Precise Branching Ratio of ^{24m}Al Beta Decay

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Abstract. The branching ratio of the isomeric γ decay of ^{24m}Al has been measured to be 69.6(7)% which is much smaller than the previously accepted value of 82.5(30)%. As a result, the branching ratio to the ^{24}Mg ground state increases up to 24.1(7)% assuming that the other β-decay branching ratios are the previously accepted values. The half-life of ^{24m}Al was also precisely determined to be 130.9(13) ms. The B(GT) value from the ground state of ^{24}Mg to the ^{24m}Al of 0.0577(16) deduced from the β decay is now in good agreement with that deduced from charge-exchange reactions.

1. Introduction

A β decay measurement provides important information on the structure of mother and daughter nuclei such as ft values, energy levels, and spin-parity. The β-decay ft values enables us to deduce the Gamow-Teller(GT) transition strength B(GT) when the transition has $\Delta L = 0$ and $\Delta S = 1$. The B(GT) can be deduced not only from β-decay ft values but also from charge-exchange reactions [1]. The B(GT) values obtained in these two methods are usually in good agreement. However, the B(GT) value from ^{24}Mg(0^+, g.s.) to ^{24m}Al(1^+, 426 keV) of 0.024(8) deduced from the β-decay ft value [2] is about half of the value of 0.050(1) from (p, n) reaction [3] and 0.054(1) from (^{3}He, t) reaction [4] for the same transition. In Ref. [2], they adopted previous value of 2.3(6) as the ratio between the branching ratio to the ground state and to the first exited state [5], since β branching to the ^{24}Mg ground state could not be measured. In order to clarify this disagreement, we studied the decay of ^{24m}Al using a β- and γ-ray spectrometer at a modern fragment-separator facility. Figure 1 shows the decay scheme for the ^{24m}Al with the branching ratios and log ft values give in Ref [2, 6]. We measured the absolute branching ratio of the isomeric γ decay with the total β branch obtained by counting the number of β rays.

2. Experiment

The experiment was carried out at HIMAC synchrotron and fragment-separator facility [7]. A ^{24m}Al beam was produced through the charge-exchange reaction of a 100A MeV ^{24}Mg primary

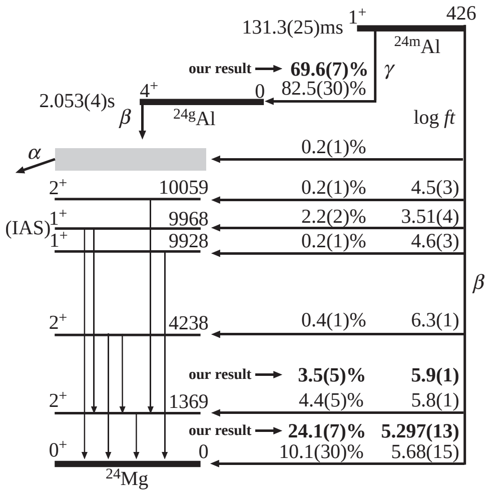

Figure 1. Decay scheme with branching ratios (BR) and log ft values given in Ref. [2, 6]. Our results are shown by bold letters.

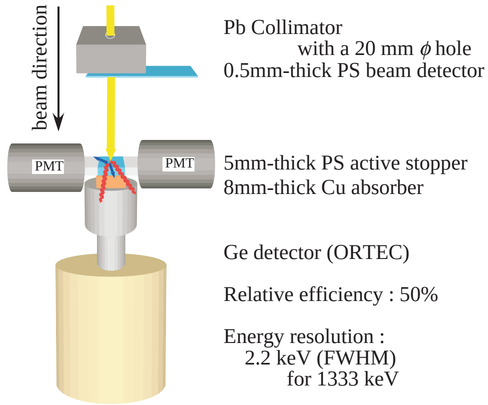

Figure 2. Experimental setup of the β- and γ-ray spectrometer.

