New Facet in the Study of Gamow-Teller Transitions

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Abstract. We introduce high-resolution \(^3\text{He}, t\) reaction at 0° and at an intermediate beam energy as a new spectroscopic tool for studying Gamow-Teller (GT) excitations. Owing to the high energy resolution of the reaction (≈ 30 keV), individual transitions can be observed up to the region of GT giant resonance. In addition, the strengths of GT transitions can now be compared with the strengths of analogous GT transitions from \(\beta\) decays, \(M1\) transitions from \(\gamma\) decays or \((e, e')\) reactions. The study on GT transitions with astrophysical interest, isospin symmetry of nuclei and other related topics are discussed.

1. Introduction
A Gamow-Teller (GT) excitation represents a very basic spin-isospin (\(\sigma\tau\)) nuclear response. The most direct information on the GT transition strengths, \(B(\text{GT})\), is obtained from the studies of GT beta decays, but the accessible range of excitation energy \(E_x\) is limited by the “\(Q\) window” of the decay. The breakthrough came from charge-exchange (CE) reactions, like the \((p, n)\) or \((^3\text{He}, t)\) reactions, which can map the GT strengths over a wider excitation energy without suffering from the \(Q\)-value limitation. In particular, it was found that the \((p, n)\) reactions performed at angles around 0° and intermediate beam energies \((E_{\text{in}} > 100\,\text{MeV}/\text{nucleon})\) are good probes of GT transition strengths owing to the approximate proportionality between the cross sections at 0° and the \(B(\text{GT})\) values [1],

\[
\frac{d\sigma_{\text{CE}}}{d\Omega}(0^\circ) \simeq K N_{\sigma\tau} |J_{\sigma\tau}(0)|^2 B(\text{GT}) = \hat{\sigma}_{\text{GT}}(0^\circ) B(\text{GT}),
\]

where \(J_{\sigma\tau}(0)\) is the volume integral of the effective interaction \(V_{\sigma\tau}\) at momentum transfer \(q = 0\), \(K\) is a kinematic factor, \(N_{\sigma\tau}\) is a distortion factor, and \(\hat{\sigma}_{\text{GT}}(0^\circ)\) is the unit cross section for a GT transition at 0°. This can be understood by the dominance of the \(\sigma\tau\) term of the effective nucleon-nucleus interaction and also of the simple one-step reaction mechanism at these intermediate beam energies and at 0°. As a result, GT strengths missing in the low-lying region were found in the \(E_x \sim 10\,\text{MeV}\) region as bump-like GT Giant Resonances (GTGR) [2]. However, the energy resolution in the \((p, n)\) reaction was rather limited (at most a few 100 keV).

An alternative is the \(^3\text{He}, t\) reaction at an intermediate beam energy. The largest advantage of this reaction is that a magnetic spectrometer can be used for the analysis of the outgoing charged particle “triton”, but the difficulty was that a large bending power was needed for the magnetic spectrometer. In addition, how to minimize the effect of the energy spread of the incoming beam was another difficulty. Recently precise beam matching techniques were applied to the \(^3\text{He}, t\) measurements using a magnetic spectrometer at RCNP, Osaka [3]. At 0° and at a
beam energy of 140 MeV/nucleon, one order of magnitude better energy resolution of $\Delta E \approx 30$ keV was realized than in pioneering $(p,n)$ measurements. The validity of the proportionality given in Eq. (1) was also examined in the comparison with analogous GT transitions studied by $\beta$ decays [4, 5]. It was found that an approximate proportionality of about 10% is realized for the $B(GT)$ values $\geq 0.04$. Therefore, the $(^3\text{He},t)$ reaction can open new possibilities in the detailed studies of GT transitions breaking the limitation coming from the energy resolution. Some of the new features are the followings:

1) With the high energy resolution, the bump-like structures of the so-called Gamow-Teller Giant Resonances (GTGR) were resolved into many states, and fine structures have been revealed in nuclei up to $fp$-shell (see Fig. 1).

2) It became possible to compare GT transitions and isospin analogous $M1$ transitions, and the orbital contributions in the $M1$ transitions were studied. This lead us to an identification of the last and missing Nilsson orbit originating from the $sd$ shell and the band on it [10].

