is not reported in the (e, e') reaction [35]. Therefore, the $J^\pi = 1^+$ assignment for the 7.877 MeV state in ^{58}Ni and the $T = 1$ assignment for the 8.063 MeV state in ^{58}Cu are only tentative. No other state satisfied both conditions simultaneously. We, therefore, give the $T = 0$ assignment to all GT states except for the three states mentioned above.

Among those $J = 1$ states for which parity is not assigned, two states at 6.027 and 7.272 MeV are pronounced and have rather large $B(M1)\uparrow$ values if $J^\pi = 1^+$ is assumed (see table 2). Since no analog GT states with corresponding strengths are observed, we believe that they are of $J^\pi = 1^-$ nature.

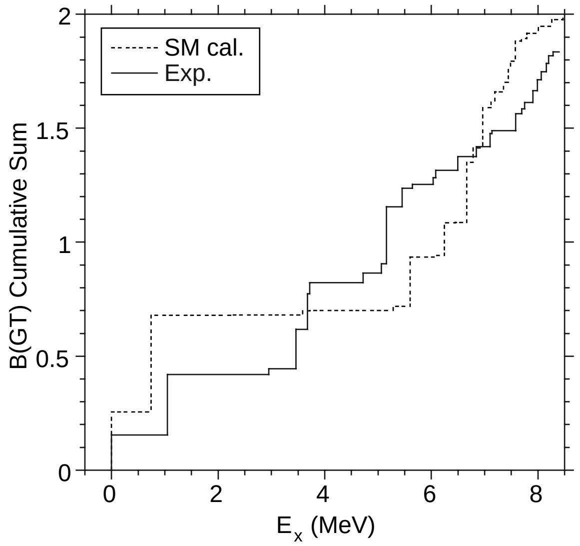

Fig. 3. Cumulative sum of $B(\mathrm{GT})$ values from the $(^3\mathrm{He}, t)$ experiment and the shell-model calculation.

3.2 Shell-model calculation

Large-scale shell-model (SM) calculations are now available for *fp*-shell nuclei. Astrophysically such studies are important as they allow to calculate the GT distributions in nuclei of the iron mass range, which in turn determine the stellar weak-interaction rates [4]. The rates have significant influence on the late-stage stellar evolution and nucleosynthesis and, in particular, the core collapse of massive stars that triggers a type II supernova explosion [43, 44]. A comparison between experimental $B(\mathrm{GT})$ data and the corresponding SM predictions is thus of considerable interest. The SM calculations employing the KB3 interaction [45] have been found to give an excellent description of nuclei at the beginning of the *fp*-shell ($A < 50$) [46].

Calculated strength distributions of the $^{58}\mathrm{Ni} \to {}^{58}\mathrm{Cu}$ GT transition have been reported by Jokinen *et al.* [10] and by Caurier *et al.* [47]. Caurier *et al.* found that the original KB3 interaction gives a larger quasiparticle gap in the $N = Z = 28$ nucleus $^{56}\mathrm{Ni}$, which results in a relative underbinding of nuclei with N or Z larger than 28. Using a modified KB3 interaction, they could, in general, well reproduce the experimental GT strength distributions up to iron isotopes. The agreement, however, was less satisfactory for the nickel isotopes [47]. The calculated strengths were concentrated in the ground state and the so-called GT resonance region centered at around $E_x = 9.5$ MeV in $^{58}\mathrm{Cu}$. The strength distribution was not so well reproduced at lower excitation energies, where the configurations above the $N = Z = 28$ shell closure are expected to play a larger role.

In order to seek a better agreement for the $A \geq 57$ nuclei, the recently developed KB3G interaction [48] has been used. The calculations of ref. [47] have been extended to include 4 particle-hole correlations using the code NATHAN [49]. To get a finer detail of the structure observed in the present high-resolution study, the calculated GT strength distribution has been obtained after 150 Lanczos iterations for each final isospin. After this number of iterations, states below ≈ 7.5 MeV are fully converged. The result of the calculation is shown in fig. 2b), where the calculated $B(\mathrm{GT})$ values include the usual "quenching factor" of $(0.74)^2$ [50]. The agreement between experiment and theory has indeed improved significantly (see fig. 2). The GT strength distribution of low-lying states is better reproduced except for few states around 3.5 MeV. It is expected that going beyond 4 particle-hole correlations will produce a further fragmentation of the theoretical low-lying peaks in better agreement with the experiment. In order to get an overview of the agreement of the distributions, the cumulative sum is plotted in fig. 3. Satisfactory agreement is obtained for the summed strengths up to 8 MeV, with some difference occurring in the slope, as expected from the different shapes of the distributions.

4 Summary and prospects

As part of the isospin symmetry study of the transitions from the ground states of $T = 1, T_z = \pm 1$ nuclei to the common excited states of $T_z = 0$ nucleus, the GT transitions from $^{58}\mathrm{Ni}$ ($T_z = 1$) to $^{58}\mathrm{Cu}$ ($T_z = 0$) have been investigated by using the $(^3\mathrm{He}, t)$ reaction at 150 MeV/nucleon. The $A = 58$ system is the heaviest for such a study, because $^{58}\mathrm{Ni}$ is the heaviest $T_z = 1$ target nucleus available for CE reactions. With the achieved energy resolution of 50 keV, many discrete GT states have been identified, and the $B(\mathrm{GT})$ values were obtained for $^{58}\mathrm{Cu}$ states up to excitation energies of 8 MeV relying on the proportionality between the $B(\mathrm{GT})$ values and the cross-sections at $\theta = 0°$. For an accurate determination of the $B(\mathrm{GT})$ values, the $\log ft$ values from recent $^{58}\mathrm{Cu} \to {}^{58}\mathrm{Ni}$ β-decay measurements with an uncertainty of less than 1% were used as calibration standard. The kinematic effects as a function of excitation energy were corrected by using the results from DWBA calculations. The obtained $B(\mathrm{GT})$ distribution was compared with the result of a state-of-the-art large-scale SM calculation. The calculated result generally reproduced the distribution up to 8 MeV, although some space for improvements remains.

For the study of isospin symmetry, a detailed measurement of $^{58}\mathrm{Zn}$ ($T_z = -1$) β-decay is planned up to highly excited states of $^{58}\mathrm{Cu}$ ($T_z = 0$) [51]. Due to the large Q_{EC} value [9.37(5) MeV] of this decay and the small proton separation energy in $^{58}\mathrm{Cu}$ [2.873(3) MeV], it is important to include efficient β-delayed proton measurements. For this purpose a project to construct a "silicon ball" is in progress at ISOLDE [52].

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