Vol. 43 (2012) *ACTA PHYSICA POLONICA B* No 2

GAMOW–TELLER TRANSITIONS — A MIRROR REFLECTING NUCLEAR STRUCTURE*

Y. Fujita, H. Fujita

Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan
and
Research Center for Nuclear Physics, Osaka University
Ibaraki, Osaka 567-0047, Japan

B. Rubio

IFIC, CSIC-Universidad de Valencia, 46071 Valencia, Spain

W. Gelletly

Physics Department, University of Surrey, Guildford GU2 7XH, Surrey, UK

B. Blank

Centre d'Etudes Nucléaires de Bordeaux Gradignan, Université Bordeaux 1
UMR 5797 CNRS/IN2P3, BP 120, 33175 Gradignan, France

(Received December 1, 2011)

Studying the weak nuclear response, especially the Gamow–Teller (GT) transitions starting from stable as well as unstable nuclei is one of the key issues in nuclear and nuclear-astrophysics. We studied the GT transitions by means of hadronic (^{3}He, t) charge-exchange reactions and complementary β decays. Owing to the simple $\sigma\tau$ nature of the operator that causes GT transitions, information on the crucial and critical part of the nuclear structure can be studied. Under the assumption that isospin is a good quantum number, symmetry is expected for the structure of mirror nuclei and the GT transitions starting from them. The results from β-decay studies and the strength distribution of GT transitions from the (^{3}He, t) reaction are compared and also combined for the understanding of nuclear structure of far-from-stability nuclei.

DOI:10.5506/APhysPolB.43.153
PACS numbers: 21.10.Hw, 23.40.–s, 25.55.Kr, 27.20.+n

* Presented at the XXXII Mazurian Lakes Conference on Physics, Piaski, Poland, September 11–18, 2011.

1. Introduction

Gamow–Teller (GT) transitions are the most common weak interaction processes of spin–isospin ($\sigma\tau$) type in atomic nuclei [1]. They are of interest not only in nuclear physics but also in astrophysics [2]; they play an important role in supernovae explosions and nucleosynthesis. The direct study of weak decay processes, however, gives relatively limited information about GT transitions and the states excited via GT transitions (GT states); β decay can only access states at excitation energies lower than the decay Q-value, and neutrino-induced reactions have very small cross sections. However, one should note that the β decay has a direct access to the absolute GT transition strengths $B(\mathrm{GT})$ from a study of half-lives, Q_β-values and branching ratios.

In contrast, the complementary charge-exchange (CE) reactions, such as the (p,n) or $(^3\mathrm{He},t)$ reactions at intermediate beam energies and $0°$, can selectively excite GT states up to high excitation energies in the final nucleus. In recent $(^3\mathrm{He},t)$ measurements, one order-of-magnitude improvement in the energy resolution has been achieved. This has made it possible to make one-to-one comparisons of GT transitions studied in CE reactions and β decays. Thus GT strengths in $(^3\mathrm{He},t)$ reactions can be normalized by the β-decay values.

The main features of GT transitions can be summarized as follows:

(1) They start from a nucleus with Z and N and lead to states in a neighboring nucleus with $Z \pm 1$ and $N \mp 1$. Thus the β^+-type GT transitions have the nature of $\Delta T_z = +1$ and the β^--type GT transitions $\Delta T_z = -1$, where T_z is defined by $(N-Z)/2$ and is the z component of the isospin T. As a result, they are of isovector (IV) nature with $\Delta\boldsymbol{T} = \mathbf{1}$ ($\Delta T = \pm1$ or 0). Since GT transitions involve $\Delta\boldsymbol{S} = \mathbf{1}$ and $\Delta\boldsymbol{L} = 0$, they also have $\Delta\boldsymbol{J} = \mathbf{1}$ ($\Delta J = \pm1$ or 0) and no parity change.

(2) They can be studied either in β decay (weak interaction) or in charge exchange (strong interaction) reactions.

(3) Since the $\sigma\tau$ operator has no spatial component, transitions between states with similar spatial shapes are favored.

