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DETERMINATION OF GT-TRANSITION STRENGTHS IN A = 34 ISOBARS USING CHARGE EXCHANGE (^{3}HE, t) REACTION

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Abstract. *Under the assumption that isospin T is a good quantum number, mirror transitions $T_z = +1 \to 0$ and $T_z = -1 \to 0$ were studied in $A = 34$ isobars, where T_z is z component of iospin T and is defined by $T_z = (N - Z)/2$. With a high energy resolution of 35 keV in $^{34}S(^3He,t)^{34}Cl$ reaction measurement at 0° scattering angle and at an incident energy of 140 MeV/nucleon, strengths of Fermi and Gamow-Teller (GT) transitions from the $J^\pi = 0^+$, $T_z = +1$ ground state of ^{34}S to the $J^\pi = 1^+$, $T_z = 0$ excited states in ^{34}Cl were determined up to excitation energy (E_x) of 7.08 MeV. The corresponding isospin-symmetric transitions connecting $T_z = -1$ and $T_z = 0$ states can be studied in the ^{34}Ar β^+ decay. The strengths of the $(GT)_\pm$ transitions were compared up to the excitation energy of 3.1 MeV. A good agreement was observed for two strong transitions to 2.580 MeV and 3.129 MeV states, while a disagreement about 45% was observed for a weaker transition to 0.666 MeV low-lying state.*

I. INTRODUCTION

If the charge-symmetric and charge-dependent characteristics were assumed with relatively small effect of electromagnetic interaction, then the interactions between proton-proton, neutron-neutron and proton-neutron are identical [1,3]. In this case, isospin T is a suitable tool to study structure of isobars. Moreover, the isobaric nuclei with the same mass number A and different T_z are expected to exhibit a mirror-symmetrical structure. Due to the analogous nature the corresponding states in isobars are called isobaric analog states (or simply analog states) and are expected to have the same nuclear structure. The transitions connecting various combinations of analog states are also analogous and the lowest $J^\pi = 0^+$ state in $T_z = 0$ nucleus (^{34}Cl) is called isobaric analog state (IAS) of the 0^+ ground states in $T_z = \pm 1$ nuclei (^{34}S and ^{34}Ar) (see Fig. 1).

Gamow-Teller (GT) transition is fundamental quantity in weak-interaction nuclear processes. The GT transitions play important roles in universe. At the end of the evolution of a massive star, if the iron core in the center exceeds the 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 [2]. In this early stage of the collapse, electron capture and β decay of fp-shell nuclei become important nuclear processes. Under supernova conditions electron capture and β decay are dominated by GT (and also by Fermi) transitions.

The GT transitions are characterized by $\Delta L = 0$, $\Delta S = 1$ and $\Delta T_z = \pm 1$, where L and S are orbital and spin quantum numbers, whereas the Fermi transition is characterized by $\Delta \mathrm{L} = 0$, $\Delta \mathrm{S} = 0$ and $\Delta \mathrm{T}_z = \pm 1$. Two these types of the transitions are effective tools to investigate nuclear structure in isobars because they can be performed via beta decay and charge-exchange (CE) reactions, such as (p,n) or (^{3}He,t).

An important physical quantity for understanding the nuclear structure is the reduced GT transition strength, B(GT). The most direct information on B(GT) values is obtained from GT β-decay experiments because GT β-decay is governed by the pure isospin-spin flip operators, $\sigma\tau_\pm$. By measuring the total decay half life and branching ratios of the transitions from one state of the mother nucleus to the states of daughter nucleus, the partial half-lives for each transition are determined. Thus, the absolute B(GT) values are derived directly from β-decay studies, but the accessible range of excitation energy (E_x) is limited by the decay Q-value. Charge-exchange reactions, however, like the (p,n) or (^{3}He,t), can access to the GT transitions at higher excitation energies without the Q-value limitation. In addition, these CE reaction measurements performed at angles around 0° and at intermediate incident energies (E ¿ 100 MeV/nucleon) were shown to be good probes of GT transition strengths due to the approximate proportionality between the cross section at 0° and B(GT) values [4-7].

For the β^--type (^{3}He, t) CE reactions at intermediate beam energies, precise beam matching techniques were applied [8,13]. As a result, in comparison to pioneering (p,n) work, nearly one order of magnitude better resolution ($\Delta \mathrm{E} \leq 35$ keV) was achieved. This high energy resolution allows the study of transition strengths to individual GT states. These strengths can then be compared directly with those of analogous GT transitions which are investigated in the mirror β^+ decay.