beam impinging on a 4.5mm-thick polyethylene (CH_2) target. The charge-exchange reaction on a proton is expected to provide a larger isomeric ratio and a larger production cross section than that on a Be target due to the pure inverse (p, n) reaction. The beam duration was about 100 ms. We got the beam every 6 or 10 seconds. The ^{24m}Al beam was separated by the fragment separator with two dipole magnets and a 1.2mm-thick wedge-shape Al degrader. The intensity and purity of the ^{24m}Al beam was about 1000 particles per pulse and 75%, with contaminants of 23% ^{23}Mg and 2% ^{22}Na.

The experimental setup of the β- and γ-ray spectrometer is shown in Fig. 2. The secondary beam was defined by a Pb collimator with a hole of 20 mm ϕ. A 0.5mm-thick plastic scintillator (PS) placed after the Pb collimator enables us to count the number of incident heavy ions. The beam was implanted into an active stopper made of a 5mm-thick plastic scintillator with an area of 35 mm $\times$ 37 mm for β rays. The scintillator signals were read out by two photomultiplier tubes. Because a coincidence of two signals reduced noises caused by dark current, we could set the detection threshold low. A HPGe detector with an efficiency of 50% relative to the standard NaI crystal and an energy resolution of 2.2 keV (FWHM) at 1333 keV of ^{60}Co was installed behind the active stopper. A 8mm-thick Cu absorber was placed between the active stopper and the Ge detector to prevent β rays from entering the Ge detector.

We measured the number of 426-keV γ rays and the β rays to determine the branching ratio of the isomeric γ transition. Figure 3 shows the γ-ray energy spectra of the Ge detector. The upper line shows the singles spectrum and the lower line shows the spectrum in coincidence with β rays. As shown in Fig. 4, the detection efficiency for the 426-keV γ ray was determined to be 0.0175(4) using the known β-delayed γ rays of ^{22}Mg and ^{23}Mg. These beams with the same range in the active stopper as the ^{24}Al beam were used for the calibration. To determine the energy dependence, radioactive sources such as ^{22}Na, ^{60}Co, ^{133}Ba, ^{137}Cs, and ^{152}Eu were also used. The result of GEANT simulation shown by the solid line is in good agreement with these data. A high β-ray detection efficiency for the active stopper of 99(1)% was obtained by comparing between the number of single γ rays and the number of γ rays gated by the signal of β rays in the stopper. One reason for so high efficiency is that the β-ray energy deposit ΔE is large enough by implanting the ^{24m}Al beam in the center of the 5mm-thick active stopper

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and another reason is that the detection threshold of the active stopper was set low enough. The β-ray energy spectrum for the active stopper is shown in Fig. 5. Similar efficiencies were also obtained using the ^{22}Mg and the ^{23}Mg beams. The GEANT simulation estimates that the 7(1)% of the 426-keV γ rays emit additional photons in the active stopper by the Compton scattering process, and they pretend as if they are from the β-decay. This effect was taken into account in the determination of the β-decay counts.

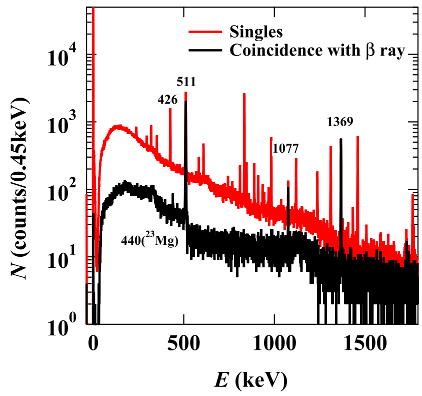

Figure 3. The γ-ray energy spectra. Upper line shows the singles spectrum and lower line shows the spectrum in coincidence with β rays.

