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Role of Hexadecupole Deformation in the Shape Evolution of Neutron-rich Nd Isotopes

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A new isomer with μs half-life was observed in ^{160}Nd at RIBF, RIKEN Nishina Center by using in-flight fission of a ^{238}U beam and a cluster-type Ge detector array, EURICA. The experimental results and a PSM calculation indicate that the isomer in ^{160}Nd is a 2 quasi-particle excitation of neutrons with a configuration of $\nu 1/2[521] \otimes \nu 7/2[633]$ as the case in other $N = 100$ isotones. The $E(4^+)/E(2^+)$ ratio of the ground-state band, 3.29, shows the ^{160}Nd is well deformed and the ground band has a rotational nature. The 4^- excitation of ^{160}Nd showed an increase in energy by ~ 100 keV compared to that of ^{162}Sm as predicted by the PSM calculation. A PSM calculation was performed by changing input β_4 value and confirmed that the large hexadecupole deformation in Nd was responsible for the increase of the isomer energy.

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1. Introduction

One of the unique features of the nuclear shells is that they have intruder orbitals from larger N quantum number by large spin-orbit interaction. Such shell structure can make a higher-order deformed shape energetically favored in a certain nucleus due to a large interaction between orbitals with higher-order multipolarity.

In stable rare-earth nuclei, a large hexadecupole deformation (β_4) is observed in the ground state of Nd ($Z = 60$) isotopes such as ^{148}Nd ($\beta_4 \sim 0.07$) [1]. Although, in general, quadrupole deformation is sufficient to explain primary phenomena in nuclei, higher-order deformations can cause significant change in the single particle structures. However, higher-order deformations such as hexadecupole deformation have not been well studied for unstable nuclei far from the line of β stability. Therefore, it is important to know how such deformation evolves as neutron number increases and how it affects to the single particle levels.

The neutron-rich nuclei in the $A \sim 160$ rare-earth region are known to be well deformed that is evidenced by the $E(4^+)/E(2^+)$ ratios of the ground-state rotational bands, ~ 3.3 [2]. Many low-lying two quasi particle (qp) isomers with $\sim \mu$s half-lives with strongly hindered E1 γ decays are known in the neutron-rich Nd and Sm isotopes [6, 7, 8, 9]. In the even-even $N = 100$ isotones from Sm to Yb, 2-qp isomers with a dominant configuration of $\nu 1/2[521] \otimes \nu 7/2[633]$ are known above ~ 1 MeV in excitation energy [3, 4, 5]. It is expected that a 2-qp state with this configuration in ^{160}Nd also can be observed as an isomer. According to the potential energy surface calculation in [9], significantly non zero β_4 and β_6 values are required to reproduce the observed energy of the isomeric state in ^{164}Sm. Theoretically, an FRDM [10] and RMF [11] calculations predict large hexadecupole deformation in the neutron-rich Nd isotopes. It is expected that the large hexadecupole deformation in Nd isotopes changes the single particle orbitals significantly and it may be observed as the change of excitation energies of isomers.

The experimental results on the Nd isotopes that will be shown in this article have been published as Ref. [12]. More details of the experimental methods and results can be found in the article.

2. Experiment

An isomer spectroscopy study on neutron-rich $Z \sim 60$ isotopes was performed at the RIBF, RIKEN Nishina Center. Neutron-rich Nd isotopes were produced by using in-flight fission of a 345 MeV/nucleon ^{238}U beam, bombarded on a 4-mm thick Be target. The typical intensity of the ^{238}U beam was ~ 7 pnA. The ions of interest were separated from other fission fragments and identified event-by-event in the BigRIPS, in-flight separator [13]. Particle identification was performed by measuring the time-of-flight (TOF) and magnetic rigidity ($B\rho$) in the second stage of the BigRIPS and also by the energy loss (ΔE) in an ion chamber at the final focal plane, F11. The TOF was obtained from the time difference between plastic scintillators at the F3 and F7 achromatic foci. The $B\rho$ value was obtained by the trajectory reconstruction from position and angular information measured by position-sensitive parallel plate avalanche counters (PPACs) [14] at F3, F5, and F7 foci. Details of the procedure for the particle identification at the BigRIPS can be found in [15]

The measurement was conducted in two different stopper setups at F11. One was optimized for isomer spectroscopy by using a copper passive stopper with 1-mm thick in order to accept a wide range of nuclides with high implantation rates of ~ 1 kHz. In the other setup, an active stopper WAS3ABi [16] consisted of five layers of Double Sided Silicon Strip Detectors (DSSSDs) was used for β-γ measurements. Each layer of the DSSSDs had 40×60 strips and each had 1-mm width. In the latter setup with WAS3ABi, the total implantation rate of ions were limited up to ~ 100 Hz. In total, 1.70×10^5 and 1.34×10^4 ions of ^{158}Nd and ^{160}Nd, respectively, were implanted in the two stoppers.