In this work the isospin symmetry in A = 34 isobar system (^{34}S, ^{34}Cl and ^{34}Ar) is investigated in order to identify the GT states at the high excitation energies, where $T_z = -1 \to 0$ GT transition strengths have been determined via β decay from ground state of ^{34}Ar to four accessible low-lying states in ^{34}Cl. These strengths can be, then, used as standard values by normalization to determine those of analogous $\mathrm{T}_z = +1 \to 0$ transitions to the excitation states in ^{34}Cl induced by the ^{34}S(^{3}He, t)^{34}Cl reaction.

II. EXPERIMENT

II.1. B(GT) evaluation from β decay

In the $A = 34$ nuclear system, as mentioned above, the GT transitions from $J^\pi = 0^+$ ground states of the $T_z = \pm 1$ even-even ^{34}S and ^{34}Ar nuclei to 1^+ states (GT states) in the $T_z = 0$ odd-odd ^{34}Cl nucleus are analogous (see Fig. 1). The transitions observed in the ^{34}S(^{3}He,t) reaction can be compared with those seen via the β decay by ^{34}Ar, in which the analogous transitions have the same $B(GT)$ values.

The B(GT) values from the $^{34}\mathrm{Ar} \to$ ^{34}Cl β^+ decay, in general, were used as standard values. Thus, the investigation of B(GT) distribution and absolute B(GT) strengths can be extended to higher excitation energies in $^{34}\mathrm{Cl}^*$ by using the (^{3}He, t) reaction

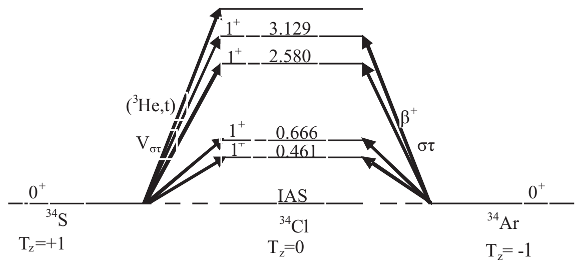

Fig. 1. Schematic view of isospin analogous transitions from the $T_z = \pm 1$ nuclei to the $T_z = 0$ nucleus in $A = 34$ isobars, where the Coulomb displacement energies was subtracted.

without Q-value limitation by normalizing to those obtained in β decay measurements. Therefore, the both β-decay and CE reaction studies are complementary

In a β decay, the partial half-life t of a GT transition multiplied by the f factor is related to $B(GT)$ value [7-9]:

$$ft = K/\lambda^2 B(GT), \tag{1}$$

where K is called kinematical factor which is equal to 6145 $\pm$ 4 and $\lambda = g_A/g_V$ = -1.266 $\pm$ 0.004 [11]. The ^{34}Ar β^+ decay has Q_{EC}valueof 6.602 MeV and the half-life ($T_{1/2}$) of . Then the B(GT) values have been determined up to 3.219 MeV state by using Eq. (1) and are listed in column 3 of Table 1, where the log(ft) values are referred in [17].

II. 2. B(GT) evaluation from (^{3}He,t) reaction data and discussion.

The B(GT) values observed in the β decay by ^{34}Ar to four accessible low-lying states in excitation energy spectrum of the ^{34}Cl daughter nucleus were determined. In order to map B(GT) values to higher excitation energies of ^{34}Cl, the ^{34}S(^{3}He,t)^{34}Cl reaction was used. It is expected that the $T_z = +1 \to 0$ and $T_z = -1 \to 0$ GT transitions have the same B(GT) values. Relying on the proportionality between the B(GT) value and the cross section at 0°, the B(GT) values of the states at higher excitation energies could be also deduced at momentum transfer $q = 0$ [4-7]:

$$d\sigma_{GT}/d\Omega(0^\circ) = \sigma^{GT}(0^\circ)B(GT) \tag{2}$$

where $\sigma^{GT}(0^\circ)$ is the GT unit cross section at 0° for specific mass A system. Therefore, the study of B(GT) values can reliably be extended up to high excitation if a "standard B(GT) value" from the β decay is available.

