The Search for Isomers of ^{156}Pm through the β-decay of ^{156}Nd

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The search for isomers of ^{156}Pm has been performed through the β-decay of ^{156}Nd. The sources of the ^{156}Nd were obtained from mass-separated fission products of ^{235}U at the Kyoto University Reactor (KUR). Plastic scintillators, two HPGe detectors, and a Si(Li) detector were used. In the present experiment, more than 30 γ-rays from the β-decay of the ^{156}Nd were newly observed. The 150.8 keV isomeric transition (I.T.) from ^{156m}Pm was successfully measured. This transition was assigned to the M3 multipolarity, from the result of the conversion electron measurement. A spin and a parity of 1^- were reasonable for the isomeric state based on the M3 multipolarity of the I.T. and the 4^- β-decaying state of the ^{156}Pm.

1. Introduction

Nuclear data of neutron-rich isotopes are required for estimation of a decay heat of nuclear reactors and studies for a utilization of radioactive waste. For odd-odd nuclei, nuclear data are insufficient compared to neighboring even-even or odd-A nuclei, whose data are preferentially acquired from the viewpoint of nuclear physics. For substantial nuclear data, odd-odd nuclei must be studied as well as the other nuclei. Neutron-rich odd-odd nuclei with the mass number around A=150 have a characteristic that many of them have isomeric states. In this region, an isomer search is significant for substantial nuclear data.

We can expect isomers of ^{156}Pm, because isomers have been reported at the mass number of A=152, 154 in neutron-rich Pm isotopes[1, 2)]. Concerning excited levels of ^{156}Pm, some authors have been reported in refs.[3-5)]. But level structure of the ^{156}Pm is not made clear and isomers are not reported. In this work, we aimed at searching isomers of the ^{156}Pm through

the β-decay of the ^{156}Nd by means of a decay spectroscopy.

2. Experiment

The sources of the ^{156}Nd were obtained from fission products of ^{235}U using the on-line mass separator installed at the T-1 through tube of the Kyoto University Reactor (KUR-ISOL). The amount of 50 mg of UF_4 target was irradiated by thermal neutrons with a flux of 3×10^{12} n/cm^2·s. Fission products were transported to a thermal ion source by the He-N_2 gas-jet system[6]. They were ionized and mass separated by an analyzing magnet, whose resolution was ΔM/M~1/600. The mass separated fission products were collected on an alminium-coated Mylar tape and moved to a measuring position after a predetermined time interval of 12.5 s. This interval was estimated from the reported half-life of 5.47(11) s of the ^{156}Nd[3].

In measuring conversion electrons, three detectors were used; a Si(Li) detector (500 mm^2×6 mm^t) for conversion electrons, a 31 % GMX detector for γ-rays and plastic scintillator (80 mm×90 mm×1 mm^t) for β-rays. In measuring γ-rays, the Si(Li) detector was replaced by a LOAX detector (52 mm$^\phi$×20 mm^t) for low energy γ-rays. The plastic scintillator was placed at the distance of near zero from the Mylar tape for covering large solid angle. The small vacuum chamber for the Si(Li) detector was separated from the ISOL chamber by a 0.5 μm^t polyester film to protect the cooled surface of the Si(Li) detector against residual vapors.

Measurements on A=156 nuclei were performed during about 55 hours for both conversion electrons and γ-rays. Singles and β-gated singles spectra for conversion electrons, γ-rays, γ-γ and e-γ coincidence data were taken. Singles spectra were measured in the Spectrum Multi Scaling mode to determine the half-life of the ^{156}Nd.

To search isomers, we compared the β-gated spectra with the singles spectra[7]. The I.T. from the long-lived isomer is expected that it is scarcely observed in the β-gated spectrum. This expectation was backed up by the measurement of the 168.5 keV I.T. from mass-separated ^{93m}Y. Thus, the present measurement system of the Si(Li) detector can distinguish I.T.s from the other transitions. The efficiency and the energy calibrations for the HPGe detectors were made by the standard sources of ^{133}Ba, ^{152}Eu and ^{137}Cs. These calibration of the Si(Li) detector were made by the mass-separated sources of ^{93m}Y, ^{93}Rb, ^{140}Cs and ^{146}La. The Monte Carlo calculations (EGS4) were also used to estimate a peak efficiency of the Si(Li) detector. The efficiency of the Si(Li) detector was constant in the energy range from 70 keV to 1000 keV.