The delayed γ rays from the implanted ions were detected by the EURICA [17] array with 12-cluster type HPGe detectors. Each cluster of the EURICA consists of seven crystals. The total detection efficiency of the array for photons of 1332 keV was ~ 8.4 %. The energies of delayed γ rays were measured in a time window of 16 μs following the ion implantation.

3. Results

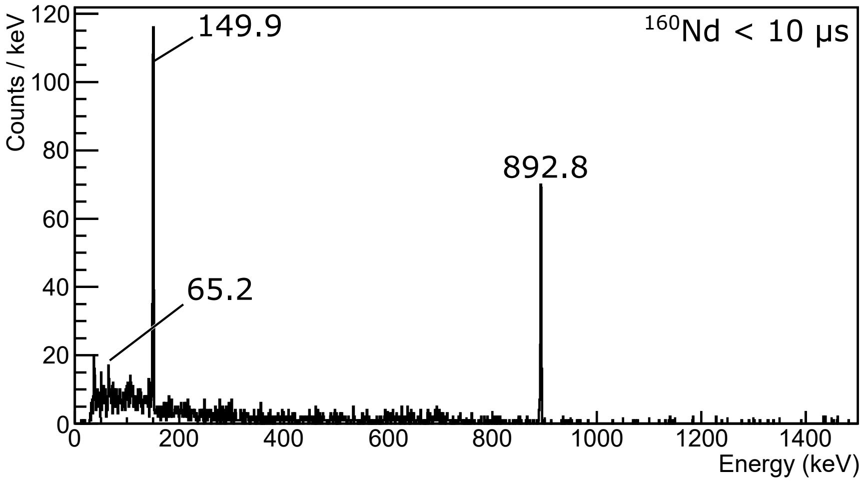

Figure 1: A delayed γ-ray spectrum for ^{160}Nd.

Figure 1 shows a spectrum of delayed γ rays detected in coincidence with ^{160}Nd ions. Three peaks at 65.2, 149.9, and 892.8 keV were identified as γ rays from the decay of ^{160}Nd isomer. Coincidences was observed between the two γ rays at 149.9- and 892.8 keV, which is an evidence that the two decay form a cascade. Coincidences with 65.2-keV peak were not detected for both of the γ rays because the number of peak counts are small for 62.5-keV γ ray due to the high internal conversion coefficient. Only the 8.6 % of the 65.2-keV transitions emits γ rays according to the internal conversion coefficient for E2 transition given by BrIcc [18]. The 65.2-keV decay is also expected to form a single cascade with other two γ rays from the relative intensities. The relative intensities of the three decays including internal conversions were 83(28), 100(7), and 97(8) % for the 65.2-, 149.9-, and 892.8-keV transitions and agreed with each other. A half-life of 1.63(21) μs was determined for the isomeric states of ^{160}Nd by fitting an exponential function to the time spectrum of ion-γ coincidences summed for the three γ rays.

4. Discussions

A level scheme was proposed as shown in Fig. 2. The 65.2- and 149.9-keV γ rays were assigned as $2^+ \to 0^+$ and $4^+ \to 2^+$ decay of the ground-state rotational band. The energy ratio, $E(4^+)/E(2^+)$, was 3.299 which indicates that the ground-state band of ^{160}Nd nucleus has a rotational nature. The 892.8-keV γ ray was assigned to be a decay from isomeric state to the 4^+ state of the ground-state band. The isomer is expected to have the same configuration as 4^- isomers in other $N = 100$ isotones [3, 4, 5], $\nu 1/2[521] \otimes \nu 7/2[633]$. The $B(E1)$ value for the decay from the isomeric state of ^{160}Nd was $2.0(3) \times 10^{-10}$ W. u. (Weisskopf units). This value is consistent with the ones from 2-qp isomers in the neighboring isotopes, $9 \times 10^{-9} \geq B(E1) \geq 3 \times 10^{-12}$ [6, 7, 8, 9].