A similar proportionality is also expected for the Fermi transition to the IAS [4-7]:

$$d\sigma_F/d\Omega(0^\circ) = \sigma^F(0^\circ)B(F) \tag{3}$$

where $\sigma^F(0^\circ)$ and $B(F)$ are, respectively, the unit cross section and the strength for the Fermi transition at 0°. Normally, it can be assumed that $B(F) = N - Z$ due to the concentration of the Fermi transition strength to the IAS [4,5].

Let us introduce R^2 value defined by the ratio of the GT and Fermi unit cross sections at 0° [4-7]:

$$R^2 = \frac{\sigma_{GT}(0^\circ)}{\sigma_F(0^\circ)} = \frac{\sigma_{GT}}{B_{GT}}/\frac{\sigma_F}{B_F} \tag{4}$$

where σ^{GT} and σ^{F} are, respectively, cross sections for production of the GT and IAS states in ^{34}Cl via the ^{34}S(^{3}He,t)^{34}Cl reaction.

The ^{34}S(^{3}He,t)^{34}Cl experiment was performed at the Research Center for Nuclear Physics (RCNP), Osaka University, by using a 140 MeV/nucleon ^{3}He beam delivered by the K=400 Ring Cyclotron and the QDD-type Grand Raiden spectrometer placed at 0° [13-15]. In order to reduce the energy spread of outgoing triton, the target was a thin self-supporting foil of enriched (92.47%) ^{34}S with an areal density of ≈ 3.3 mg/cm^2. The ejectile tritons were momentum analyzed within the full acceptance of the spectrometer (±20 mrad and ± 40 mrad in horizontal (x) and vertical (y) directions, respectively) [8, 13, 16]. They were detected at the focal plane by using a multi-wire drift-chamber system (MWDC) allowing for track reconstruction. The ray-trace information made it possible to subdivide the acceptance angle of the spectrometer by a soft-ware cut. In this experiment a high energy resolution of about 35 KeV (full width at half maximum) was achieved by using the dispersion-matching technique for beam transport [8, 13, 16]. The "0° spectrum" up to $E_x \approx 5$ MeV is shown in Fig. 2. The g.s 0^+, $T = 1$ IAS and four low-lying GT ($J^\pi = 1^+$) states were found via the β decay of ^{34}Ar.

In order to determine accurately the scattering angle (θ_s) near 0°, angle measurements in both the x direction (θ) and y direction (ϕ) are necessary, where θ_s is defined by $\theta_s = \sqrt{\theta^2 + \phi^2}$. Good θ and ϕ resolutions, which are better than 8 mrad, were achieved by using the angular dispersion matching technique [13] and the "overfocus mode" in the spectrometer [16], respectively.

The energy calibration for the excitation energy spectrum in ^{34}S has been done using the well-known E_x values of ^{24,25,26}Al, ^{16,18}F and ^{12,13}N which were observed in the reference spectrum from a ^{nat}MgO + PVA target. This allowed us to identify the high excited states in ^{34}Cl, up to E_x = 7.08 MeV. The results are shown in column 4 of Table 1, where the difference in energy losses of the incoming beam and outgoing triton in two targets was corrected.

Cross sections for $L = 0$ transitions decrease with increasing scattering angle beyond 0°, whereas those for $L = 1$ and higher multipoles increase. To identify the $L = 0$ nature of states, therefore, intensities of peaks in the spectra with angular cuts (θ_s) 0.5°- 1.0°, 1.0°- 1.5° and 1.5°- 2.0° were compared with those in the cut $\theta_s \leq 0.5°$. The states showing a decrease in intensity with increasing angle, as observed for the strong 3.129 MeV GT state, were identified to have L = 0. As a result, the $J^\pi = 0^+$ g.s and five states at 0.666, 2.580, 3.129, 4.611 and 4.941 MeV were assigned with L = 0. Since the Fermi strength is concentrated in the transition to the IAS, it is very probable that these L = 0 states are all GT states. The results obtained in this work for $E_x \leq 5$ MeV region are consistent with those given in [1]. The identification for all GT states up to 7.08 MeV are given in column 5 of Table 1.

In this experiment the R^2 value was determined using the IAS and 3.129 MeV states in the excitation spectrum, where B(GT) value is obtained from the β-decay data [17]. It should be noted that the $\sigma^{GT}(0^o)$ gradually decreases as function of excitation energy, a distorted wave Born approximation (DWBA) calculation with the code DW81 was performed for this correction up to the excitation energy of interest [4,5]. This allowed

Table 1. Accessible excited $J^{\pi} = 1^{+}$, L = 0 states in ^{34}Cl and GT transition strengths B(GT) from ^{34}Ar → ^{34}Cl β^{+} decay and the present ^{34}S(^{3}He, t)^{34}Cl reaction at 140 MeV/nucleon.