(4) In a simple, independent particle picture where the individual nucleons are in an orbit with orbital angular momentum ℓ and spin s, a GT transition connects initial and final states with the same ℓ. Therefore, the transitions are among the spin–orbit partners, *i.e.*, the $j_>$ $(= \ell + 1/2)$ and the $j_<$ $(= \ell - 1/2)$ orbits. The $j_> \leftrightarrow j_<$ transition and the transitions between the same orbits (*i.e.*, $j_> \leftrightarrow j_>$ and $j_< \leftrightarrow j_<$) are separated, in first order, by 3 to 6 MeV, the separation in energy of the spin–orbit partners.

(5) In contrast to the Fermi transitions, where only the T_z is changed by the τ operator and hence only a single state (the so-called Isobaric Analog State) is populated in the final nucleus, GT transitions involve both the σ and the τ operators and a variety of different states can be populated. As a result, one can extract more information about nuclear structure in the final nucleus.

(6) Besides the information on nuclear structure, GT transitions are also important in terms of our understanding of many processes in nuclear astrophysics.

On the assumption that the nuclear interaction is charge-symmetric, isospin is a good quantum number. As a result, isobars with $\pm T_z$ should exhibit a symmetric structure. Therefore, corresponding (analogous) GT transitions with, for example, $T_z = \pm 1 \rightarrow 0$ and $T_z = \pm 2 \rightarrow \pm 1$ are expected to have the same transition strengths. They can be studied by charge-exchange (CE) reactions and β decay [3]. It should be noted that the relative GT strengths can be well studied up to high excitation energy in CE reactions, but the absolute $B(\mathrm{GT})$ strengths are obtained by normalizing to those obtained in β-decay studies. Thus, studies of β decay and CE reactions are complementary. A project to study the GT transitions in various p-shell, sd-shell and pf-shell nuclei is in progress.

2. Properties of charge-exchange $(^3\mathrm{He}, t)$ reaction

The $(^3\mathrm{He}, t)$ reaction studies are performed at the high energy-resolution facility of RCNP, Osaka, consisting of high-dispersion beam line "WS course" and the "Grand Raiden" spectrometer using a beam from the $K = 400$ "Ring Cyclotron" [4]. The reaction performed at the intermediate incoming energy of 140 MeV/nucleon and at 0° is a unique tool for the study of GT transition strengths owing to the high selectivity of exciting GT states and the high energy-resolution. Unlike the (p, n) reaction used for the study of GT transitions, the emitted tritons can be momentum analyzed by using a magnetic spectrometer. In addition, we use dispersion matching techniques to improve the energy resolution as well as angular resolution in the spectrum obtained. The ion-optical concepts of the matching conditions are found in Ref. [3]. By applying these matching techniques, a resolution better than the momentum (energy) spread of the beam can be realized. For a typical beam energy resolution of 120 keV, a resolution of 30 keV is achieved in the $(^3\mathrm{He}, t)$ spectrum.

In CE reactions at intermediate incoming energies of more than 100 MeV/nucleon, the reaction mechanism becomes simple and the $\sigma\tau$ part of the effective interaction becomes dominant. As a result, at momentum transfer $q = 0$ there is a close proportionality between the cross sections and the $B(\mathrm{GT})$ values. This close proportionality that was first established in (p,n) reactions at intermediate energies of 120–200 MeV [5] was also observed in the $(^3\mathrm{He},t)$ reaction [3]

$$\frac{d\sigma_{\mathrm{GT}}}{d\Omega}(0) = \hat{\sigma}_{\mathrm{GT}}(0)B(\mathrm{GT})\,, \tag{1}$$

where $\hat{\sigma}_{\mathrm{GT}}(0)$ is a unit cross section for the GT transition at the momentum transfer $q = 0$ ($\approx 0^\circ$). Although there are exceptions, the $B(\mathrm{GT})$ values from the $(^3\mathrm{He},t)$ CE reactions usually agreed within 5% with the β-decay $B(\mathrm{GT})$ values by applying only one normalization parameter [3].

3. Gamow–Teller response functions for *p*-shell nuclei

It is expected that the response of nuclei to GT transitions varies considerably reflecting the structures of initial and final nuclei. Here we show high energy-resolution $(^3\mathrm{He},t)$ spectra obtained on p-shell nuclei at 0° and the intermediate energy of 140 MeV/nucleon, where the reaction mechanism is mainly one step.

Due to the low level density, we can observe the GT states in p-shell nuclei as individual states. However, when these states are situated above the particle separation energies (either S_p or S_α), they can have a particle decay width. In addition, we will find that the transition strengths in these nuclei are strongly related to the cluster structure.