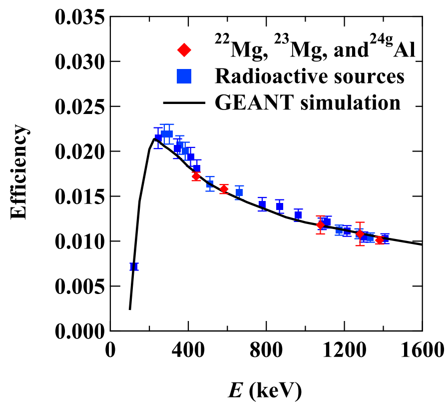

Figure 4. The γ-ray detection efficiency determined by using standard γ sources and the ^{22}Mg and ^{23}Mg radioactive ion beam.

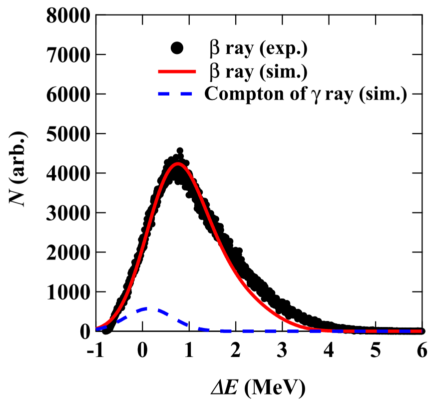

Figure 5. The β-ray energy spectrum from active stopper made of 5mm-thick plastic scintillator. Solid circles show the experimental result. Solid and Dashed lines show the GEANT simulated energy deposit of β ray and 426-keV γ ray by Compton scattering, respectively.

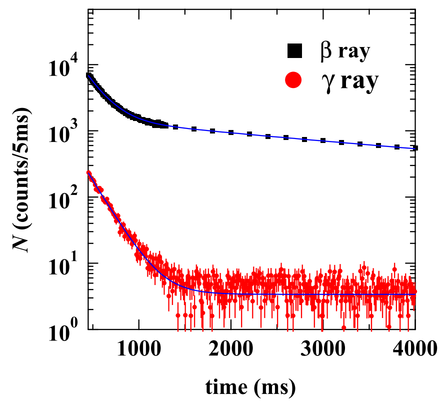

Figure 6. The β- and γ-ray time spectra. Solid squares are time spectrum of β ray. Solid circles are time spectrum of 426-keV γ ray.

3. Analysis and Discussion

The decay time spectra for the β rays of the active stopper and the 426-keV γ ray of the Ge detector are shown in Fig. 6. The decay-time analysis of the β decay including the isomeric γ transition is different from that of a simple β decay. Let us consider a cocktail beam with the number of ^{24m}Al N_m and the number of ^{24g}Al N_g is implanted in the stopper at $t = 0$. The count rate of the isomeric γ ray $N^\gamma(t)$ and that of all the β rays $N^\beta(t)$ are given by

$$N^\gamma(t) = \epsilon_m^\gamma R\lambda_m N_m e^{-\lambda_m t} \tag{1}$$

$$N^\beta(t) = \epsilon_m^\beta(1-R)\lambda_m N_m e^{-\lambda_m t} + \epsilon_g^\beta R\lambda_g N_m \frac{\lambda_m}{\lambda_m - \lambda_g}\left(e^{-\lambda_g t} - e^{-\lambda_m t}\right) + \epsilon_g^\beta \lambda_g N_g e^{-\lambda_g t}, \tag{2}$$

where R, λ_m, λ_g, ϵ_m^γ, ϵ_m^β, and ϵ_g^β are the branching ratio of the isomeric γ transition, the decay constant of ^{24m}Al (ln(2)/131 ms), that of ^{24g}Al (ln(2)/2.053 s), the detection efficiency of the γ ray, that of the β ray of ^{24m}Al, and that of the β ray of ^{24g}Al, respectively. In Eq. (2), the first term is for the β decay of the ^{24m}Al, the second term is for the β decay of the ^{24g}Al derived from the isomeric γ decay of ^{24m}Al, and the third term is for the β decay of the ^{24g}Al derived from the beam. In order to fit Eq. (1) and Eq. (2) to the experimental data, it is useful to replace them by