3. Results

Gamma-ray singles spectrum for A=156 nuclei measured by the GMX detector is shown in Fig.1. In the present experiment, we observed about 40 γ-rays associated with the β-decay

of the ^{156}Nd from coincidences with Pm X-rays. More than 30 γ-rays were newly observed. The 150.8 keV γ-ray was the most intense among measured γ-rays. The γ-ray intensities agreed with those of K. Okano *et al.*[4]. Using the 144.8-, 169.2- and 190.2 keV γ-rays, we determined the β-decay half-life of the ^{156}Nd. Decay curves of these γ-rays are presented in Fig.2. We tentatively obtained the half-life of 5.2(1) s as a weighted mean value of half-lives of three γ-rays. This half-life is somewhat shorter compared to the result reported by Greenwood *et al.*[3].

A portion of electron singles spectrum around 100 keV is shown in Fig.3 together with the β-gated spectrum. The 105.6-, 143.4- and 149.1 keV electron peaks were corresponded to the K-, L- and M-conversion electron peaks of the 150.8 keV I.T. from ^{156m}Pm. The following results confirmed that these electron peaks were originated from the I.T.; (1) no coincidences with β-rays, (2) coincidences with X-rays from the Pm, (3) approximately the same half-life as the γ-rays from the β-decay of the ^{156}Nd. In Fig.3, the K-, L- and M-electron peaks of the 150.8 keV transition were scarcely observed in the β-gated spectrum. From the e-γ coincidence data, the 105.6 keV K-electron peak was coincident with K_α and K_β X-rays of Pm. It means that the electrons were emitted from an excited level of the ^{156}Pm. The decay curve of the 105.6 keV K-electron peak is also presented in Fig.2. The half-life of the electron peak was 5.13(2) s. This value agrees with the half-life of 5.2(1) s of γ-rays from the β-decay of the ^{156}Nd. If the radiative equilibrium is approved between the ^{156}Nd and the ^{156m}Pm, the half-life of 5.13(2) s of the electron peak leads to conclusion that the electrons are emitted from the excited level of the daughter nucleus of the ^{156}Nd, that is, the ^{156m}Pm. This assumption is correct from the multipolarity of the 150.8 keV transition described later. From foregoing results, the 150.8 keV transition is the I.T. from the ^{156m}Pm.

Experimental K- and L-internal conversion coefficients (I.C.C.s) of the 150.8 keV I.T. are presented in Fig.4 together with the theoretical values[8]. Experimental values were obtained from the electron and the γ-ray singles spectra. We found the ratio of the interested I.C.C. to the well evaluated one and determined the value of the interested I.C.C.s. The normalization of the conversion coefficients was made using the 267.8 keV known E2 transition following the β-decay of the ^{156}Pm. Errors are estimated from the upper and the lower value of the I.C.C.s, which are obtained from the different normalizations and at two measuring positions of the GMX detector (8 mm and 46 mm). From the Fig.4, the 150.8 keV I.T. was assigned to be the M3 multipolarity. Using Moszkowski formula, the half-life of the isomer is estimated to be 253 ms. The radiative equilibrium is considered to be approved between the ^{156}Nd and the ^{156m}Pm because the half-life of the ^{156m}Pm is much shorter than the one of the ^{156}Nd.

4. Discussion

A spin and a parity of the isomer were estimated based on a placement of the 150.8 keV I.T. in the decay scheme, M3 multipolarity of the I.T. and the 4^- β-decaying state of the ^{156}Pm[5]. From the e-γ coincidence data, the 105.6 keV K-electron peak was only coincident with K_α and K_β X-rays of Pm and not coincident with the other γ-rays. Then, the I.T. directly populates the 4^- state of the ^{156}Pm. In consideration for the M3 multipolarity of the I.T., the isomer is likely to be 1^- state.

We tentatively propose a proton-neutron configuration for the 1^- isomeric state from systematics of ground states in neighboring odd-A nuclei. In odd-A isotones with the neutron number of N=95, the ν3/2[521] was reported for the ground states of ^{157}Sm and ^{159}Gd. In odd-A isotopes with the proton number of Z=61, the π5/2[532] for ^{153,155,157}Pm and the π5/2[413] for ^{151}Pm were reported as a configuration of the ground state. From these configurations, $\{\pi 5/2[413]\text{-}\nu 3/2[521]\}_{1^-}$ is the only probable configuration for the 1^- isomeric state. If the 4^- state is the ground state, the configuration of the 1^- state may be an example of a violation of Gallagher-Moszkowski rules[9]. Concerning energy level ordering of the 1^- and the 4^- states, detailed analyses are now in progress.

