Gamow-Teller Transitions Studied in RCNP High Resolution (^{3}He, t) Measurements and their Isospin Mirror Transitions in β-decay Studies

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1 Introduction

Gamow-Teller (GT) transitions are associated with the simple $\sigma\tau$ operator [1]. As a consequence, some of the important features in GT transitions are: (1) states with similar spatial shapes are favorably connected, (2) due to the σ operator, states with different structures (configurations) can be connected, (3) combined $\sigma\tau$ operator means that isospin quantum number T plays an important role.

The names "Gamow-Teller" and also "Fermi" come from the "allowed" transitions in β decay. Since β decays favor $\Delta L = 0$ transitions, they can study clearly the GT and Fermi transitions. There, the partial half-life t_i of the ith GT transition and $t_{\rm F}$ of the Fermi transition multiplied by the phase-space factor (f-factor) are related to the GT transition strength B(GT) and the Fermi transition strength B(F),

$$ft_i = K/\lambda^2 B(\mathrm{GT}) \quad \text{and} \quad ft_{\rm F} = K/B(\mathrm{F})(1-\delta_c), \tag{1}$$

where $K = 6147.8(16)$, $\lambda = g_A/g_V = -1.270(3)$, δ_c is the Coulomb correction factor [2], and $f_{\rm F}$ and f_i are the phase-space factors (f-factors) of the β decay to the isobaric analog state (IAS) and to the ith GT state, respectively. The f-factor becomes smaller if the decay Q value is smaller. Therefore, the decays to higher excited states are suppressed.

Charge-exchange (CE) reactions, including the (^{3}He, t) reaction, allow access to transitions to higher excited states. At intermediate energies ($\geq$ 100 MeV/nucleon) and at forward angles including 0°, GT states are prominent in the CE reactions, because of their $L = 0$ nature and the dominance of the $\sigma\tau$ part of the effective nuclear interaction [3]. It was shown that they are good probes of GT transitions due to the fact that there is a simple proportionality between the GT cross sections at 0° and the B(GT) values [4]

$$\sigma^{\rm GT}(0°) = \hat{\sigma}^{\rm GT}(0°)B(\mathrm{GT}), \tag{2}$$

where $\hat{\sigma}^{\rm GT}(0°)$ is the GT unit cross section at 0°, which depends on the mass A of the system and gradually decreases as a function of excitation energy [4]. Because of this proportionality, the study of B(GT) values can reliably be extended up to high excitations if a "standard B(GT) value" from β decay is available.

In this report, we first present a typical example showing the three important features of the GT ($\sigma\tau$) operator. They were observed in a high energy-resolution ^{9}Be(^{3}He, t)^{9}B reaction at RCNP. Then, we present the latest progress in the study of GT transitions starting from stable as well as unstable pf-shell nuclei, that are of interest in nuclear physics as well as in astrophysics. It is suggested that these GT transitions play important roles in supernovae explosions as well as in rp-process nucleosynthesis [5]. In order to derive the standard B(GT) values and the GT transition strengths in pf-shell nuclei, we combine the information on isospin mirror GT transitions that is obtained from β-decay studies of proton-rich unstable pf-shell nuclei and high resolution (^{3}He, t) measurements on stable mirror nuclei.

2 High Resolution (^{3}He, t) Reaction at 0°

Studies of GT strengths in pf-shell nuclei using (p, n) reactions at intermediate energies started in the 1980s. They provided rich information on the overall GT strength distributions [6], but individual transitions were poorly studied due to their limited energy resolution of $\approx$ 300 keV. Therefore, it was not easy to calibrate the unit cross section $\hat{\sigma}^{\rm GT}(0°)$ by using β-decay "standard B(GT) values" on a level-by-level base [4].

