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Observation of M3 isomeric transition from ^{156m}Pm through the β^--decay of ^{156}Nd

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Abstract. An $M3$ transition in a doubly odd nucleus of ^{156}Pm was identified by internal conversion electron measurement through the β-decay of ^{156}Nd which was separated from the fission products of ^{235}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 $150 \leq A \leq 189$

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 ^{148}Pr and ^{151}Pr and the energies of the isomeric states were clarified [1,2]. In addition, concerning the odd-odd nuclei ^{152,154}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}Pm, isomeric states are expected according to the systematics of the promethium isotopes. However, decay studies of ^{156}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 γ-rays of 84.8 and 150.7 keV in the decay of ^{156}Nd and proposed the half-life of 5.47(11) s from the decay curves of the two γ-rays and Pm KX-ray with the mass-separated ^{156}Nd from the spontaneous-fission products of ^{252}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 γ-rays including the above two γ-rays following the decay of ^{156}Nd. They also did not refer to any decay properties [7].

However, concerning its daughter nuclide of ^{156}Pm, the properties of the ground state were proposed by Hellström *et al.* through the β-decay of ^{156}Pm to ^{156}Sm [8]. They studied the decay of ^{156}Pm in detail and suggested that the ground state of ^{156}Pm was likely to be 4^- $\{\pi 5/2^+[413]+\nu 3/2^-[521]\}$ on the basis of the $\log ft$ values in the levels of ^{156}Sm; however, they did not refer to the possibility of the isomeric states in ^{156}Pm. By Helmer [9], the spin-parity of the ground state of ^{156}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}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 $K^\pi = 1^-$, 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}Pm [12] and $5/2^-[532]$ in ^{153,155,157}Pm [13–15], while those for the 95th neutron are $3/2^-[521]$ in both ^{157}Sm [15] and ^{159}Gd [16], $5/2^+[642]$ in ^{161}Dy [17] and $5/2^-[523]$ in ^{163}Er [18]. The proton orbital in the ground state of ^{156}Pm is considered most likely to be $5/2^-[532]$. If the 4^- state is really the

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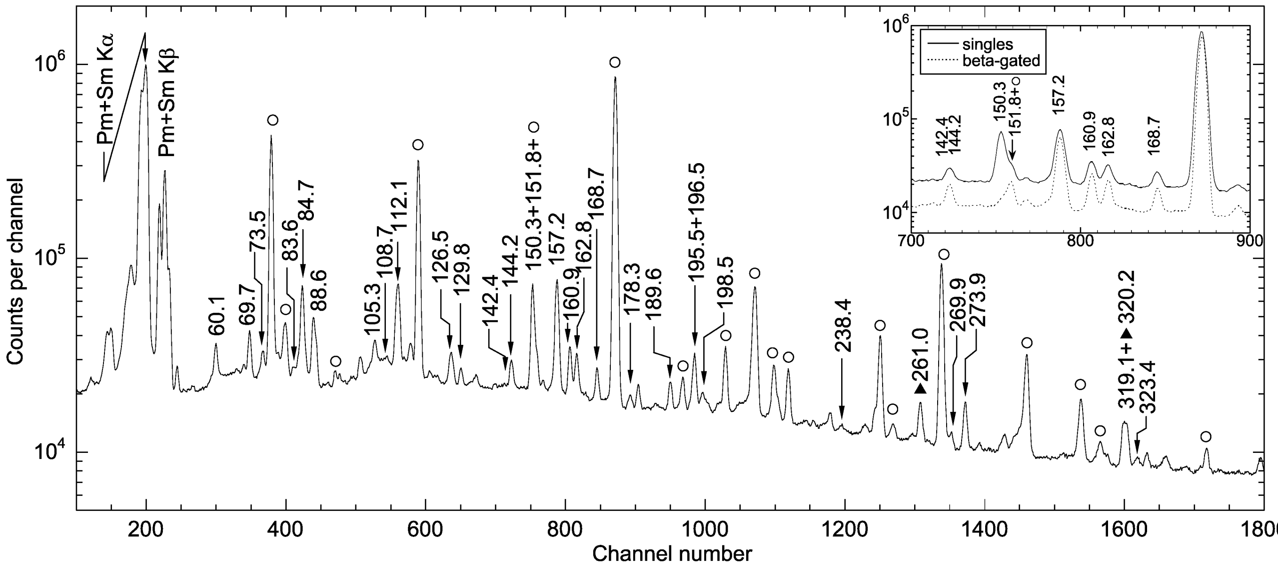