3.1. Isospin selection rule and shape effects in A = 9 nuclei

With the realization of high resolution in CE reactions, it became possible to measure the decay widths even at intermediate incoming beam energies. In addition, the high resolution studies provide a powerful tool for the detection of sharp but weakly excited states that co-exist with broad peaks in the high excitation region.

An interesting example is the observation of a sharp state at $E_x \approx$ 15 MeV in the $^9\mathrm{Be}(^3\mathrm{He},t)^9\mathrm{B}$ spectrum [6]. This is a $T_z = +1/2 \rightarrow -1/2$ transition. In CE spectra taken in the past, a 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. 1 (a). In $^9\mathrm{B}$, all states are situated above the proton- and α-separation energies of $S_p = -0.186$ MeV and $S_\alpha = -1.689$ MeV, respectively [8]. Therefore, thinking in terms of the uncertainty principle, it is anticipated that states can have rather large widths at excitation energies of a few MeV (*i.e.*, the energy of the Coulomb barrier) above these particle separation energies.

As shown in Fig. 1 (b), when the vertical scale is expanded, we start to see a sharp state at $E_x = 14.66$ MeV. High sensitivity accompanied by high energy-resolution of about 30 keV was essential to observe this weakly excited state on the continuum. 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 14.6550(25) MeV state has an isospin value of $T = 3/2$ (the so-called $T_>$ state), and is the IAS of the g.s. of ^{9}Li and ^{9}C [8]. The proton decay of ^{9}B results in ^{8}Be (observed as two αs in the resulting breakup). 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 sharp. In a similar way, the isospin selection rule prohibits the α decay.

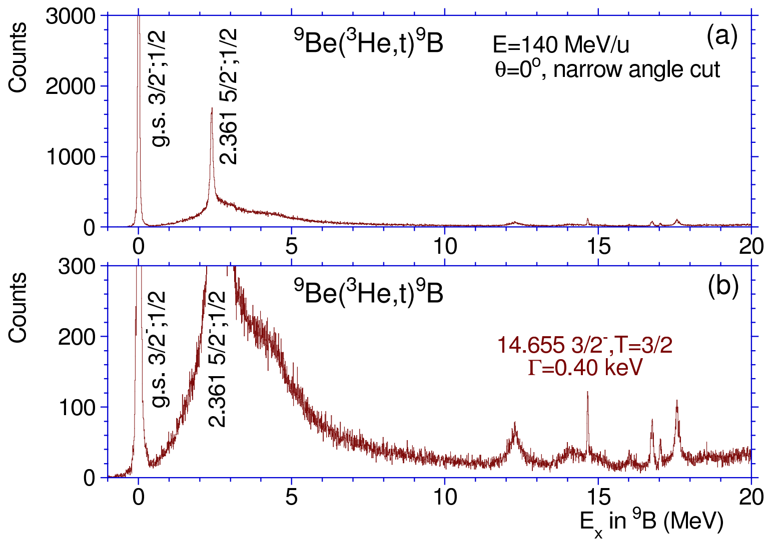

Fig. 1. The ^{9}Be(^{3}He, t)^{9}B spectrum on two vertical scales. (a) The structure shown in this figure was discussed in earlier CE reactions [7]. (b) By magnifying the vertical scale by one order-of-magnitude, fine structure was observed in the $E_x =$ 14–18 MeV region. The 14.66 MeV state was weak but sharp.

In addition, the weak excitation of the $E_x = 14.66$ MeV state is explained by the difference of the spatial shape from the g.s. of ^{9}Be (see Fig. 2).

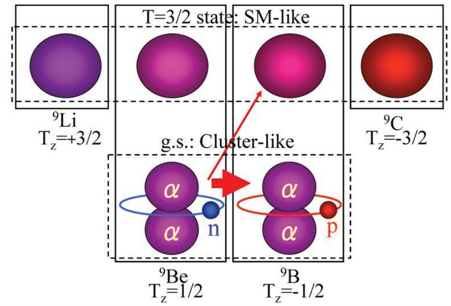

Fig. 2. ^{9}Be and ^{9}B are $T_z = \pm 1/2$ mirror nuclei. It is thought that the main component of their ground states is 2α+one-nucleon [9]. On the other hand, the $E_x = 14.66$ MeV, $T = 3/2$ state in ^{9}B is the IAS of the g.s. of ^{9}Li and ^{9}C having a spherical shape. It should be noted that ^{9}Li and ^{9}C are the $p_{3/2}$ closed-shell nuclei.