The development in full beam matching techniques [7, 8, 9] realized an energy resolution of $\approx$ 30 keV in (^{3}He, t) reactions at an intermediate energy of 140 MeV/nucleon and 0°. With this one order-of-magnitude better resolution, we can now study GT and Fermi states that were unresolved in the pioneering (p, n) reactions (see Fig. 1). The validity of the proportionality [Eq. (2)] was examined by comparing the GT transition strengths in the (^{3}He, t) spectra to the B(GT) values from mirror β decays. Good proportionality of $\approx$ 5%

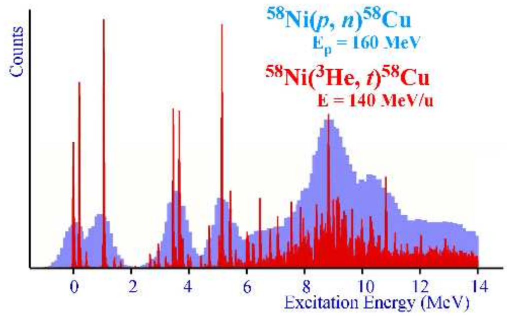

Figure 1: Energy spectra of charge-exchange reactions at 0°. The broad spectrum is from ^{58}Ni$(p, n)^{58}$Cu reaction measured in 1980's [6]. In the recent ^{58}Ni$(^3$He$, t)^{58}$Cu reaction [10] fine structure and sharp states have been observed up to the excitation energy of 13 MeV. The proton separation energy (S_p) is at 2.87 MeV. A increase of continuum is observed above $E_x = 6$ MeV.

was demonstrated for "$L = 0$" transitions with $B(\mathrm{GT}) \geq 0.04$ in studies of the $A = 26$ and 27 nuclear systems [11, 12, 13]. In some of the transitions, however, larger deviations from the proportionality were observed [14, 15]. The DWBA calculations performed using the transition matrix elements from shell-model calculations showed that the contribution of the Tensor interaction is responsible for these deviations from proportionality. It was found that in these cases two major $\Delta L = 0$ configurations, each of them having a large $\sigma\tau$ matrix element, contribute destructively to the GT transition strength. Then, the contribution of the $\Delta L = 2$ configurations activated by the $T\tau$ interaction is not negligible [14].

Owing to the high energy-resolution and the close proportionality given by Eq. (2), the $(^3$He$, t)$ reaction is recognized as an excellent tool for the study of the GT transitions in nuclei, especially of the strengths to discrete states. In addition, one obtains information on the widths of the discrete states.

2.1 Observation of isospin and shape selection rules

It was thought that a low energy-resolution was sufficient for the study of light nuclei due to the low level-density. However, the possibility of studying decay widths changed this perception. An interesting example is the observation of a sharp state at $E_x \approx 15$ MeV in the ^{9}Be$(^3$He$, t)^9$B spectrum. This is a $T_z = +1/2 \to -1/2$ transition. In CE spectra taken in the past, a very simple structure consisting of a sharp $J^\pi = 3/2^-$ g.s. and a broader 2.36 MeV state on top of a few-MeV-wide bump-like structure was identified, just as we see in Fig. 2(a). In ^{9}B, all states are situated above the proton and α separation energies of $S_p = -0.186$ MeV and $S_\alpha = -1.689$ MeV, respectively [16]. Therefore, from the uncertainty principle, it was expected that states should have large widths.

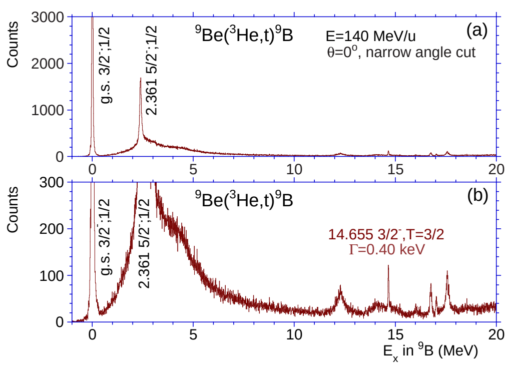

Figure 2: The ^{9}Be$(^3$He$, t)^9$B spectrum in two vertical scales. (a) Simple structure as shown in this figure was identified in earlier CE reactions. (b) By magnifying the vertical scale by one order-of-magnitude, a weak, but sharp state is observed at $E_x = 14.66$ MeV.