Fig. 1. The low-energy portion of singles γ-ray spectrum obtained with an HPGe detector (LO-AX). The open circle (○) indicates the γ-ray following the decay of ^{156}Pm proposed with ref. [8]. The triangle (▲) indicates the γ-ray decaying with a shorter half-life than 26.7 s. In the inset, the solid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

ground state of ^{156}Pm and it has the $5/2^-[532]$ as its odd-proton orbital, then the odd-neutron orbital would have $K^\pi = 3/2^+$ 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 isomer has not been observed. According to the GM rules, if the configuration of the ground state of ^{156}Pm is 4^- $\{\pi 5/2^-[532] + \nu 3/2^+[651]\}$, it is expected that an $M3$ IT de-exciting from an excited 1^- $\{\pi 5/2^-[532] - \nu 3/2^+[651]\}$ 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 γ-rays were measured through the β-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 $3 \times 10^{12}\,\mathrm{n/cm^2 \cdot s}$. 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 γ-ray singles were measured with a 31% HPGe (ORTEC GMX) detector and a short coaxial Ge detector (ORTEC LO-AX: $52\,\mathrm{mm}^\phi \times 20\,\mathrm{mm}^t$) with open geometry, the source-to-detector distances of 5 cm. The ICEs were measured with a cooled Si(Li) ($500\,\mathrm{mm}^2 \times 6\,\mathrm{mm}^t$) 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 β-γ and β-e coincidence measurements, a thin plastic scintillation detector ($80 \times 90\,\mathrm{mm}^2 \times 1\,\mathrm{mm}^t$) was set in front of the HPGe detector. The γ-γ coincidence was measured with close geometry, and the e-γ 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 γ-γ, e-γ, β-γ, and β-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 γ-ray and that of the LO-AX detector

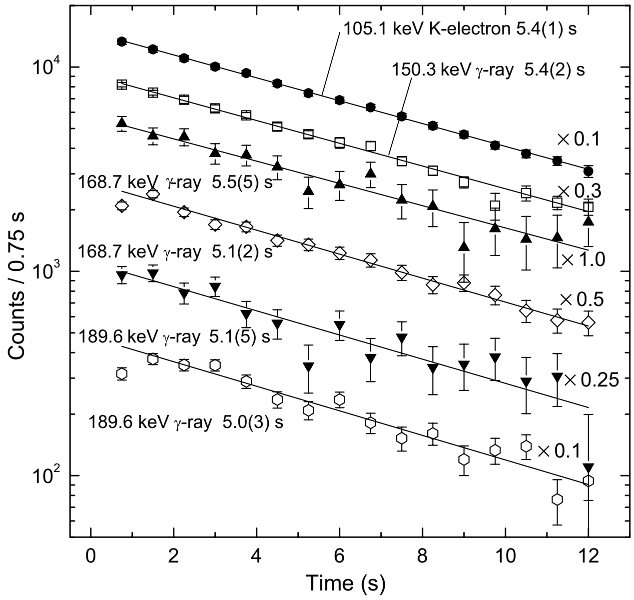

Fig. 2. Decay curves of 168.7 and 189.6 keV γ-rays obtained with the two HPGe detectors. The isomeric transitions of the 150.3 keV γ-ray and the corresponding K-conversion electron at 105.1 keV are also shown for comparison (see the text).

was 780 eV at the 122 keV γ-ray, while that of the Si(Li) detector was 2.2 keV at the 127 keV electron. The γ-rays following the decay of ^{156}Pm were used for the energy calibration.

3 Results and discussion

3.1 Gamma-ray measurements and β-decay half-life of ^{156}Nd

In this experiment, many γ-rays following the decay of ^{156}Nd were newly observed up to 1.5 MeV. The low-energy portion of singles and the β-gated γ-ray spectra obtained with the LO-AX detector are shown in fig. 1.