3) Individual GT transitions analogous to those studied in $\beta$ decays are separately observed for nuclei with wide mass range. Therefore, even in heavy nuclei, in which the level density is high, it is possible to determine precise unit GT cross sections $\hat{\sigma}_{GT}(0^\circ)$ directly using the $\beta$-decay $B(GT)$ values, which can make the accuracy of $B(GT)$ derivation in heavy nuclei much better.

The impact is not only on Nuclear Physics, but also on other fields like Astrophysics.

2. Experiment
In order to study detailed excitations of GT states, we use $0^\circ$, $(^3\text{He},t)$ reactions at an intermediate beam energy of 140 MeV/nucleon. Due to a factor of two difference of charge states between the $^3\text{He}$ beam and outgoing tritons, an access to $0^\circ$ scattering is easy if a magnetic spectrometer can be used for the analysis of outgoing tritons. However, for the analysis of intermediate-energy tritons a large bending power is required for the spectrometer. The combination of QDD-type Grand Raiden spectrometer [13] and a good-quality $^3\text{He}$ beam from the $K = 400$, RCNP Ring Cyclotron is the best choice at the moment. The $^3\text{He}$ beam was stopped by a Faraday cup inside the first dipole magnet.

Figure 1. Comparison of spectra taken by two types of charge exchange reactions at intermediate beam energies and at $0^\circ$. (upper panel) a $^{58}\text{Ni}(p,n)$ spectrum from Ref. [6] and (lower panel) a high resolution $^{58}\text{Ni}(^3\text{He},t)^{58}\text{Cu}$ spectrum [7, 8]. The overall features are very similar. The bump-like structure of Gamow-Teller Giant Resonance was resolved into individual states. It is known that the sharp state at $E_x = 10.8$ MeV is the so-called $T > (T = 2)$ state [9]. The proton decay from this state is hindered by the isospin selection rule.
A resolution far better than the momentum spread of the beam was realized by applying the dispersion matching technique [3]. Using the new high-resolution "WS" course [14] for the beam transport and the "faint beam method" to diagnose the matching conditions [15], an energy resolution of 30-50 keV [full width at half maximum (FWHM)] was achieved for $fp$-shell target nuclei. As shown in Fig. 1, states in high excitation energies have been clearly resolved. In the $E_x = 8 - 12$ MeV region of $fp$-shell nuclei, so-called GT resonances were observed as a "bump-like" structure in pioneering $(p, n)$ reactions [2]. In our high-resolution spectra, the GT resonances were resolved into many states, whose envelopes show bump-like structures.

In accurately determining the scattering angle $\Theta$ near $0^\circ$, scattering angles in both the $x$ direction ($\theta$) and $y$ direction ($\phi$) should be measured equally well, where $\Theta$ is defined by $\sqrt{\theta^2 + \phi^2}$. Good $\theta$ and $\phi$ resolutions were achieved by applying the angular dispersion matching technique [3] and the "overfocus mode" in the spectrometer [16], respectively. The acceptance of the spectrometer was subdivided in the software analysis by using the track information. The "$0^\circ$ spectrum" in the figure shows events for scattering angles $\Theta \leq 0.5^\circ$.

3. GT Transitions of Astrophysics Interest

The GT transitions are very fundamental in the sense that they play important roles in all over the universe. At the end of the evolution of a massive star, if the iron core in the center exceeds the so-called Chandrasekhar mass limit, the electron degeneracy pressure can no longer support the core that produces no energy by the nuclear fusion, and the star starts to collapse. This is the beginning of a type II supernova. In this early stage of the collapse, electron capture and $\beta$ decay by $fp$-shell nuclei are important nuclear processes. Under supernova conditions, electron captures and $\beta$ decays are dominated by GT (and Fermi) transitions. These weak-interaction rates used in presupernova models were systematically and phenomenologically estimated by Fuller, Fowler and Newman [17] for nuclei in the mass range $A < 60$, and recently by the state-of-the-art shell-model calculations [18, 19]. With this extremely high temperature, GT transitions up to highly excited region can make contributions to these stellar processes, and presupernova models are affected by the details of the GT strength distributions.

One of the most important nuclei involved in the presupernova process is $^{54}$Fe [20]. In our high-resolution ($^3$He, t) study on $^{54}$Fe, GT states were separated up to high excitation energy, and the cross section to each GT state, proportional to the $B(GT)$ value, have been derived [22]. The difficulty for obtaining the absolute $B(GT)$ values for $fp$-shell nuclei in the iron region is that no direct normalization standard is available from the $\beta$ decay studies. In the studies using $(p, n)$ reaction, the so-called unit GT cross section $\hat{\sigma}(GT)$ was used for deriving the absolute $B(GT)$ values after correcting for the kinematic factor. However, it is known that this value is not universal and rather different for different mass $A$ nuclei [1]. Therefore, a large error might be expected in the $B(GT)$ derivation.