2-qp states in ^{160}Nd have been predicted by a projected shell model (PSM) calculation [19]. The 4^- state is the lowest 2-qp excitation in the calculation, which is 1.2 MeV above the ground-state. This is very close to our result. The systematics of the 4^- isomers are shown in Fig. 3 with the PSM predictions. The PSM calculation also predicts low-lying 4^- 2-qp state in ^{162}Sm. They predict an increase of the isomer energy by ~ 100 keV from ^{162}Sm to ^{160}Nd by employing larger hexadecupole deformation in Nd ($\beta_4 = 0.032$) than in Sm ($\beta_4 = 0.008$). Our result on ^{160}Nd, 1108 keV of the isomer energy also shows a ~ 100 keV increase from ^{162}Sm. In order to identify the effect of the hexadecupole deformation to the single particle energy, we have calculated qp energies of $\nu 1/2[521] \otimes \nu 7/2[633]$ excitation by using a PSM code [20]. By using exactly the same deformation parameters as the calculation in [19], we obtained qp energies of 1.03 MeV for ^{162}Sm and 1.15 MeV for ^{160}Nd. As we decreased input β_4 value of ^{160}Nd to 0.008, the qp energy became lower to 1.01 MeV. This result suggests that the increase of qp energy due to the large hexadecupole deformation in Nd is responsible for the increase of the excitation energy of the 4^- isomeric state from ^{162}Sm to ^{160}Nd.

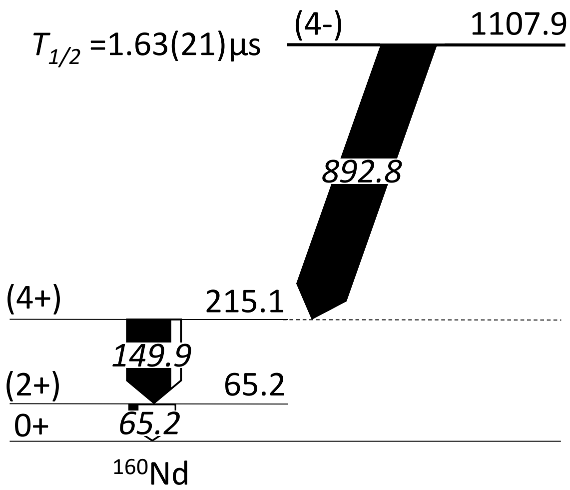

Figure 2: A level scheme of ^{160}Nd proposed from the present experiment. The width of the arrows are proportional to the relative intensity of the corresponding transition.

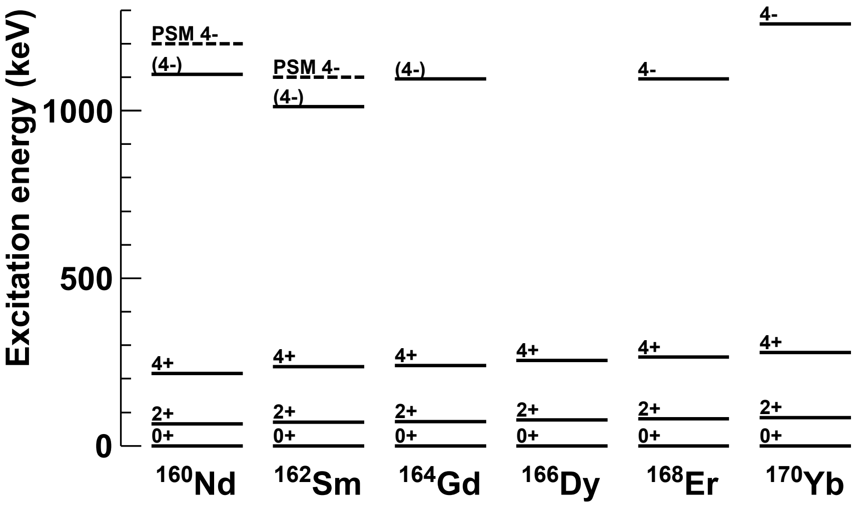

Figure 3: Systematics of the excitation energies of $K^{\pi} = 4^{-}$ isomers and ground-band 4^{+} and 2^{+} state. Dashed lines indicates the prediction of PSM calculation [19].

5. Conclusions

A new isomer with μs half-life was observed in ^{160}Nd. The low $E(2^{+})$ value as 65.2 keV and the $E(4^{+})/E(2^{+})$ ratio of 3.29 indicate the ^{160}Nd nucleus is well deformed and the ground band has a rotational nature. This isomer have been assigned as a 2 qp excitation of neutrons with a configuration of $\nu 1/2[521] \otimes \nu 7/2[633]$ as the case in other $N = 100$ isotones. Our result showed an increase of the isomer energy by $\sim$ 100 keV compared to that of ^{162}Sm as predicted by the PSM calculation. We also confirmed that the large hexadecupole deformation in Nd was responsible for the increase of the isomer energy in the PSM calculation. This shows that the most neutron-rich Nd isotopes with its excited states ever measured, ^{160}Nd, have large hexadecupole deformation compared to a neighbor nucleus ^{162}Sm.

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