Gamma-rays following the decay of ^{156}Nd were assigned on the basis of the β-γ, X-γ, γ-γ coincidence relations and also the decay half-lives. Most of the γ-rays are coincident with the Pm KX-rays. The intensities and coincidence relation of the γ-rays will be proposed with the decay scheme in another paper, but here the γ-rays in the low-energy region are proposed to explain the identification of an isomer. The low-energy γ-ray intensities are proposed in table 1 and compared with the previous results by Okano *et al.* [7]. They are almost in agreement with the previous results, but those of the 150.3 and 319.1 keV γ-rays are much smaller than those of ref. [7]. The reasons for this were considered to be as follows: As clearly observed in the spectrum, there are γ-rays in the higher-energy side of the 150.3 keV γ-ray. It was found that this region contains two γ-rays from the coincidence results, one coincidence with the Pm KX-rays and the other coincidence with the Sm KX-rays. The 319.1 keV γ-ray was also found to be contaminated with the 320.2 keV γ-ray following the decay of ^{156}Pm through the coincidence results. These results were first observed in this experiment. Okano *et al.* [7] measured the γ-rays under the condition of the tape cycle of 144 s that is one order of magnitude longer than 12 s of this experiment; therefore, the ^{156}Pm grew much more compared to in this experiment. The results showed that the previous intensities of the 150.3 and 319.1 keV γ-rays are larger than those in this experiment. The β-decay half-life of the ^{156}Nd was determined to be 5.06(13) s by the decay curves of the 168.7 and 189.6 keV γ-rays (fig. 2). These γ-rays are relatively intense and have no contaminated peaks, and are in coincidence with both the β-ray and Pm KX-rays. The decay curves of both γ-rays were obtained with the HPGe and also the LO-AX

Table 1. Energies and relative intensities of the γ-rays following the decay of ^{156}Nd in low-energy region.

E_γ	Relative I_γ(%)	
(keV)	Present	Previous[a]
49.2(2)	8.8(11)	
60.1(2)	34(2)	24(6.4)
69.7(2)	33(19)	
73.5(2)	34(3)	
83.6(2)	13(2)	
84.7(1)	100(3)	100*
88.6(2)	38(3)	
105.3(1)	25(3)	
108.7(1)	3.1(13)	
112.1(2)	67(7)	
126.5(2)	18(3)	
129.8(1)	6.4(13)	
142.4(2)	3.8(12)	
144.2(1)	20(2)	
150.3(1)	91(5)	159(25)
151.8(3)	< 11[§]	
157.2(1)	116(4)	124(25)
160.9(1)	51.6(18)	56(8)
162.8(1)	25.8(15)	
168.7(1)	23(3)	
178.3(1)	11(2)	
189.6(1)	25(3)	
195.5(2)	7(2)	
196.5(2)	39(2)	44(9.4)
198.5(1)	38(2)	
238.4(2)	7(2)	
269.9(1)	13.0(14)	
273.9(1)	47.0(17)	57(13)
319.1(1)	37(3)	51(8)
323.4(3)	5.7(13)	

[a] Previously proposed in ref. [7].
[§] The upper limit value is shown because this γ-ray is mixed with a γ-ray in the decay of ^{156}Pm.
* The intensities are re-normalized by this γ-ray.

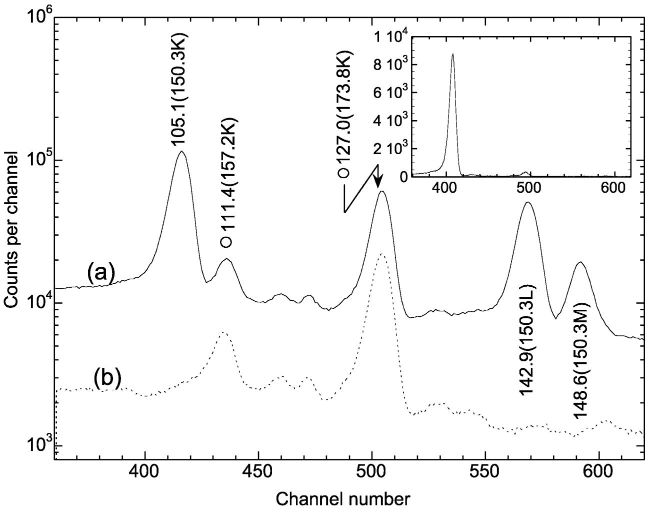

Fig. 3. The portion of the singles (a) and β-gated (b) internal conversion electron spectra obtained with the Si(Li) detector. The K, L, M electrons for the 150.3 keV transition are not observed in the β-gated spectrum. The open circle (∘) indicates the electrons following the decay of ^{156}Pm. The inset shows a coincidence spectrum of internal conversion electrons gated by the Pm K_βX-ray. The 105.1 keV peak, which is the K-conversion electrons of the 150.3 keV γ-ray, is clearly observed.

detectors, and then the weighted mean value of the four values was adopted.