4. Determination of Absolute $B(GT)$ Values

In order to overcome the difficulty, we notice the fact that there is also a simple proportionality for a Fermi transition between the cross section at $0^\circ$ and the $B(F)$ value

$$\frac{d\sigma_F}{d\Omega}(0^\circ) \simeq K N_e |J_r(0)|^2 B(F) = \hat{\sigma}_F(0^\circ) B(F),$$

In addition the Fermi strength usually concentrates to one state, i.e., to the IAS, and it consumes the sum rule value of $B(F) = N - Z$. The idea is that if we use the ratio of GT and Fermi unit cross sections $\sigma_{GT}/\hat{\sigma}_F$ called the $R^2$ value [1] as a reference, then the strong dependence of the unit cross sections on the individual mass $A$ can be compensated in this ratio. Therefore, if the cross section of the Fermi transition with the known $B(F)$ value is measured, and the unit
Fermi cross section $\sigma_F$ is calculated, the $\sigma_{GT}$ value for a specific mass $A$ nucleus can be deduced by combining with the systematics of the $R^2$ value.

The $R^2$ values have been experimentally determined for several mass $A$ systems in which $B(GT)$ values can directly be normalized in $\beta$-decay studies. The obtained $R^2$ values are shown in Fig. 2, where the target nuclei used in the ($^3$He, $t$) reaction are shown. It is found that $R^2$ values increase smoothly as mass $A$ increases. By interpolating in mass $A$, the $R^2$ value can be obtained for any $fp$-shell nucleus with an accuracy of typically $10 - 15\%$.

![Figure 2. The $R^2$ values as a function of mass number $A$. Rather smooth increase is observed as a function of mass number $A$, except at $A = 42$ and 58. It was found that a second-order polynomial fit can well reproduce the experimental values.](image)

Let us take $A = 54$ system as an example. The $^{54}$Fe($p, n$)$^{54}$Co experiment was performed at $E_p = 160$ MeV and at $0^\circ$ with a resolution of 250 keV [21], and a bump-like GTGR was observed. On the other hand, the 25 keV-resolution achieved in the $^{54}$Fe($^3$He, $t$)$^{54}$Co measurement showed a spectrum with many individual levels. However, when the latter spectrum was smeared with the 250 keV resolution, it was found that both spectra were very similar, showing that both reactions measure, in principle, the same physical quantity. It was reported that the $B(GT)$ value of the GT transition to the first excited state of $^{54}$Co at 0.94 MeV was 0.74(5) in the $^{54}$Fe($p, n$) reaction assuming a universal unit cross section. On the other hand, a smaller value of 0.50(6) was deduced from the $R^2$ systematics in the $^{54}$Fe($^3$He, $t$) measurement. We plan to derive $B(GT)$ values for a variety of $fp$-shell nuclei. High resolution ($^3$He, $t$) experiments have been performed for several $fp$-shell target nuclei, like Ti, Cr, Fe, and Ni isotopes [22].

5. Isospin symmetry of $T_z = \pm 3/2 \rightarrow \pm 1/2$ mirror Gamow-Teller transitions in $A = 41$ nuclei

Under the assumption that isospin $T$ is a good quantum number, isobaric analog states and various analogous transitions are expected in isobars with mass number $A$. The strengths of $T_z = \pm 3/2 \rightarrow \pm 1/2$ analogous GT transitions and analogous $M1$ transitions within the $A = 41$ isobar quartet were compared in detail.

The $T_z = +3/2 \rightarrow +1/2$ GT transitions from the $J^\pi = 3/2^+$ ground state of $^{41}$K leading to excited $J^\pi = 1/2^+, 3/2^+$, and $5/2^+$ states in $^{41}$Ca were measured using the ($^3$He, $t$) charge-exchange reaction. With a high energy resolution of 35 keV, many fragmented states were observed, and the GT strength distribution was determined up to 10 MeV excitation energy. The main part of the strength was concentrated in the $E_x = 4 - 6$ MeV region. The obtained GT strength distribution is shown in Fig. 3(a). The mirror symmetric $T_z = -3/2 \rightarrow -1/2$ GT transitions can be studied in the $\beta$ decay of $^{41}$Ti to $^{41}$Sc. Two independent $\beta$-decay measurements have been reported [23, 24]. As seen from Figs. 3(b) and 3(c), the reported $B(GT)$ distributions were significantly different especially in the energy region above $E_x = 6$ MeV.