3.2. The "odd mass Hoyle state" in A = 11 nuclei

The nuclei ^{11}B and ^{11}C are mirror nuclei. As shown in Fig. 3 (a), the GT strength observed in the 0°, ^{11}B(^{3}He, t)^{11}C spectrum was fragmented. It was found that the fragmentation can be roughly understood by the coupling of a $p_{3/2}$ proton hole (for ^{11}B) or neutron hole (for ^{11}C) to the ^{12}C core. The coupling to the 0^+ g.s. in ^{12}C produces the $J^\pi = 3/2^-$ ground states in ^{11}B and ^{11}C, and the coupling to the 2^+ first excited state at 4.44 MeV will produce a multiplet of states with $1/2^-$, $3/2^-$, $5/2^-$ and $7/2^-$. The $1/2^-$, $3/2^-$, $5/2^-$ states in ^{11}C can be reached from the $3/2^-$ g.s. of ^{11}B by GT transitions. As reported in [10], the GT strength distribution was well reproduced by a classical shell-model calculation using the Cohen–Kurath interaction [11] with the introduction of a quenching factor, and also by an *ab initio* no-core shell-model calculation including a three-nucleon interaction [12, 13]. It should be noted that the latter could reproduce the absolute B(GT) strengths without introducing the quenching factor.

Because of the excellent energy-resolution in the (^{3}He, t) experiment, a peak observed at 8.4 MeV in an earlier (p, n) experiment [11] was resolved into 8.105 and 8.420 MeV states in agreement with [14]. It was found that there was almost no strength in the transition to the second excited $J^\pi = 3/2^-$ state at 8.105 MeV, although the transition from the ^{11}B g.s. with $J^\pi = 3/2^-$ is allowed by the J^π selection rule. We can see this state only by magnifying the vertical scale by a factor of thirty as shown in Fig. 3 (b). Interest in this state is not only due to its weak excitation, but also its absence in the shell-model calculations. These features strongly suggest that this 8.105 MeV state has a completely different spatial structure from the other strongly excited states.

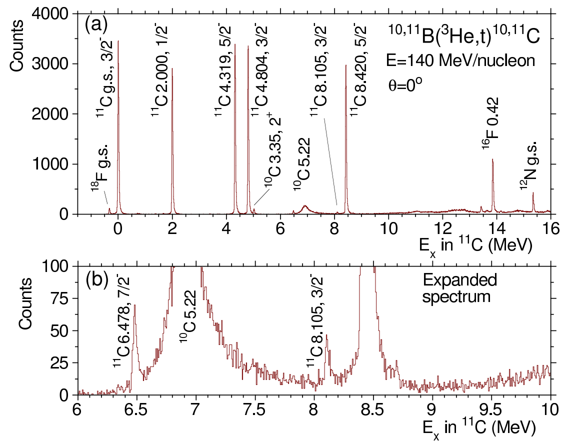

Fig. 3. Energy spectra from the ^{11}B(^{3}He, t)^{11}C reaction at 0° on two scales. (a) The spectrum up to $E_x = 16$ MeV. (b) The expanded 6–10 MeV region. The weakly excited $J^\pi = 3/2^-$, 8.105 MeV state is observed.

The answer came from recent calculations within the antisymmetrized molecular dynamics (AMD) framework. It was shown that the second excited $3/2^-$ state in ^{11}B and ^{11}C and the first excited 0^+ state at 7.65 MeV in ^{12}C have a strong similarity from the viewpoint of cluster structure [15]. As is well known, this 7.65 MeV, 0^+ state, the "Hoyle state," is situated just above the three α threshold and is interpreted as a dilute gas state of three weakly interacting α particles [16,17,18]. It plays an essential role in the formation of ^{12}C by the triple alpha reaction in the Cosmos. Correspondingly, the AMD calculation shows that the second excited $3/2^-$ states in ^{11}B and ^{11}C have the well-developed cluster structures of 2α + ^{3}H and 2α + ^{3}He with dilute density, respectively. Therefore, these states may be called "odd mass Hoyle states." The similarity of the structures of these states and the Hoyle state was suggested experimentally by the similarity of the angular distributions of them in the ^{11}B and ^{12}C(d, d') reactions [19].