3.2 Half-life of isomer ^{156m}Pm

The 150.3 keV transition is not coincident with the β-ray, as clearly observed in the inset of fig. 1, and was also not coincident with any other γ-rays in the decay of ^{156}Nd. In addition, the ICEs of the 150.3 keV γ-ray, the 105.1, 142.9 and 148.6 keV electron peaks correspond to the K-, L- and M-conversion electrons of the 150.3 keV γ-ray, were also not observed in the β-gated ICE spectra (fig. 3). The coincidence results mean that the 150.3 keV transition is an isomeric transition having a relatively long half-life. On the other hand, the K-conversion electron of 105.1 keV is strongly and only coincident with the Pm K_βX-ray, as shown in the inset of fig. 3. These results led us to conclude that the 150.3 keV state is the isomeric state that directly de-excites to the ground state of ^{156}Pm with a considerably long half-life, because both the β-e and β-γ coincidence timings are out of the TPHC range of 5 μs. Both decay curves of the 150.3 keV γ-ray and the 105.1 keV K-conversion electron seems to be 5.4 s, as shown in fig. 2, and those are almost the same as the β-decay half-life of ^{156}Nd. If the half-life of the isomer is much longer than that of ^{156}Nd, then the decay curve should show a growth-and-decay property. The 105.1 keV K-electron decay curve was carefully analyzed by using two exponential functions in which one half-life was fixed at 5.06 s. As a result, it was found that the uncertainty is large; nevertheless, another half-life was possibly evaluated to be 2.3(20) s. In fact, the decay curve shows almost a line in a semi-log plot. This means that the half-life of the isomer is 5 s at most, which is not much longer than the half-life of the decay curves, which show the growth-and-decay property clearly.

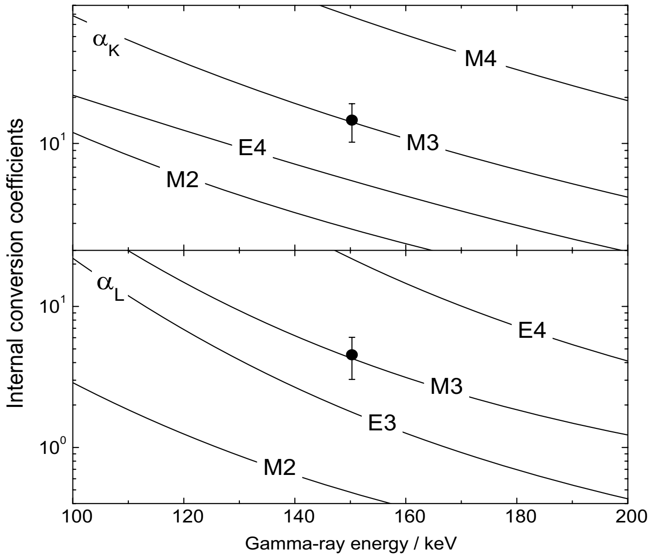

Fig. 4. Experimental internal conversion coefficients for the 150.3 keV γ-rays in ^{156}Pm together with the theoretically calculated values by ref. [21].

Table 2. Experimental internal conversion coefficients and theoretical ones for the 150.3 keV γ-ray in ^{156}Pm.

Internal conversion coefficients α							
α	This work	Theoretical[a]					Assigned
		$M2$	$E3$	$M3$	$E4$	$M4$	
K	14(4)	2.8	1.4	13.8	5.7	67.4	$M3$
L	4.5(15)	0.5	1.8	4.3	21.8	40.5	$M3$

[a] Calculated by ref. [21].

3.3 Internal conversion coefficients

Internal conversion coefficients (ICCs) were deduced by taking the intensity ratios between γ-rays and the corresponding electrons. The 267.8 keV γ transition which is known as a pure $E2(2^+ \rightarrow 0^+)$ transition in the doubly even nucleus of ^{156}Sm was adopted for the normalization of the Si(Li) and HPGe detectors. The analyzing procedure is described elsewhere [1,2]. The results for ICCs are shown in fig. 4 and table 2 together with the theoretically calculated values [21]. The result of the ICC shows that the 150.3 keV transition is an $M3$ transition.