If isospin is a good quantum number, the transition strengths of the $T_z = \pm 3/2 \rightarrow \pm 1/2$ GT mirror transitions should not be much different. It was found that the general feature of the $B(GT)$ distribution deduced by Honkanen et al. [23] was similar to that observed in the present $^{41}$K($^3$He, $t$)$^{41}$Ca measurement. In addition, the good energy resolution achieved by Honkanen et al. in the delayed proton measurement after the $\beta$ decay was comparable with our resolution.
Although the gross features of the GT strength distributions were similar for the isospin analogous $T_z = \pm 3/2 \rightarrow \pm 1/2$ transitions, the details were somewhat different. From the difference of the distributions, isospin-asymmetry matrix-elements of $\approx 8$ keV were deduced. Isospin-asymmetry can also be seen from the difference of excitation energies of the corresponding states. The differences were studied for analog states as a function of excitation energy. An energy increase of about 50 keV was observed at $E_x = 3.8$ MeV, suggesting a change of configuration in the wave function of the GT states below and above this energy.

The $M1$ transitions strengths in $^{41}$Ca from the IAS, i.e., the isobaric analog state of the g.s. of $^{41}$K, to low-lying five excited states were compared with the analogous GT transition strengths derived from the $^{41}$K$(^3$He, $t)^{41}$Ca study. It was found that ratios of the $M1$ and GT transition strengths, except for one transition, were similar. This suggests that the contribution from the $\ell\tau$ term, which is inherent to an $M1$ transition and has no corresponding term in a GT transition, is small in these $M1$ transitions. It is known that the contribution of the $\ell\tau$ term can be large if a nucleus is deformed. Details of this work is found in Ref. [25].

6. Prospects
We started to use the high-resolution property of the $(^3$He, $t)$ reaction at $0^\circ$ and at the intermediate energy of 140 MeV/nucleon as a tool to study the details of GT transitions. Owing to the $\approx 30$ keV resolution of the measurements, comparison with corresponding or various analogous transitions became possible. By comparing with $\beta$-decay results, unit cross sections $\hat{\sigma}_{GT}(0^\circ)$ can now be determined even in heavier mass $A$ nuclei. The detailed comparison of analogous transitions started to give the information on the symmetry (and/or asymmetry) structure of isobars. In addition, it is expected that the accurate determination of the GT transition strengths in $fp$-shell nuclei will contribute to the understanding of the astro-physical...
processes.

The property of the \(^{3}\text{He},t\) reaction itself has also been understood better. It has been found that the proportionality of the \(0^+\) cross sections with the \(\beta\)-decay \(B(\text{GT})\) values that is usually good within 10% uncertainty is not valid in two cases. One of the exceptions is for the transitions with \(j_{\text{c}} \rightarrow j_{\text{c}}\) configurations [25, 26]. In the \(^{3}\text{He},t\) reaction, the uncertainty of 30-50% order has been found for a few low-lying states in \(A = 37\) and 41 nuclei in which the \(d_{3/2}\) configuration is largely involved. A similar findings were also reported in \((p,n)\) reactions [27]. The other exception has been found for a configuration with a radial node. It was found that the g.s.−g.s transition from \(^{56}\text{Ni}\) to \(^{58}\text{Cu}\), and also the transition from the g.s. of \(^{56}\text{Fe}\) to the lowest \(1^+\) state of \(^{56}\text{Co}\) are enhanced by about 50%. It should be noted that the neutron number of the initial nuclei is 30, and it is expected that the contribution from the \(2p_{3/2} \rightarrow 2p_{3/2}\) configuration is the largest in these transitions. It seems that the unit GT cross section related to the \(2p_{3/2}\) wave function with a radial node is different from those for the wave functions without a radial node in the \(^{3}\text{He},t\) reaction having surface-like nature [28]. We believe that the importance of the \(^{3}\text{He},t\) reaction as a tool to study the details of the GT strength distributions by its high resolution capability will increase with such deeper understanding of reaction mechanisms.

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