Evaluated values[a]			Present experiment	
E_x (MeV)	J^{π}	B(GT) β decay	E_x (MeV)	B(GT) (^{3}He,t)
0.0	0^{+}	0.0188 ± 0.0003	0.0	
0.461	1^{+}	0.064 ± 0.003	0.461	0.017 ± 0.04
0.666	1^{+}	0.298 ± 0.027	0.666	0.091 ± 0.009
2.580	1^{+}	1.360 ± 0.094[b]	2.581	0.289 ± 0.023
3.129	1^{+}		3.131	1.355 ± 0.103
4.206	$(1,2)^{+}$		4.209	0.039 ± 0.005
4.611	(2,3)		4.611	0.192 ± 0.016
4.942	$(1,2)^{+}$		4.943	0.253 ± 0.021
4.996	$(1,2)^{+}$		4.997	0.014 ± 0.004
5.785	(1^{+} to 3^{-})		5.791	0.020 ± 0.003
6.029	$(1,2)^{+}$		6.027	0.032 ± 0.004
6.361	(1^{+} to 3^{+})		6.364	0.014 ± 0.003
6.901	1^{+}		6.896	0.007 ± 0.003
6.991	1^{+}		6.989	0.021 ± 0.004
7.058	1^{+}		7.056	0.016 ± 0.003

[a]From ref. [17]
[b]B(GT) used for determination of the R^2 value.

us to obtain $R^2 = 7.04 \pm 0.25$ for the A = 34 system. As a consequence, the B(GT) values up to $E_x = 7.08$ MeV were determined (see column 7 of Table 1).

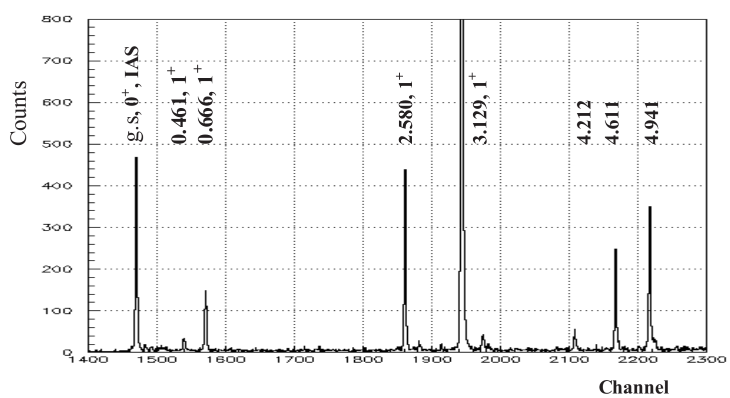

Fig. 2. The ^{34}S(^{3}He,t)^{34}Cl spectrum at angle cut $\theta \leq 0.5°$, where the GT states are identified.

We found that for the 2.580 MeV state the B(GT) value derived in this way was in a good agreement with that via β decay. However, for the 0.666 MeV state a deviation of about 45% was found between the B(GT) results obtained by the (^{3}He, t) reaction and β decay. This suggests that the proportionality can be inaccurate for this week transition.

III. CONCLUSION

The mirror transitions from $T_z = \pm 1$ even-even ^{34}Ar and ^{34}S nuclei to $T_z = 0$ odd-odd ^{34}Cl nucleus were studied based on the assumption about the isospin symmetry in $A = 34$ isobaric system.

In this work we have identified the excited $J^\pi = 1^+$, $L = 0$ states in the excitation spectrum of ^{34}Cl up to the energy 7.08 MeV produced by the high-resolution ^{34}S(3He,t)^{34}Cl reaction at the incident energy of 140 MeV/nucleon. The B(GT) values in the (^{3}He, t) reaction were determined by using the B(GT) value derived from the strongly excited 3.129 MeV state in β^+ decay of ^{34}Ar. A good consistence between B(GT) values obtained by the β-decay and (^{3}He, t) reaction was found for the strongly excited states at 2.580 and 3.129 MeV. However, at the 0.666 MeV state which correspond to the weak GT transition (B(GT) = 0.091) a deviation of about 45% was observed.

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