$$N^\gamma(t) = A_m^\gamma e^{-\lambda_m t} \tag{3}$$

$$N^\beta(t) = A_m^\beta e^{-\lambda_m t} + A_g^\beta e^{-\lambda_g t} \tag{4}$$

where A_m^γ, A_m^β, and A_g^β are defined as

$$A_m^\gamma = \epsilon_m^\gamma R\lambda_m N_m \tag{5}$$

$$A_m^\beta = \epsilon_m^\beta(1-R)\lambda_m N_m - \epsilon_g^\beta\left(\frac{\lambda_g}{\lambda_m - \lambda_g}\right) R\lambda_m N_m \tag{6}$$

$$A_g^\beta = \epsilon_g^\beta \lambda_g N_g + \epsilon_g^\beta\left(\frac{\lambda_g}{\lambda_m - \lambda_g}\right) R\lambda_m N_m. \tag{7}$$

Utilizing the relation of Eq. (5) and Eq. (6), the branching ratio R is given by

$$R = \frac{(A_m^\gamma/\epsilon_m^\gamma)}{(1+\alpha)(A_m^\gamma/\epsilon_m^\gamma) + (A_m^\beta/\epsilon_m^\beta)}, \tag{8}$$

where the correction factor α is described as

$$\alpha = \frac{\epsilon_g^\beta}{\epsilon_m^\beta}\left(\frac{\lambda_g}{\lambda_m - \lambda_g}\right) . \tag{9}$$

If λ_g was much smaller than λ_m, the correction factor α could be zero. However, the fact that α is 0.068 in this case is not negligibly small compared with our desired precision of R.

By fitting Eq. (3) to the γ-decay time spectrum and by fitting Eq. (4) to the β-ray spectrum, we obtained A_m^γ, A_m^β, and A_g^β. Here, the background of the other gamma rays which are derived from natural backgrounds and the β decay of ^{23}Mg were took into account properly. The dead-time effect of the data taking system was corrected properly by using the artificial 100-Hz trigger clock. Pile-up effect was negligibly small. Substituting obtained values into Eq. (8), the branching ratio R has been determined to be 69.6(7)% as shown in Table 1. The uncertainty mainly comes from the uncertainty of γ-ray detection efficiency and that of the estimation of

Compton scattering probability in the active stopper. The internal conversion coefficient for this transition is negligibly small. The present value is a factor four more precise than previous values of 82.5(30)% [2] and 78(3)% [8]. Our value differs from them over the error bars. The precise half-life $T_{1/2}$ of ^{24m}Al is also determined to be 130.9(13) ms by analyzing the γ-decay time spectrum. The present value is similar to the previous values [6] within the error bars, and is twice more precise than the weighted average of them. The isomeric ratio of the beam was found to be 84.4(18)% by comparing between A^{γ} and A_2^{β}. The branching ratio to the 1369-keV, 2^+ state in ^{24}Mg was also obtained to be 3.5(5)%, which indicates that the ratio of the γ-ray intensity of 1369 keV to that of 426 keV is in good agreement with the previous value given in Ref. [2]. The other intensities of γ rays with high energies could not be determined due to their small detection efficiencies and small branching ratios.

Table 1. Branching ratio of ^{24m}Al decay in units of %.

	^{24}Al(1^+, g.s.)	^{24}Mg(0^+, g.s.)	^{24}Mg(2^+, 1369keV)
Present	69.6(7)	24.1(7)*	3.5(5)*
J. Honkenen et al.[2]	82.5(30)**	10(3)**	4.4(5)**
T. Shibata et al.[8]	78(3)	–	–
A. J. Armini et al.[5]	93(2)	4.4(12)	1.9(5)

*These values were used relative γ-ray intensities given in Ref. [2]. **These values were used relative branching ratio of ^{24}Mg(0^+, g.s.) to ^{24}Mg(2^+, 1369 keV) given in Ref. [5].