3.4 Properties of the isomer

It is worthwhile to find out whether the isomer decays to levels in ^{156}Sm or not. For convenience of explanation, a partial decay scheme of ^{156}Nd together with ^{156}Pm is shown in fig. 5 on the basis of the coincidence results in this experiment. The decay curves of the 117.4 and

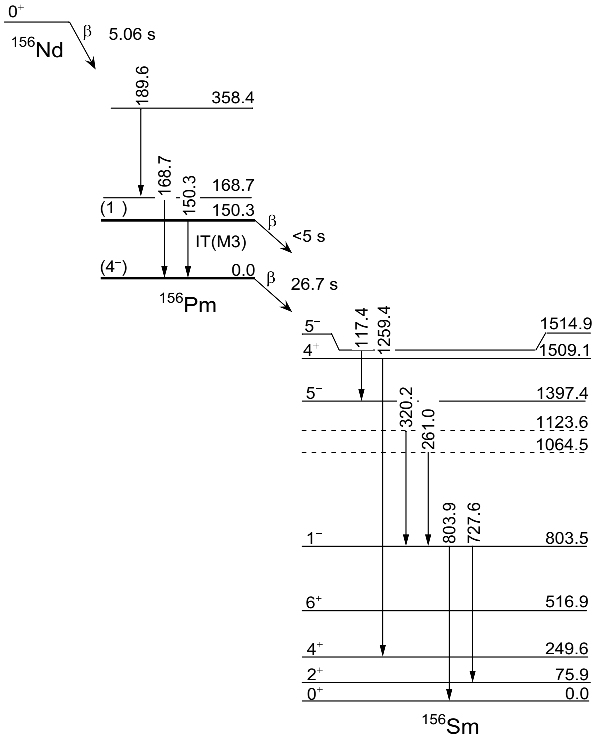

Fig. 5. Partial decay scheme of ^{156}Nd and ^{156}Pm.

1259.4 keV γ-rays which de-excite from the higher-energy 5^- or 4^+ levels in ^{156}Sm in ref. [8], shows half-lives of 27(5) s and 30(18) s, respectively, in this experiment (fig. 6). The measurement cycle of 12 s in this experiment is not long enough to precisely deduce the half-life of ^{156}Pm. The results therefore have large uncertainties, but support the previous results of 26.7(1) s [8] nevertheless. It is understood that these two decay curves slightly show the growth-and-decay property owing to the isomer of ^{156}Pm. On the other hand, as shown in fig. 6, the decay curves of the 727.6 and 803.9 keV γ-rays show half-lives of 8.6(10) s and 9.9(6) s, respectively. These γ-rays de-excite from the 1^- level at 803.9 keV in ^{156}Sm, which was tentatively assigned in ref. [8]. In addition, two newly observed 261.0 and 320.2 keV γ-rays, which are coincident with both the 727.6 and 803.9 keV γ-rays in ^{156}Sm, also show half-lives of 6.8(6) s and 12(2) s, respectively (fig. 6). These half-lives are apparently shorter than 26.7 s. This means that the short-lived isomer of ^{156}Pm probably decays to some low-spin states in the excited states in ^{156}Sm directly, and does not decay to the high-spin states in the higher-energy region in ^{156}Sm that much. It is difficult to determine the branching ratios of IT to β-decay from the isomer, but these ratios can be evaluated as follows.

The ten γ-ray intensities (%/decay) following the decay of the daughter nuclide ^{156}Pm are listed in table 3. The intensities of eight γ-rays deduced from this experiment are in agreement with the previous ones, but those of the 727.6 and 803.9 keV γ-rays, which decay with shorter half-lives, are apparently larger than the previous ones. This means the peak counts of the two γ-rays are composed of two components, one originating from the isomer