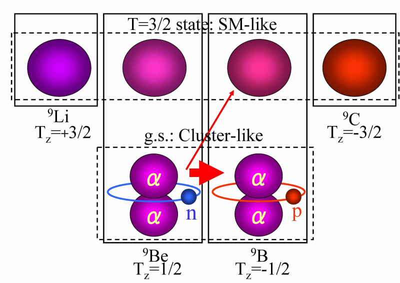

Figure 3: ^{9}Be and ^{9}B are mirror nuclei having $T_z = +1/2$ and $-1/2$, respectively. It is suggested that g.s. of them have the main structure of 2α + one-nucleon. On the other hand, the $E_x = 14.66$ MeV, $T = 3/2$ state in ^{9}B is the IAS of the g.s. of ^{9}Li and ^{9}C having a spherical shape [17]. It should be noted that ^{9}Li and ^{9}C are the $p_{3/2}$ closed-shell nuclei.

By magnifying the vertical scale [see Fig. 2(b)], we can see a sharp state at $E_x = 14.66$ MeV. A high sensitivity accompanied by an energy resolution of about 30 keV was essential to observe this weakly excited state on top of the continuum. We found that the sharpness of the state can be explained by the isospin selection-rule that prohibits proton (and also α) decay. It is known that this 14.66 MeV state has an isospin value of $T = 3/2$, and is the IAS of the g.s. of ^{9}Li and ^{9}C [16]. The proton decay of ^{9}B results in ^{8}Be (actually two α particles). The nucleus ^{8}Be and the proton have isospin values of $T = 0$ and $1/2$, respectively. The vector sum of these two isospin values cannot form an isospin value of 3/2; thus the proton decay is forbidden and the state is kept sharp. A recent analysis showed that several sharp states observed above 10.8 MeV in the ^{58}Ni$(^3$He$, t)^{58}$Cu reaction (see Fig. 1) have $T = 2$ [10]. Although these $T = 2$ states are located at nearly 10

MeV above the S_p value of 2.87 MeV, the proton decay into ^{57}Ni ($T_z = +1/2$, and thus the g.s. has $T = 1/2$) and a proton ($T = 1/2$) is not allowed.

It is known that both the g.s. and this 14.66 MeV state in ^{9}B have $J^\pi = 3/2^-$. Thus, they can be connected by an allowed GT transition with the $J^\pi = 3/2^-$ g.s. of ^{9}Be. However, in reality, the transition strengths differ by two orders-of-magnitude. It should be noted that the GT ($\sigma\tau$) operator cannot connect the states with different spatial shapes. Therefore, it is suggested that the g.s. of ^{9}Be (and of ^{9}B) have a different structure from the 14.66 MeV state in ^{9}B, which is the IAS of the g.s. of ^{9}Li and ^{9}C (see Fig. 3). In a recent calculation using the method of antisymmetrized molecular dynamics (AMD), a structure consisting of 2α + one-nucleon was predicted for the g.s. of ^{9}Be and ^{9}B, while a mean-field like structure is predicted for the 14.66 MeV state in ^{9}B and its IASs [17]. A detailed analysis is in progress [18].

3 Combined Analysis of (^{3}He, t) and β-decay Results: for the study of Gamow-Teller transitions in pf-shell nuclei

Gamow-Teller transitions starting from stable as well as unstable pf-shell nuclei are of interest not only in nuclear physics, but also in astrophysics. The $T_z = +1 \rightarrow 0$ transitions have been studied via (^{3}He, t) reactions on the stable $T_z = +1$ target nuclei ^{42}Ca [19], ^{46}Cr [20], ^{50}Cr [21], ^{54}Fe [19] and ^{58}Ni [10]. The $T_z = -1 \rightarrow 0$ transitions can be studied by the β decay from far-from-stability $T_z = -1$ nuclei (see Fig. 4). Assuming that these analogous GT transitions have the same B(GT) values, the B(GT) values from β decays can in principle be used as "standard B(GT) values" to determine the $\hat{\sigma}^{\mathrm{GT}}(0°)$ value for each A system. Once the $\hat{\sigma}^{\mathrm{GT}}(0°)$ value is known, the B(GT) values can be determined for the transitions up to highly excited states using Eq. (2). However, due to large uncertainties in the β-decay B(GT) values for the pf-shell nuclei, this idea is not practical.