4. Combined study of β-decay and CE reaction

New results from various β-decay experiments are coming out. By combining them with the results from high-resolution (^{3}He, t) experiments, studies of GT transitions become fruitful. Here, we report the comparison of these two results for the $T_z = \pm 1 \to 0$ GT transitions in the pf-shell nuclei. We also show the complementary $T_z = \pm 2 \to \pm 1$ studies using the (^{3}He, t) reaction and β-decay. We have reported $T_z = +1 \to 0$ GT transitions in $A = 46, 50$ and 58 nuclear systems [20, 21, 22] and the β-decay studies of mirror $T_z = -1 \to 0$ transitions have also been partly reported [23].

4.1. Isospin symmetry and analogous transitions

The Gamow–Teller (GT) transitions starting from stable as well as proton-rich unstable pf-shell nuclei play an important role in the core-collapse stage of type II supernovae [2]. However, our experimental study of the GT transitions starting from unstable nuclei with $T_z = -1$ or -2 is rather poor; accurate β-decay half-lives have been measured for several $T_z = -1$ and -2 nuclei [24], but the determination of GT transition strengths, $B(\mathrm{GT})$s, have been out of reach in decay studies. This is due to the small production rate of such far-from-stability nuclei, and also the small f-factors in the feedings to higher excited states, which makes the accurate determination of branching ratios difficult.

Under the assumption that isospin T is a good quantum number, an analogous structure is expected for nuclei with the same mass A but with different T_z (isobars). The corresponding states in isobars are called isobaric analog states (or simply analog states), and are expected to have the same nuclear structure. Transitions connecting corresponding analog states are also analogous and have corresponding strengths (see *e.g.* Ref. [25]).

4.2. (^{3}He,t) *reactions on* $T_z = +1$ *nuclei at RCNP and the mirror* β*-decay studies at GSI*

The $T_z = +1 \rightarrow 0$ GT transitions were measured on target nuclei ^{42}Ca, ^{46}Ti, ^{50}Cr and ^{54}Fe in the (^{3}He, t) reaction, while $T_z = -1 \rightarrow 0$ GT transitions were studied in the β decay of $T_z = -1$ mirror nuclei ^{42}Ti, ^{46}Cr, ^{50}Fe and ^{54}Ni. The isospin symmetry is schematically shown in Fig. 4 for the $A = 54$ transitions.

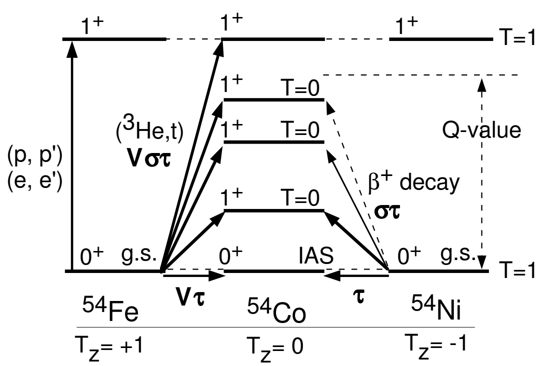

Fig. 4. Schematic illustration of the isospin symmetry GT transitions in the "$T = 1$ system" for $A = 54$ nuclei. The $T_z = \pm 1 \rightarrow 0$ transitions can be studied by the (^{3}He, t) reaction and β decay, respectively, for the pf-shell nuclei. Coulomb displacement energies are removed to show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

In order to compare results from these $T_z = \pm 1 \rightarrow 0$ GT transitions up to high excitation energies, it is important to achieve a good resolution in the $(^3\mathrm{He}, t)$ reaction to identify each transitions, while it is important to get high statistics in the β-decay measurements. This is illustrated in Fig. 5 for the $A = 54$ mirror GT transitions.

