Observation of M3 isomeric transition from $^{156}\text{mPm}$ through the $\beta^-$-decay of $^{156}\text{Nd}$

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Abstract. An M3 transition in a doubly odd nucleus of $^{156}\text{Pm}$ was identified by internal conversion electron measurement through the $\beta$-decay of $^{156}\text{Nd}$ which was separated from the fission products of $^{235}\text{U}$ using the on-line mass separator KUR-ISOL. The isomeric state at 150.3 keV de-excites to the ground state with the M3 transition, and the spin-parity is considered to be $1^-$. Nilsson configurations are also discussed on the basis of the systematics.

PACS. 23.20.Nx Internal conversion and extranuclear effects – 27.70.+q 150 ≤ A ≤ 189

1 Introduction

Studies on isomeric transitions are very useful for studying the Nilsson configuration in deformed nuclei because they reflect the nuclear structure in detail. Especially for isomeric transitions which have high multipolarity, it is useful to measure the internal conversion electrons. The search for isomeric transitions (ITs) has been successively carried out at the on-line mass separator KUR-ISOL in neutron-rich rare-earth elements with internal conversion electron spectroscopy. Recently, isomeric transitions were observed in $^{149}\text{Pr}$ and $^{151}\text{Pr}$ and the energies of the isomeric states were clarified [1,2]. In addition, concerning the odd-odd nuclei $^{152,154}\text{Pm}$, isomeric states have also been proposed, but only their relative positions and spin-parities have been proposed on the basis of the $Q_β$ measurements and log $ft$ values. The isomeric transitions have not been observed, and therefore the properties of the ground states are still unclear [3,4]. Here, by turning our attention to $^{156}\text{Pm}$, isomeric states are expected according to the systematics of the promethium isotopes. However, decay studies of $^{156}\text{Nd}$ are scarce and no excited states have been reported. Up to now, only two groups have studied its decay. Greenwood et al. reported two $\gamma$-rays of 84.8 and 150.7 keV in the decay of $^{156}\text{Nd}$ and proposed the half-life of 5.47(11) s from the decay curves of the two $\gamma$-rays and Pm KX-ray with the mass-separated $^{156}\text{Nd}$ from the spontaneous-fission products of $^{252}\text{Cf}$ [5] for the first time. (The following year, they re-proposed the half-life of 5.5 s [6].) They only reported the technique used to prepare the neutron-rich isotopes. After that, Okano et al. proposed eight $\gamma$-rays including the above two $\gamma$-rays following the decay of $^{156}\text{Nd}$. They also did not refer to any decay properties [7].

However, concerning its daughter nuclide of $^{156}\text{Pm}$, the properties of the ground state were proposed by Hellström et al. through the $\beta$-decay of $^{156}\text{Pm}$ to $^{156}\text{Sm}$ [8]. They studied the decay of $^{156}\text{Pm}$ in detail and suggested that the ground state of $^{156}\text{Pm}$ was likely to be $4^-\{\pi f/2^+[413]+\nu 3/2^-[521]\}$ on the basis of the log $ft$ values in the levels of $^{156}\text{Sm}$; however, they did not refer to the possibility of the isomeric states in $^{156}\text{Pm}$. By Helmer [9], the spin-parity of the ground state of $^{156}\text{Pm}$ was evaluated to be $4^-$ according to Hellström et al. [8]. However, in the last evaluation [10], Reich proposed that the $4^-$ state is not necessary to the ground state of $^{156}\text{Pm}$ for the following reasons. According to the Gallagher-Moszkowski (GM) rules [11], the coupling of these two orbitals which was proposed by Hellström et al. is expected to lie above a level of $K^=1^-$, hence, the $4^-$ state would not be the ground state. In the Pm isotopes, the possible configurations of the 61st proton are $5/2^+[413]$ in $^{151}\text{Pm}$ [12] and $5/2^-[532]$ in $^{154,155,157}\text{Pm}$ [13–15], while those for the 95th neutron are $3/2^-[521]$ in both $^{157}\text{Sm}$ [15] and $^{159}\text{Gd}$ [16], $5/2^+[642]$ in $^{161}\text{Dy}$ [17] and $5/2^-[523]$ in $^{163}\text{Er}$ [18]. The proton orbital in the ground state of $^{156}\text{Pm}$ is considered most likely to be $5/2^-[532]$. If the $4^-$ state is really the
ground state of $^{156}$Pm and it has the $5/2^-$ [532] as its odd-proton orbital, then the odd-neutron orbital would have $K^+ = 3/2^+$ with $3/2^+$ [651] being the most probable according to the Nilsson model. As a consequence, Reich regards the $4^-$ state as the ground state as far as an iso-mer has not been observed. According to the GM rules, if the configuration of the ground state of $^{156}$Pm is $4^-$ \{5/2$^-$ [532] + $\nu 3/2^+$ [651]\}, it is expected that an M3 IT de-exciting from an excited $1^-$ \{5/2$^-$ [532] - $\nu 3/2^+$ [651]\} state to the $4^-$ ground state can be observed. In this experiment, in order to search for the isomeric transitions of the doubly odd nucleus of $^{156}$Pm, internal conversion electrons (ICEs) as well as $\gamma$-rays were measured through the $\beta$-decay of $^{156}$Nd.