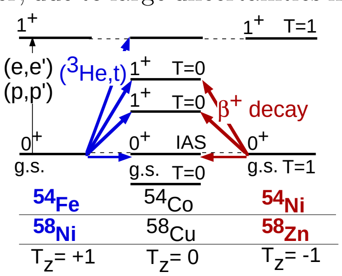

Figure 4: Schematic illustration of the isospin symmetry GT transitions in the "$T = 1$ system" for $A = 54$ and 58. The $T_z = \pm 1 \rightarrow 0$ transitions can be studied by the (^{3}He, t) reaction and β decay, respectively, for the pf-shell nuclei. Coulomb displacement energies are removed to show the isospin symmetry structure.

3.1 Merged analysis combining charge-exchange and β-decay information

Assuming the symmetry for the strengths of $T_z = \pm 1 \rightarrow 0$ analogous GT transitions, we can combine the results from the (^{3}He, t) reaction and β-decay for the better determination of absolute B(GT) values [21]. The "merged analysis" starts with the fundamental formula of the β decay; the inverse of the total half-life $T_{1/2}$ is the sum of the inverse of the partial half-life t_{F} of the Fermi transition and partial t_is of GT transitions

$$(1/T_{1/2}) = (1/t_{\mathrm{F}}) + \sum_{i=\mathrm{GT}} (1/t_i). \tag{3}$$

Since the inverse of the half-life represents the transition strength, this formula simply shows that the total transition strength is the sum of the Fermi and GT transition strengths. In a β decay, the accurate determination of t_is for the transitions to higher excited states is more difficult due to the smaller f-factors. On the other hand, in the studies of analogous GT transitions using the (^{3}He, t) reactions, transition strengths proportional to B(GT) values can be accurately obtained even for these higher excited states from the measured cross sections at 0° [see Eq. (2)]. Applying Eq. (1), one can eliminate both t_{F} and t_i, and we get

$$\frac{1}{T_{1/2}} = \frac{1}{K}\left[B(\mathrm{F})(1-\delta_c)f_{\mathrm{F}} + \sum_{i=\mathrm{GT}} \lambda^2 B_i(\mathrm{GT}) f_i\right]. \tag{4}$$

Here f_{F} and f_i are geometrical factors which can be calculated, $B(\mathrm{F}) = |N - Z|$ and the relative strengths proportional to B_i(GT) can be studied in the (^{3}He, t) reaction. Therefore, if the total half-life $T_{1/2}$ of the β decay is known accurately, the relative strengths B_i(GT) studied in the (^{3}He, t) reaction can be converted into absolute values.

4 New β-decay experiments

New results from various β-decay experiments are presented. By combining them with the results from high-resolution (^{3}He, t) experiments, studies of GT transitions become fruitful.

4.1 Half-life measurement of ^{54}Ni and the merged analysis

We now apply the "merged analysis" to the $A = 54$ system. The $T_z = \pm 1 \rightarrow 0$ mirror GT transitions are measured in the ^{54}Fe(^{3}He, t)^{54}Co reaction and the ^{54}Ni β decay (see Fig. 4). Since an accurate half-life is important in the analysis, we first had to start with the determination of an accurate $T_{1/2}$ value for the β decay in the $A = 54$ system.

The β-decay of the proton-rich nucleus ^{54}Ni was studied at the CRC, Louvain-la-Neuve. The ^{54}Fe(^{3}He, $3n$)^{54}Ni fusion evaporation reaction at the beam energy of 45 MeV was used for the production of ^{54}Ni. Nickel was selectively ionized in a laser ion-source using a two-step ionization scheme, and $A = 54$ nuclei were selected by the Leuven isotope separator facility (LISOL) [22, 23]. The mass separated ions were implanted in a tape system surrounded by three plastic β detectors and two MINIBALL Ge detectors.

