Gamow-Teller strengths in $A = 42$ isobars deduced in the combined analysis of $T_z = \pm 1 \rightarrow 0$ mirror transitions

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Due to the simplicity of the operator $\sigma\tau$, a strength distribution of Gamow-Teller (GT) transitions directly represents the nuclear structure of initial and final nuclei. Detailed distributions of GT transition strengths, $B(\mathrm{GT})$ values, in pf-shell nuclei are of astrophysical interest [1].

In this report, we discuss the $B(\mathrm{GT})$ values in $A = 42$ nuclei. Direct information on the $B(\mathrm{GT})$ values were studied by the β-decay experiment of ^{42}Ti with the nature of $T_z = -1 \rightarrow 0$ [2, 3]. The total half-life $T_{1/2}$ was evaluated with relatively good accuracy and strong feeding to the ground state (g.s.) and the state at 0.611 MeV were studied. However, the branching ratios were not measured with good accuracy and the information on higher excited states was ambiguous due to the decrease of phase-space factor (f-factor) with the excitation energy. The (p, n) type charge-exchange (CE) reactions can access GT transitions at higher excitations. It was found that at scattering angles around 0° and at intermediate incident energies more than 100 MeV, there is a simple proportionality between measured cross section and $B(\mathrm{GT})$ value, $\sigma_{\mathrm{GT}} = \hat{\sigma}_{\mathrm{GT}} B(\mathrm{GT})$ [4]. The $\hat{\sigma}_{\mathrm{GT}}$ is called the unit cross section. The $T_z = +1 \rightarrow 0$ GT transition strengths were studied up to 10 MeV in a $^{42}\mathrm{Ca}(p, n)^{42}\mathrm{Sc}$ reaction at E_p=160 MeV and at $\theta_{\mathrm{lab}} = 0°$[5]. However, with an energy resolution larger than 1 MeV, the g.s. and the state at 0.611 MeV were not separated. Therefore, there was no direct way to calibrate the unit cross section $\hat{\sigma}_{\mathrm{GT}}$.

In a recent paper [6], we have shown that a combined analysis of the data on $T_z = \pm 1 \rightarrow 0$ GT-transitions that come from a CE reaction and a β decay, respectively, can overcome the difficulties that former cannot get the absolute $B(\mathrm{GT})$ values and the latter cannot access the higher excited states.

Under the assumption that isospin T is a good quantum number, an analogous structure is expected for nuclei with the same mass number A but with the different T_z. The corresponding states in isobars are called analog states, and are expected to have the same nuclear structure. Various transitions connecting corresponding analog states are called analogous transitions and have corresponding strengths. In the $A = 42$, "$T = 1$" triplet, GT and also Fermi transitions from the g.s. of $T_z = \pm 1$ nuclei ^{42}Ca and ^{42}Ti to 1^+ states and the 0^+ state in the $T_z = 0$ nucleus ^{42}Sc are analogous, respectively, (see Fig. 1).

In a β decay, the partial half life t_i of the ith GT transition and t_{F} of the Fermi transition multiplied by the f-factor are related, respectively, to the $B(\mathrm{GT})$ and $B(\mathrm{F})$,

$$f_i t_i = K/\lambda^2 B(\mathrm{GT}) \quad (1)$$

$$f_{\mathrm{F}} t_{\mathrm{F}} = K/B(\mathrm{F})(1 - \delta_c), \quad (2)$$

where $K = 6144.4 \pm 1.6$, $\lambda = g_A/g_V = -1.266 \pm 0.004$, δ_c is the Coulomb correction factor and f_{F} and f_i are the f-factors of the β decay to the Isobaric Analog State (IAS) and to the ith GT state, respectively. The Fermi transition strength is concentrated to the IAS and have the value $|N-Z| = 2$ in the ^{42}Ti β decay.

Absolute $B(\mathrm{GT})$ values can be deduced by further combining the total half-life $T_{1/2}$ of the β decay. The inverse of $T_{1/2}$ is the sum of the inverse of the partial half life t_{F} of Fermi transition to the IAS and those of t_i's of GT transitions to the ith GT states

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

Applying Eq. (1) and (2), t_{F} and also t_i's can be eliminated,

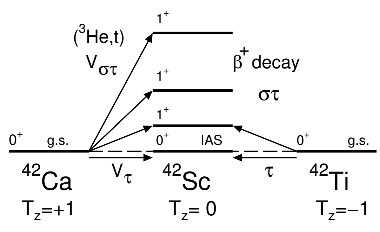

Figure 1: The isospin symmetry transitions from the $T_z = \pm 1$ nuclei to the $T_z = 0$ nucleus in the $A = 42$ isobar system. The Coulomb displacement energies are removed.