The ^{54}Co spectrum observed in the $^{54}\mathrm{Fe}(^3\mathrm{He}, t)$ reaction is shown in Fig. 5 (a). As mentioned, the peak yields (or heights of peaks) are almost proportional to the B(GT) values. In the mirror β decay, *i.e.*, in the decay of ^{54}Ni, it is expected that the branching ratios to the higher excited states are hindered by the phase-space factor (f-factor) shown in Fig. 5 (b). The transition strength in the β decay is proportional to $1/t_i$, where t_i is the partial half-life for the GT transtion to the ith excited state and is related to the B_i(GT) by

$$1/t_i = f\left(\lambda^2/K\right) B_i(\mathrm{GT})\,. \tag{2}$$

Since λ^2 and K are constant, the "β-decay spectrum" showing the yields in the β decay can be deduced by multiplying the $^{54}\mathrm{Fe}(^3\mathrm{He}, t)$ spectrum with the f-factor. The estimated ^{54}Ni β-decay energy spectrum is shown in Fig. 5 (c). Suppression of the feeding to higher excited states is obvious.

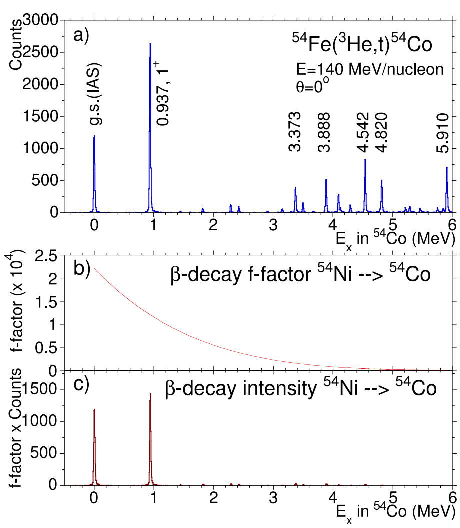

Fig. 5. (a) The 0° spectrum of $^{54}\mathrm{Fe}(^3\mathrm{He}, t)^{54}\mathrm{Co}$ reaction. Major $\Delta L = 0$ states are indicated by their excitation energies in MeV. (b) The f-factor for the ^{54}Ni β decay, calculated from the decay Q-value of 8799(50) keV. (c) The estimated strength distribution of ^{54}Ni β decay (^{54}Ni β-decay spectrum). 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 $(^3\mathrm{He}, t)$ reaction.

4.3. Measurement of delayed γs at GSI

The $T_z = -1 \rightarrow 0$ β-decays of ^{42}Ti, ^{46}Cr, ^{50}Fe and ^{54}Ni and their delayed γ rays were studied in order to measure the feeding ratios up to higher excitations and accurate half-lives. It should be noted that in these measurements, we study the mirror GT and Fermi transitions that are observed in (^{3}He, t) reactions on $T_z = +1$ nuclei ^{42}Ca, ^{46}Ti, ^{50}Cr and ^{54}Fe.

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 [27]. Even γ rays higher than 4 MeV could be identified. A good symmetry is suggested for the $T_z = \pm 1 \rightarrow 0$ GT transitions.

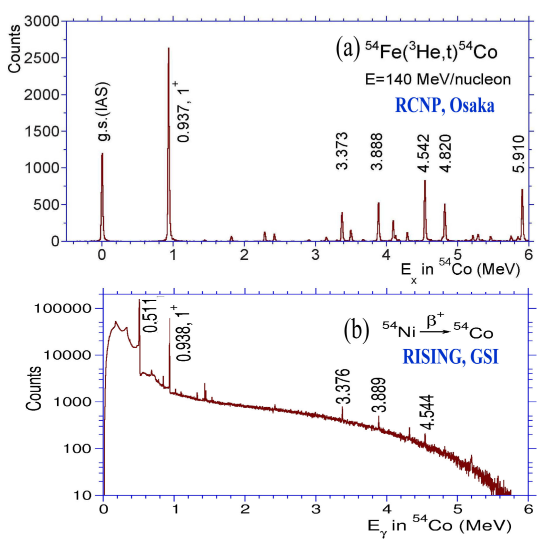

Fig. 6. (a) The 0°, ^{54}Fe(^{3}He, t)^{54}Co spectrum. Major excited $\Delta L = 0$ states are indicated by energies in MeV. (b) γ-ray spectrum at RISING, GSI, measured in coincidence with the β particles from the ^{54}Ni decay. The existence of γ-ray peaks and CE-reaction peaks at corresponding energies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

An interesting feature of the $M1$ γ decays from the excited $T = 0$, 1^+ states in the $T_z = 0$ daughter nucleus ^{54}Co is that they mostly decay directly to the $T = 1$, 0^+, ground state (the IAS of ^{54}Ni, ground state). This can be mainly explained by the fact that the coupling constant (the g-factor) of the $\sigma\tau$ component in the $M1$ operator is much larger than that of the σ component. In the $T_z = 0$ nucleus ^{54}Co, the $\sigma\tau$ component can contribute only to the $M1$ γ decays with $T = 0 \to 1$, but not to the $T = 0 \to 0$ decays, where the latter can be caused by the weak σ component.