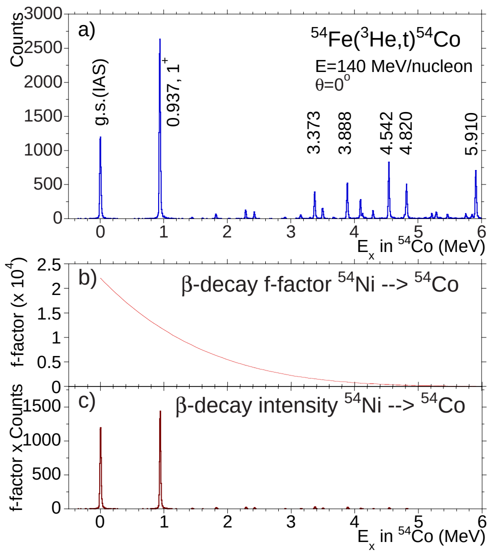

Figure 5: (a) The ^{54}Fe(^{3}He, t)^{54}Co spectrum for events with scattering angles $\Theta \leq 0.5°$. Major $L = 0$ states, most probably the GT states, are indicated by their excitation energies in MeV. (b) The f-factor for the ^{54}Ni β decay, calculated from the decay Q-value of 8799(50) keV. (c) The estimated ^{54}Ni β-decay energy spectrum that is obtained by multiplying the f-factor to the ^{54}Fe(^{3}He, t) spectrum. Suppression of the feeding to higher excited states is obvious. Note that the IAS is stronger by a factor of ≈ 5 in the real β-decay measurement due to the different coupling constants in the β decay and the (^{3}He, t) reaction.

The $T_{1/2}$ value of ^{54}Ni was determined by observing the exponential decay of the intensity of the 937 keV delayed γ rays from the first $J^\pi = 1^+$ GT state to the g.s. of ^{54}Co (see Fig. 5). A preliminary analysis of the decay curve for the 937 keV γ rays gave $T_{1/2} = 115 \pm 4$ ms. This value is longer than the published value of 106 ± 12 ms [24]. It is important to note that the uncertainty has been reduced due to higher statistics.

In Ref. [24], a B(GT) value of 0.68(16) was obtained for the transition to the 0.937 MeV state assuming that all β-decay GT strength is concentrated in this decay. However, the longer half-life and the finding of the feeding to higher excited states in the ^{54}Fe(^{3}He, t)^{54}Co reaction [19] suggest that the GT transition strength to the $E_x = 937$ keV state should be smaller. In the "merged analysis", we obtain B(GT) $= 0.46(8)$; a value smaller by about 30% compared to the previous one. The $T_z = +1 \rightarrow 0$ transition strength to this state has been measured in a ^{54}Fe(p, n) reaction at $E_p = 135$ MeV [25]. Compared to their B(GT) value of 0.74(5), which was derived from their own systematics, our new value is more than 35% smaller.

4.2 Measurement of feeding ratio at GSI

The $T_z = -1 \rightarrow 0$ β-decays of ^{42}Ti, ^{46}Cr, ^{50}Fe and ^{54}Ni and associated delayed γ rays were studied in order to measure the feeding ratios up to higher excitations. The experiment was performed as part of the RISING stopped beam campaign [26] at the FRagment Separator (FRS), GSI, Darmstadt. Beams of ^{42}Ti, ^{46}Cr, ^{50}Fe and ^{54}Ni were produced by the fragmentation process from a primary 680 MeV/nucleon ^{58}Ni beam of 0.1 nA on a Be target. Each beam was well separated by the FRS facility and ions were implanted into an active stopper system consisting of three layers of double-sided silicon strip detectors (DSSDs). They were surrounded by the RISING γ-ray array composed of 15 EUROBALL cluster Ge detectors. The overall γ-ray detection efficiency was about 15% at 1.33 MeV.

Due to the high production rate for ^{54}Ni and the good detection efficiency of the RISING setup high-energy delayed γ rays could be seen [Fig. 6(b)] at the energies corresponding to the GT states observed in the ^{54}Fe(^{3}He, t)^{54}Co measurement [19]. A good symmetry is suggested for the $T_z = \pm 1 \rightarrow 0$ GT transitions, which supports the basis of the "merged analysis" of the β-decay and (^{3}He, t) results.