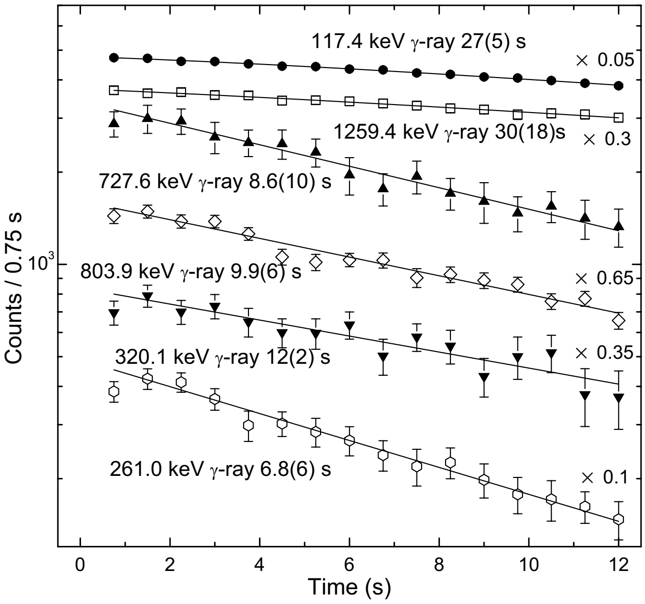

Fig. 6. Decay curves of some γ-rays in ^{156}Sm. The 117.4 keV and 1259.4 keV γ-rays de-excite between $5^- \rightarrow 5^-$ and $4^+ \rightarrow 4^+$, respectively. The two decay curves slightly show the growth-and-decay property. The 727.6 and 803.9 keV γ-rays de-excite from the 1^- level at 803.9 keV. Two γ-rays of 261.5 and 320.3 keV are newly observed and are coincident with the 727.6 and 803.9 keV γ-rays.

Table 3. Comparison of γ-ray intensities following the decay of ^{156}Pm.

E_γ	Intensity (%/decay)	
(keV)	Present	Previous[a]
117.4	13.8(3)	13.8(7)*
173.8	50.0(10)	52.0(20)
727.6	2.2(2)	0.9(2)
803.9	2.1(2)	1.1(2)
880.4	11.2(3)	10.4(5)
894.4	9.3(3)	8.4(4)
934.0	12.8(4)	12.3(6)
1147.8	19.9(4)	20.5(1)
1259.4	11.9(3)	12.6(6)
1433.7	7.9(3)	8.4(4)

[a] Taken from ref. [8].
* Normalized by this intensity.

via the ground state of ^{156}Pm with IT, and the other originating from the β-decay of the isomer. The excesses of the intensities of the γ-rays at least correspond to the contribution of the isomeric β-decay. The contribution from isomeric β-decay is evaluated by taking the averaged value of the excesses for two γ-rays as the following relation, $C_\gamma \times (1 - I_{\gamma(\text{ref. [8]})}/I_{\gamma(\text{present})})/\epsilon_\gamma$, where C_γ, I_γ and ϵ_γ indicate the peak counts, intensities and efficiencies for the 727.6 and 803.9 keV γ-rays, respectively. On the other hand, the intensity of IT is evaluated to be $C_{\gamma(150)} \times (1+\alpha_{\mathrm{T}\gamma(150)})/\epsilon_{\gamma(150)}$, where $C_{\gamma(150)}$, $\alpha_{\mathrm{T}\gamma(150)}$ and $\epsilon_{\gamma(150)}$ indicate the peak counts in the singles spectrum, total conversion coefficients and detection efficiency for the 150 keV γ-ray, respectively. As a result, taking account of the total internal conversion coefficient 21.1 for the $M3$ transition, the intensity of the isomeric β-decay was evaluated to be not less than 2%. Assuming the half-life of 5 s and the transition intensity for IT of 98%, the hindrance factor was estimated to be approximately 3. This value is consistent with the value of $10^0 \sim 10^3$ for the nuclei around $A \sim 150$, ^{142,144,148}Pr and ^{158}Tb [22,23,1,24].

Finally, probable Nilsson configurations will be discussed. On the basis of the result in this experiment and the previously reported assignments, the low-spin state having a shorter half-life than that of the 4^- state lies at 150.3 keV. The spin-parity for the isomeric state is considered to be lower than or equal to 4^-, and the spin-parity was probably a 1^- state. The configurations of 4^- and 1^- are likely to be $\{\pi 5/2^-[532] + \nu 3/2^+[651]\}$ and $\{\pi 5/2^-[532] - \nu 3/2^+[651]\}$, respectively, as suggested by Reich [10]. This results is consistent with the GM rules that the spin of the ground state of $I = \Omega_p + \Omega_n$, if $\Omega_p = \Lambda + 1/2$ and $\Omega_n = \Lambda + 1/2$.

4 Conclusion

The isomeric state at 150.3 keV that de-excites to the 4^- ground state of ^{156}Pm with an $M3$ transition was observed for the first time from the internal conversion electron measurements through the β-decay of ^{156}Nd. The spin-parity of the isomer was probably 1^-.

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