4.4. The ^{52}Cr(^{3}He,t) *reaction at RCNP and the mirror* ^{52}Ni β *decay at GANIL*

The isospin symmetry of analog states and the analogous GT and Fermi transitions in the "$T = 2$ quintet" are shown in Fig. 7 for the $A = 52$ isobars.

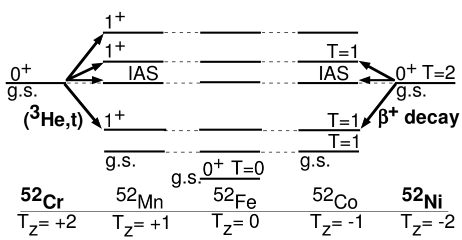

Fig. 7. Schematic view of the analog states and the isospin symmetry transitions in the mass $A = 52$, $T = 2$ quintet, where the Coulomb energy is removed. The (^{3}He, t) reaction studies the $T_z = +2 \to +1$ GT transitions and the Fermi transition to the isobaric analog state (IAS), while the β decay can study the analogous transitions with $T_z = -2 \to -1$.

The $T_z = +2 \to +1$, ^{52}Cr(^{3}He, t)^{52}Mn experiment was performed at RCNP, Osaka. A resolution of $\Delta E = 29$ keV achieved by using matching techniques was crucial in separating the IAS and the nearby 1^+, GT states (see Fig. 8 (a)). Using the proportionality (Eq. (1)) and the "merged analysis" [21] that uses the $T_{1/2}$ value (40.8(2) ms in the β decay of ^{52}Ni [24]) as an input, accurate B(GT) values are derived.

Assuming good isospin symmetry of the $T_z = \pm 2 \to \pm 1$ GT transitions, the "β-decay spectrum" of the $T_z = -2$ nucleus ^{52}Ni can be deduced by multiplying the calculated f-factor to the (^{3}He, t) spectrum on the $T_z = +2$ nucleus ^{52}Cr shown in Fig. 8 (a). By adding further the width corresponding to the resolution of the delayed-proton measurement, a spectrum shown in Fig. 8 (b) was obtained. It should be noted that the proton decay from the IAS is suppressed by the isospin selection rule (see the caption of Fig. 8). By assuming an appropriate suppression factor, we could well reproduce the delayed-proton spectrum of the ^{52}Ni β decay shown in Fig. 8 (c).

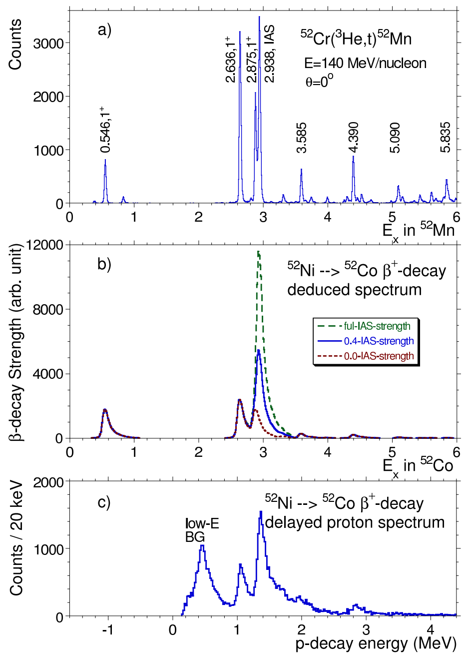

Fig. 8. (a) The ^{52}Cr(^{3}He, t)^{52}Mn spectrum for events within scattering angles $\Theta \leq 0.5°$. Major $\Delta L = 0$ states, most probably the GT states, are indicated by their excitation energies in MeV. (b) The estimated strength distribution of ^{52}Ni β decay that is obtained by multiplying the calculated f-factor to the ^{52}Cr(^{3}He, t) spectrum of the figure (a). The proton decay from the $T = 2$, IAS in the $T_z = -1$ nucleus ^{52}Co is not allowed by the isospin selection rule; the decay is possible only through the $T = 1$ isospin impurity. Therefore, the peak corresponding to the proton decay of the IAS should be suppressed. (c) The delayed-proton spectrum obtained in the ^{52}Ni, β-decay measurement (from Ref. [24]).