5. Conclusion

The search for isomers of the ^{156}Pm has been performed through the β-decay of the ^{156}Nd. In the present experiment, we observed about 40 γ-rays associated with the β-decay of the ^{156}Nd. More than 30 γ-rays were newly observed. The β-decay half-life of the ^{156}Nd was estimated to be 5.2(1) s. The 150.8 keV I.T. from the ^{156m}Pm was successfully observed and assigned to be the M3 multipolarity. This transition directly populates the 4^- β-decaying state of the ^{156}Pm. Based on these results, the spin and the parity of the new isomeric state is likely to be 1^-. The proton-neutron configuration of $\{\pi 5/2[413]\text{-}\nu 3/2[521]\}_{1^-}$ for the 1^- isomeric state was tentatively proposed from the systematics in neighboring odd-A nuclei.

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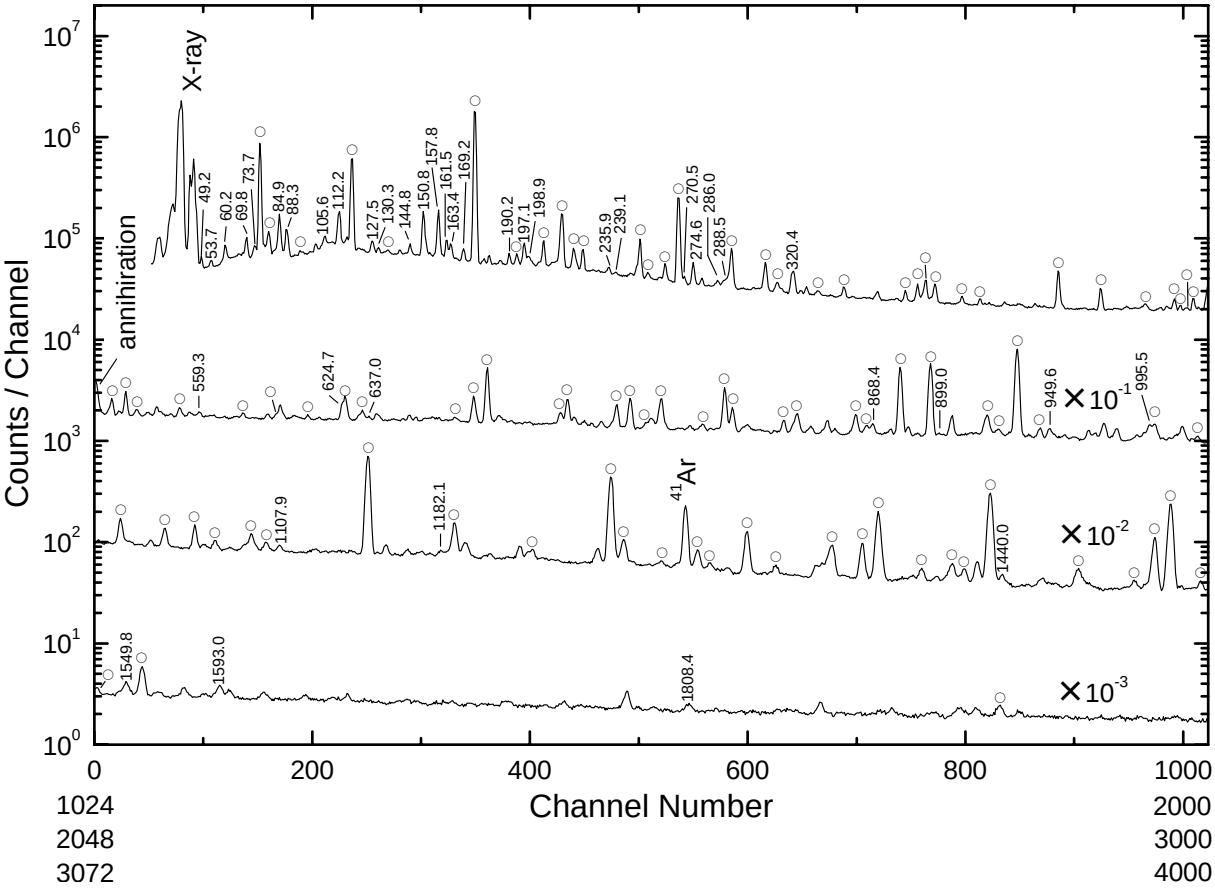

Fig.1 A γ-ray singles spectrum in the decay of the ^{156}Nd measured by the GMX detector. Energies are given in keV. Gamma-ray peaks marked by opened circles represent γ-rays from the decay of the ^{156}Pm.