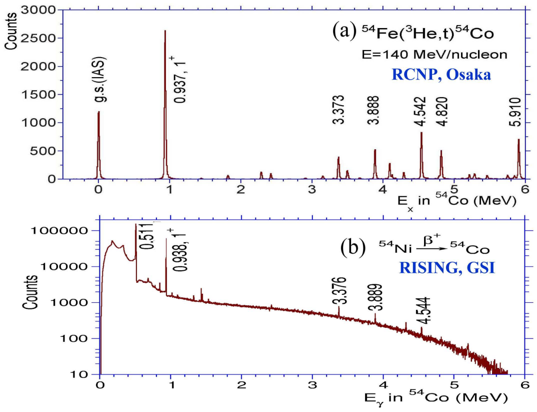

Figure 6: (a) The $^{54}\mathrm{Fe}(^{3}\mathrm{He},t)^{54}\mathrm{Co}$ spectrum for events with scattering angles $\Theta \leq 0.5°$. Major excited $L = 0$ states are indicated by energies in MeV. (b) On-line γ-ray spectrum at RISING, GSI, measured in coincidence with the β particles from the $^{54}\mathrm{Ni}$ decay. The existence of γ-ray peaks and CE-reaction peaks at corresponding energies suggests a good mirror symmetry of $T_z = -1 \rightarrow 0$ and $T_z = +1 \rightarrow 0$ GT transitions.

4.3 β-decay study of proton-rich pf-shell nuclei at GANIL

Since the S_p value of the daughter nucleus become lower as the mass number A and isospin T increase, measurements of the delayed-protons in β decay will become important for the study of proton-rich pf-shell nuclei far-from-stability. In addition, due to larger Q_{EC} values, the β^+ decay can access GT transitions to higher excited states in the daughter nucleus. The difficulty, however, is the low-production rate of such exotic nuclei, and thus the determination of the absolute yield of the decaying protons and γ rays.

Exotic nuclei such as $^{58}\mathrm{Zn}$ and $^{56}\mathrm{Zn}$ have $T_z = -1$ and $T_z = -2$, respectively. They are the isospin mirror nuclei of the stable $^{58}\mathrm{Ni}$ and $^{56}\mathrm{Fe}$, respectively. We have studied the β decay of these exotic nuclei at GANIL, France. The half-life and branching ratios obtained in the β-decay are compared and combined with the relative GT strength distributions from the high-resolution $^{58}\mathrm{Ni}$ and $^{56}\mathrm{Fe}(^{3}\mathrm{He},t)$ measurements for the better understanding of the nuclear structure of these pf-shell nuclei far-from-stability. We also plan to deduce the accurate $B(\mathrm{GT})$ values starting from these nuclei by means of the "merged analysis" described in Sec. 3.1. The $(^{3}\mathrm{He},t)$ spectra obtained for $^{58}\mathrm{Ni}$ ($T_z = +1$) [10, 27] and $^{56}\mathrm{Fe}$ ($T_z = +2$) [28] are shown in Fig. 7. The angular-distribution analysis suggests that most of the prominent levels are GT states (except the IAS).