5. Summary

With the improvement in the energy resolution in the β^--type CE reaction (^{3}He, t) performed at 140 MeV/nucleon at RCNP, 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.

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 the fragment-separator facilities (GSI and GANIL) are complementary and can be analyzed together using the information from the high-resolution (^{3}He, t) reactions.

The high-resolution (^{3}He, t) experiments were performed at RCNP, Osaka. The authors are grateful to the participants in the experiments and the accelerator group of RCNP. This work was supported in part by MEXT, Japan under Grants No. 18540270 and No. 22540310 and also by the Japan–Spain collaboration program of JSPS and CSIC. This work was also supported in part by the Spanish MEC under Grant No. EPA2005-03993, the Brix-IAP Research Program (P06/23) and the U.K. Science and Technology Facilities Council (STFC) grant No. ST/F012012/1. The β-decay experiments were partly supported through EURONS No. 506065.

REFERENCES

[1] F. Osterfeld, *Rev. Mod. Phys.* **64**, 491 (1992) and references therein.

[2] K. Langanke, G. Martínez-Pinedo, *Rev. Mod. Phys.* **75**, 819 (2003).

[3] Y. Fujita, B. Rubio, W. Gelletly, *Prog. Par. Nucl. Phys.* **66**, 549 (2011) and references therein.

[4] See web site `http://www.rcnp.osaka-u.ac.jp`

[5] T.N. Taddeucci *et al.*, *Nucl. Phys.* **A469**, 125 (1987).

[6] C. Scholl *et al.*, *Phys. Rev.* **C84**, 014308 (2011).

[7] H. Akimune *et al.*, *Phys. Rev.* **C64**, 041305(R) (2001).

[8] J.H. Kelley *et al.*, *Nucl. Phys.* **A745**, 155 (2004).

[9] Y. Kanada-En'yo, H. Horiuchi, A. Ono, *Phys. Rev.* **C52**, 628 (1995) and private communication.

[10] Y. Fujita *et al.*, *Phys. Rev.* **C70**, 011306(R) (2004).

[11] T.N. Taddeucci *et al.*, *Phys. Rev.* **C42**, 935 (1990).

[12] P. Navrátil, W.E. Ormand, *Phys. Rev.* **C68**, 034305 (2003).

[13] P. Navrátil *et al.*, *Phys. Rev. Lett.* **99**, 042501 (2007).

[14] F. Ajzenberg-Selove, J.H. Kelley, *Nucl. Phys.* **A506**, 1 (1990).

[15] Y. Kanada-En'yo, *Phys. Rev.* **C75**, 024302 (2007).

[16] A. Tohsaki, H. Horiuchi, P. Schuck, G. Röpke, *Phys. Rev. Lett.* **87**, 192501 (2001).

[17] Y. Funaki *et al.*, *Phys. Rev.* **C67**, 051306(R) (2003).

[18] M. Chernykh *et al.*, *Phys. Rev. Lett.* **98**, 032501 (2007).

[19] T. Kawabata *et al.*, *Phys. Rev.* **C70**, 034318 (2004).

[20] T. Adachi *et al.*, *Phys. Rev.* **C73**, 024311 (2006).

[21] Y. Fujita *et al.*, *Phys. Rev. Lett.* **95**, 212501 (2005).

[22] H. Fujita *et al.*, *Phys. Rev.* **C75**, 034310 (2007).

[23] F. Molina, B. Rubio, Y. Fujita, W. Gelletly, *AIP Conf. Proc.* **1265**, 49 (2010).

[24] C. Dossat *et al.*, *Nucl. Phys.* **A792**, 18 (2007).

[25] A. Bohr, B. Mottelson, *Nuclear Structure*, Benjamin, New York 1975, Vol. 2, Chap. 6, and references therein.

[26] "Stopped Beam" RISING experimental campaign at GSI, spokespersons: P.H. Regan, J. Gerl, and H.J. Wollersheim.

[27] T. Adachi *et al.*, *Nucl. Phys.* **A788**, 70c (2007).