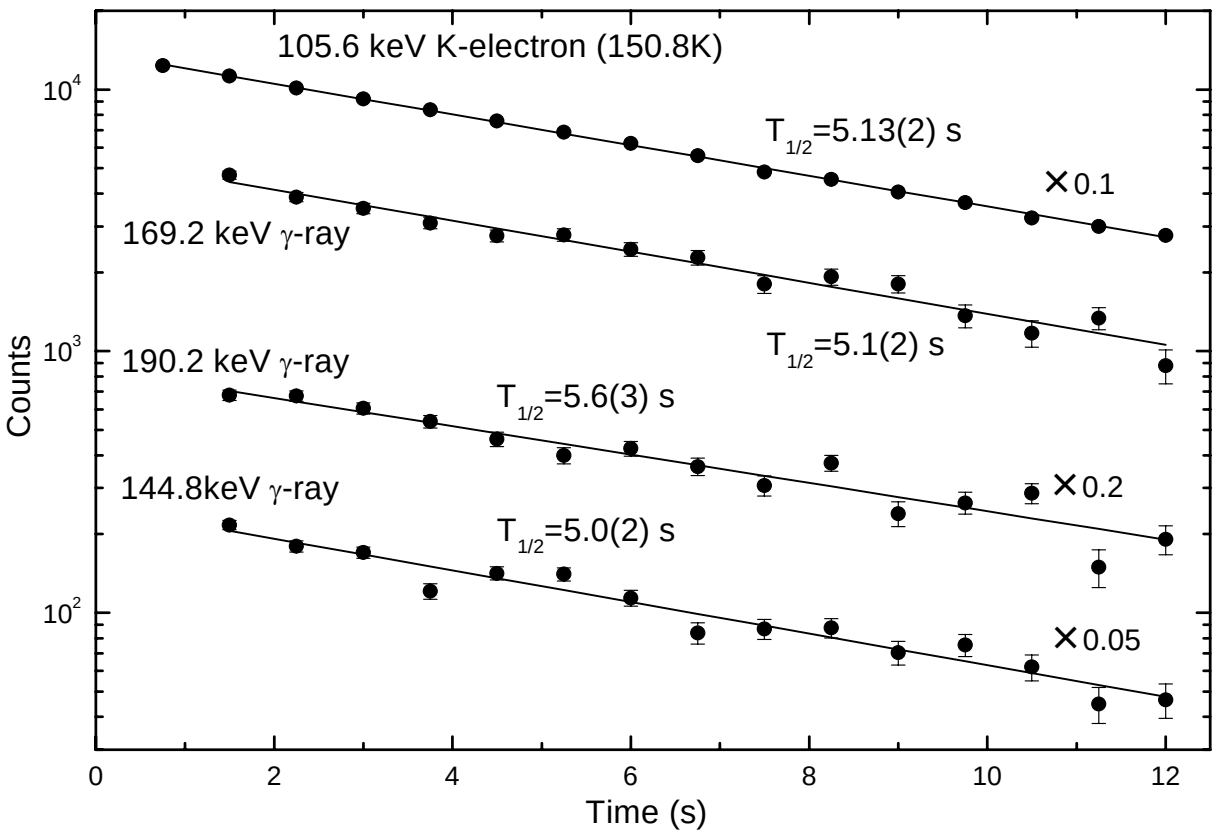

Fig.2 Decay curves of the 144.8-, 169.2-, 190.2 keV γ-ray and the 105.6 keV K-electron of 150.8 keV isomeric transition (150.8K).