The branching ratio from the ^{24m}Al(1^+, 426keV) to the ^{24}Mg(0^+, g.s.) was determined to be 24.1(7)%, by assuming that the other β-ray intensities feeding to the exited states of ^{24}Mg is 8.9(3)% of the isomeric γ decay (see Ref. [2]). The obtained branching ratio is 2.4 times larger than the previous one of 10.1(28)%. The log *ft* value of 5.297(13) is now smaller than the previous value of 5.68(15). The B(GT) value can be derived by the relationship

$$B(\mathrm{GT}) = (2J_f + 1)\frac{K}{(g_A/g_V)^2 ft} \tag{10}$$

where J_f is the spin of final state, a constant $K = 6143.6(17)$ second [9], and a coupling constant ratio $g_A/g_V = -1.270(3)$ of the axial vector current to the vector current of weak interaction [10]. The B(GT) value of 0.0577(16) have been calculated from our β-decay study as shown in Table 2. The difference between the B(GT) value deduced from the β decay and that deduced from the charge-changing reactions is now comparable to the differences for other transitions in the light mass region.

Table 2. B(GT) values from ^{24}Mg (0^+, g.s.) to ^{24m}Al (1^+, 426 keV).

	β decay (present)	β decay (previous)	(p, n) reaction [3]	(^{3}He, t) reaction [4]
B(GT)	0.0577(16)	0.024(8)	0.050(1)	0.054(1)

The observation of $M3$ transition in light nuclei is very rare. Especially, a pair of mirror nuclei ^{24m}Al and ^{24m}Na is unique in that they both decay with the isomeric M3 transition. Therefore, the data of the mirror nuclei are valuable for theoretical test of the magnetic octupole matrix elements. The $M3$ transition strength $B(M3)$ for ^{24m}Na [6] has been already determined precisely. The $B(M3)$ value for ^{24m}Al changes over 10% as shown in Table 3. The experimental ratio of $B(M3)$ for ^{24m}Na to $B(M3)$ for ^{24m}Al becomes consistent with the theoretical ratio by a shell-model calculation [11], although the theoretical prediction of the absolute values still overestimates the experimental values by 50%.

Table 3. Comparison of $B(M3)$ values in ^{24m}Al and ^{24m}Na (in units of μ_N^2 fm^4).

	^{24m}Al	^{24m}Na	$\frac{^{24m}\text{Na}}{^{24m}\text{Al}}$
Experiment (compilation)[6]	269(13)	1038(5)	3.9(2)
Experiment (present)	231(3)		4.50(7)
Shell-model calculation [11]	344	1538	4.47

4. Summary

The β-γ spectroscopy of ^{24m}Al has been carried out by using a secondary ^{24m}Al beam with high purity and high isomeric ratio at HIMAC synchrotron and fragment-separator facility. The branching ratio of ^{24m}Al isomeric γ decay was precisely determined to be 69.6(7)%. As a result, the branching ratio of the β decay to the ^{24}Mg ground state was obtained to be 24.1(7)%, where relative γ-ray intensities of previous values were assumed. By using this branching ratio, the B(GT) value from the ^{24}Mg(0^+, g.s.) to the ^{24m}Al(0^+, 426 keV) of 0.0577(16) was deduced, which is in good agreement with the B(GT) values deduced from (p, n) and (^{3}He, t) charge-exchange reactions. The half-life $T_{1/2}$ of ^{24m}Al was determined to be 130.9(13) ms precisely. The newly obtained $B(M3)$ value of the ^{24m}Al isomeric γ decay made the ratio of the experimental $B(M3)$ values between ^{24m}Na and ^{24m}Al isomeric γ transition consistent with the theoretical prediction by a shell-model calculation.

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