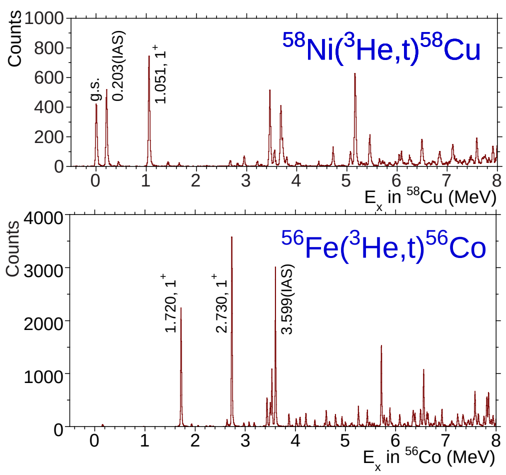

Figure 7: The $^{58}\mathrm{Ni}(^{3}\mathrm{He},t)^{58}\mathrm{Cu}$ and $^{56}\mathrm{Fe}(^{3}\mathrm{He},t)^{56}\mathrm{Co}$ spectra at 0° and an intermediate incident energy of 140 MeV/nucleon. The GT transitions in these $^{58}\mathrm{Cu}$ and $^{56}\mathrm{Co}$ spectra have the properties of $T_z = +1 \rightarrow 0$ (see Fig. 4) and $T_z = +2 \rightarrow +1$, respectively. The vertical scales of them are normalized by the heights of the IAS peaks representing Fermi transition strengths of $B(\mathrm{F}) = N - Z = 2$ and 4, respectively. Therefore, it is expected that the heights of the GT peaks in these figures are almost proportional to $B(\mathrm{GT})$ values.

Since the S_p values in $^{56}\mathrm{Cu}$ and $^{58}\mathrm{Cu}$ are 0.56 and 2.87 MeV, respectively, measurements of both delayed protons and gammas are important for the derivation of absolute $B(\mathrm{GT})$ values. In our recent experiment performed at the LISE3 facility of GANIL [29], β decay of $^{58}\mathrm{Zn}$ was studied. A $^{64}\mathrm{Zn}^{29+}$ 79 MeV/nucleon beam with an average intensity of 500 enA was accelerated by the two GANIL accelerators CSS1 and CSS2 and impinged on a $^{\mathrm{nat}}\mathrm{Ni}$ production target. The $^{58}\mathrm{Zn}$ nuclei produced by the fragmentation process were selected by the LISE spectrometer and the following Wien filter. Beryllium degraders were installed at the intermediate focal plane of LISE in order to achieve the achromatic condition for the fragments. The implantation detector setup at the focal plane consisted of a standard 300 μm-thick silicon detector providing the energy loss signal, a 1004 μm double-sided silicon strip detector (DSSD) with 16×16 strips with a pitch of 3 mm used as the implantation device, and a 4 mm thick lithium-drifted silicon detector used as a veto detector for the implantation events and also to detect β particles. The implantation array was surrounded by four germanium detectors.

We obtained an on-line value of $T_{1/2} = 90(8)$ ms for the decay of $^{58}\mathrm{Zn}$ from the β-delayed γ-ray measurement. An experiment at ISOLDE reported a value of 86(18) ms [30]. An earlier study at GANIL gave a value of 83(10) ms [31]. The more accurate value expected from the off-line analysis will make the "merged analysis" fruitful.

5 Summary and Prospects

With the improvement in the energy resolution in the β^--type CE reaction (^{3}He, t) at 140 MeV/nucleon, we have started to see the details of the GT transitions; fine structures of GT excitations, even those of GT giant resonances, and also the width of each state. By comparing the strengths of analogous GT transitions in *sd*-shell nuclei, a close proportionality between the cross-sections at 0° and B(GT) values were observed in the (^{3}He, t) reaction. We also start to understand the contributions of the $T\tau$ term for the deviations from proportionality.

Owing to the proportionality, the B(GT) values can be deduced up to high excitation energies once a standard B(GT) value is provided by the β decay. However, in the *pf*-shell region, the β-decay B(GT) values have larger uncertainties; only $T_{1/2}$ values were relatively reliable. We introduced the "merged analysis" to overcome this difficulty and to determine the absolute B(GT) values.

By the introduction of isospin symmetry and the merged analysis in the study of GT transition strength, the (^{3}He, t) measurements and the β-decay studies are now tightly connected. Newly obtained β-decay results at ISOL facilities as well as at the fragment-separator facilities (e.g. Ref. [32]) can be analyzed cooperatively using the information from the high-resolution (^{3}He, t) reactions. In addition, recent precise Q-value (mass) measurements which can be performed at trap facilities would bring more accurate f-factors. A better knowledge of them will make such a combined analysis more fruitful as the means to determine the GT strengths in stable as well as exotic *pf*-shell nuclei. They are also needed to deduce the astrophysical transition rates under extreme conditions.

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