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

By introducing the ratio R^2 of unit of GT and Fermi cross sections in a CE reaction at 0° [4]

$$R^2 = \frac{\hat{\sigma}^{\mathrm{GT}}}{\hat{\sigma}^{\mathrm{F}}} = \frac{\sigma_i^{\mathrm{GT}}}{B_i(\mathrm{GT})}\bigg/\frac{\sigma^{\mathrm{F}}}{B(\mathrm{F})(1-\delta_c)}, \tag{5}$$

we can eliminate $B_i(\mathrm{GT})$ and the inverse of the $T_{1/2}$ can be expressed by using experimental cross sections σ^{F} and σ_i^{GT} in a CE reaction measurement,

$$\frac{1}{T_{1/2}} = \frac{B(\mathrm{F})(1-\delta_c)}{K}\left[f_{\mathrm{F}} + \frac{\lambda^2}{R^2}\sum_{i=\mathrm{GT}} \frac{\sigma_i^{\mathrm{GT}} f_i}{\sigma^{\mathrm{F}}}\right]. \tag{6}$$

What Eq. (6) requires now is the accurate (relative) strengths for the Fermi and each GT transitions in a $T_z = +1 \rightarrow 0$, CE reaction on the target nucleus ^{42}Ca. The ^{42}Ca(^{3}He, t)^{42}Sc experiment at 140 MeV/u and at 0° was performed at RCNP. A thin foil of ^{42}CaCO$_3$ supported by polyvinylalcohol (PVA) was used [7]. This target is mainly a mixture of ^{42}Ca, ^{40}Ca, ^{12}C, ^{13}C,^{16}O and ^{18}O. Owing to the large negative Q values of ^{12}C,^{16}O,^{40}Ca (^{3}He, t) reactions, states in ^{42}Sc could be observed up to $E_x \sim 8$ MeV without affected by the excited states in ^{12}N, ^{16}F and ^{40}Sc. Since the ^{13}C and ^{18}O have smaller Q values, we need to eliminate the ^{13}N and ^{18}F states in the obtained spectrum. By comparing with the spectrum using the pure PVA foil as a target, ^{42}Sc states were identified. With the energy resolution of 60 keV in the spectrum as shown in Fig. 2(a), the g.s. and the excited state at 0.611 MeV were clearly separated. In order to distinguish GT states having maximum cross section at 0°, intensities of observed states were compared in the spectra for two angle cuts $\Theta = 0 - 0.5°$ and $1.5 - 2.0°$. Only two states at 1.886 and 3.688 MeV showed a decrease of intensity similar to the 0.611 MeV GT state.

Eq. (6) shows that the inverse of $T_{1/2}$ is proportional to the sum of intensities of the observed Fermi and GT states weighted by f-factors. The f-factors were calculated following Ref. [9]. Values normalized to unity at 0 MeV are shown in Fig. 2(b). By assuming isospin symmetry, the energy spectrum of GT transitions in the ^{42}Ti β decay can be estimated by multiplying the ^{42}Ca(^{3}He, t) spectrum with f-factor [Fig 2(c)].

By solving Eq. (6), we get a $R^2 = 5.3 \pm 0.3$. The error mainly comes from the uncertainty in the $T_{1/2}$ values in β-decay measurement. The absolute B(GT) values calculated using Eq. (5) are listed in columns 5 of Table 1. By using this combined analysis of (^{3}He, t) and β-decay data, accurate B(GT) values could be extracted. The B(GT) value [2.34(18)] of the first excited state was obtained with an error about 8%. This is better than that of 25% in the ^{42}Ti β-decay experiment [2.47(63)]. Our better accuracy comes from the precise determination of the branching ratios in our high resolution (^{3}He, t) measurement.

This analysis can be extended to other $T = 1$ systems and even higher T systems, thus allowing to deduce the B(GT) distributions in proton rich nuclei, which are needed to deduce the astrophysical transition rate under extreme conditions.

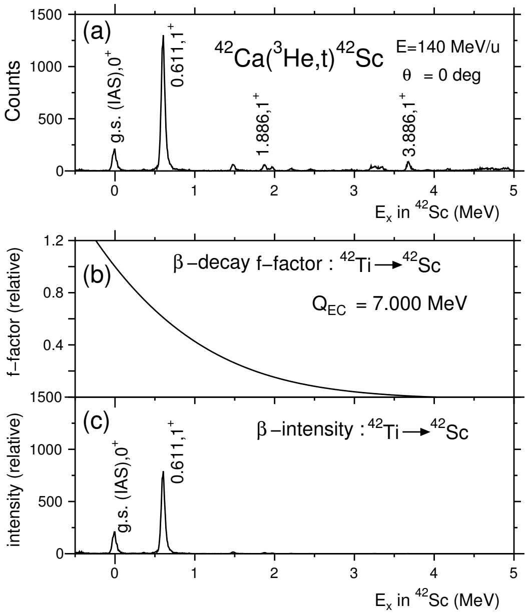

Figure 2: (a) The ^{42}Ca(^{3}He, t)^{42}Sc spectrum with scattering angles $\Theta < 0.5°$. (b) The f-factor for the ^{42}Ti β-decay, normalized to unity at $E_x = 0$ MeV. (c) The estimated β-decay energy spectrum that is obtained by multiplying the f-factor to the ^{42}Ca(^{3}He, t)^{42}Sc spectrum.

Table 1: States observed in the ^{42}Ca(^{3}He, t)^{42}Sc reaction below $E_x = 4$ MeV.

Evaluated values [a]		(^{3}He, t) [b]		
E_x (MeV)	J^π	E_x (MeV)	L	B(GT)
0.0	0^+,[c]	0.0	0	
0.611	1^+	0.611	0	2.34(18)
1.490	3^+	1.491	≥ 1	
1.889	1^+	1.886	0	0.09(1)
2.223	1^+	2.219	≥ 1	
		3.223	≥ 1	
		3.348	≥ 1	
3.688	1^+	3.688	0	0.15(2)

[a] From Refs. [8].

[b] Present work.

[c] The IAS with $T = 1$.

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