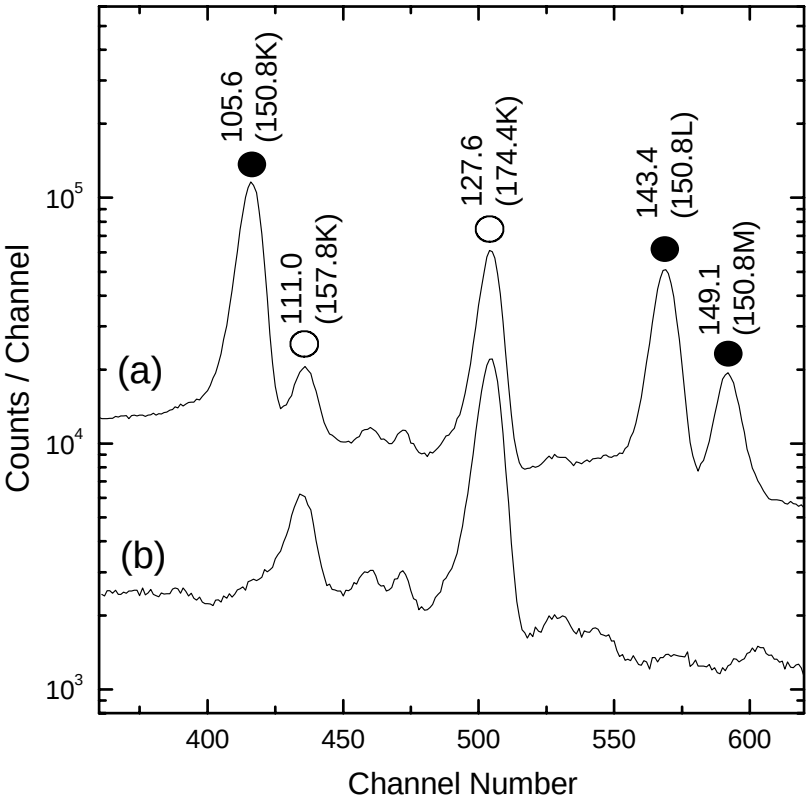

Fig.3 A portion of (a) the electron singles and (b) the β-gated electron singles spectra for A=156 nuclei. Energies are given in keV. Closed and opened circles represent electrons from the decay of the ^{156}Nd and the ^{156}Pm, respectively.

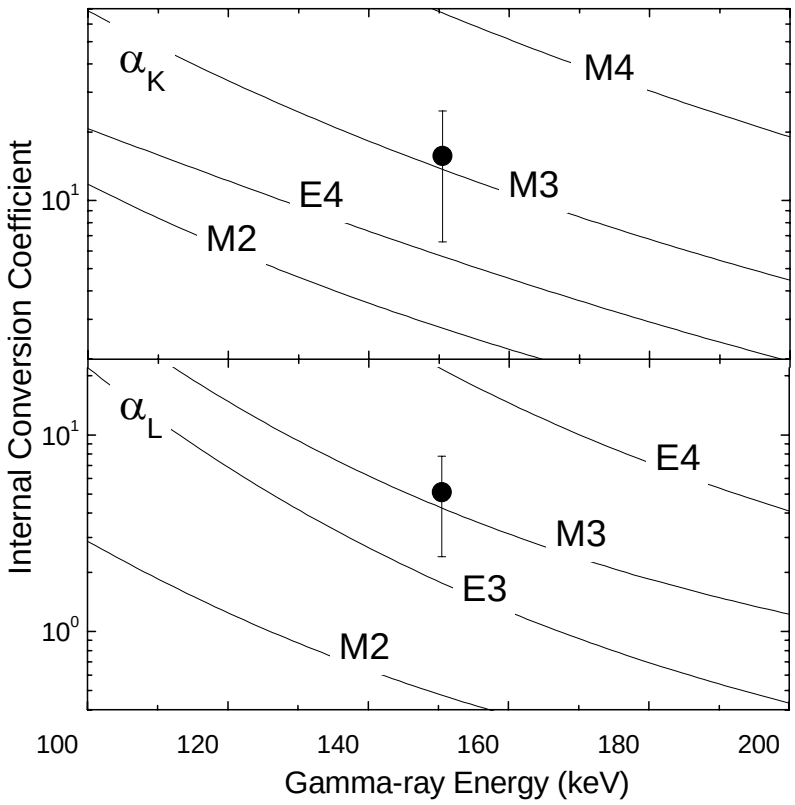

Fig.4 Experimental K- and L-internal conversion coefficients for the 150.8 keV I.T.. Solid lines mean theoretical values taken from ref.[8)].