2 Experiment

2.1 Source preparation

The experiments were carried out at the on-line mass separator KUR-ISOL at the Kyoto University Reactor. The nuclei of interest were produced via thermal neutron-induced fission of $^{235}$U [19]. The 50 mg UF$_4$ (93% enriched) target was irradiated with a through-hole facility at the reactor where thermal neutron flux is $3 \times 10^{13}$ n/cm$^2$·s. The radioactivities were transported into a thermal-ionization-type ion source with the He-N$_2$ gas jet system including a small amount of O$_2$ gas and separated with the oxidation technique in the chemical form of monoxide NdO$^+$. The mass-separated activity was deposited onto an aluminized Mylar tape in the moving-tape collection system. The tape was moved every 12 s by computer control to reduce the background of daughter and grand-daughter nuclei.

2.2 Measurements

The $\gamma$-ray singles were measured with a 31% HPGe (ORTEC GMX) detector and a short coaxial Ge detector (ORTEC LO-AX; 52 mm$^2 \times 20$ mm$^3$) with open geometry, the source-to-detector distances of 5 cm. The ICEs were measured with a cooled Si(Li) (500 mm$^2 \times 6$ mm$^3$) detector. The Si(Li) detector was separately installed from the tape chamber with 0.5 $\mu$m thick polyester film to avoid the detector surface being smeared with residual gasses in the tape chamber. In order to determine the half-life of $^{156}$Nd, spectrum-multi-scaling (SMS) measurements were carried out by setting a measurements cycle of 12 s which was divided into 16 time intervals of 0.75 s each. In the $\beta$-e and $\beta$-e coincidence measurements, a thin plastic scintillation detector ($80 \times 90$ mm$^2 \times 1$ mm$^3$) was set in front of the HPGe detector. The $\gamma$-e coincidence was measured with close geometry, and the e-$\gamma$ coincidence was measured with the source-to-detector distance for the HPGe detector of 4.6 cm and that for the Si(Li) detector of 1.5 cm. The $\gamma$, $\gamma$, $\gamma$-e, $\beta$-e, and $\beta$-e coincidence measurements were carried out setting the range of the coincidence time of a time-to-pulse height converter (TPHC) at 5 $\mu$s. The full energy peak efficiency of the HPGe detector was determined with the standard sources of $^{56}$Co, $^{133}$Ba, $^{152}$Eu and $^{241}$Am. The total efficiencies in order to correct the summing effects were determined by using sources of $^{60}$Co and $^{137}$Cs and the Monte Carlo simulation code EGS4 [20]. The uncertainties of the full energy peak efficiencies were evaluated to be 1.5%. The efficiency of the Si(Li) detector for electrons was also evaluated by using the EGS4, and that was almost constant to 700 keV. In the energy resolutions in these experiments, the full-width at half maximum (FWHM) of the HPGe detector was 2.4 keV at the 1332 keV $\gamma$-ray and that of the LO-AX detector.

Fig. 1. The low-energy portion of singles $\gamma$-ray spectrum obtained with an HPGe detector (LO-AX). The open circle (o) indicates the $\gamma$-ray following the decay of $^{156}$Pm proposed with ref. [8]. The triangle (△) indicates the $\gamma$-ray decaying with a shorter half-life than 26.7 s. In the inset, the solid line and broken line indicate the singles and $\beta$-gated spectra around 150 keV, respectively.