β-γ and isomeric decay spectroscopy of ^{168}Dy

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Abstract. This contribution will report on the experimental work on the level structure of ^{168}Dy. The experimental data have been taken as part of the EURICA decay spectroscopy campaign at RIBF, RIKEN in November 2014. In the experiment, a ^{238}U primary beam is accelerated up to 345 MeV/u with an average intensity of 12 pnA. The nuclei of interest are produced by in-flight fission of ^{238}U impinging on Be target with a thickness of 5 mm. The excited states of ^{168}Dy have been populated through the decay from a newly identified isomeric state and via the β decay from ^{168}Tb. In this contribution, scientific motivations, experimental procedure and some preliminary results for this study are presented.

1 Introduction

Atomic nuclei consisting of a number of protons and neutrons are driven towards non-spherical equilibrium shapes when moving away from shell closures. Being located in the close vicinity of the double midshell at Z = 66, N = 104, ^{168}Dy (Z = 66, N = 102) is excepted to have a large quadrupole deformation for the ground state. The excited states in such a well-deformed nucleus are characterized by collective rotation and surface oscillations, including quadrupole (β and γ) and even higher-order vibrations, as well as by other quasiparticle excitations. The intrinsic state with a multi-quasiparticle configuration is likely to be a metastable state (isomer), when the projection of the total nuclear spin on the symmetry axis, denoted by K, is largely different from that of the lower-lying levels to which the isomer decays. The presence of these collective and intrinsic excitations within a narrow range of energy results in an interplay among them to a greater or lesser extent, giving rise to a rich variety of structural aspects in deformed nuclei. Therefore, spectroscopic studies of low-energy excitations in this doubly mid-shell region will provide a good testing ground for various collective model calculations.

This article will report on the spectroscopic results of $^{168}_{66}$Dy. For $N = 102$ isotones, $K^\pi = 4^-$ isomers had been identified in $^{170}_{68}$Er ($E_x = 1269$ keV, $T_{1/2} = 43$ ns) [1], $^{172}_{70}$Yb (1641 keV, 0.5 ns) [2], and $K^\pi = 6^-$ isomers in $^{164}_{62}$Sm (1486 keV, 0.6 μs), $^{166}_{64}$Gd (1601 keV, 0.95 μs) [3], $^{170}_{68}$Er (1591 keV, 4.0 ns) [1], $^{172}_{70}$Yb (1550 keV, 3.6 μs) [4], $^{174}_{72}$Hf (1714 keV, 0.45 ns) [5]. The $K^\pi = 6^-$ and 4^- isomers are interpreted as the neutron two-quasiparticle configurations $\nu^2 7/2^+[633] \otimes 5/2^-[512]$ and $\nu^2 7/2^+[633] \otimes 1/2^-[521]$, respectively. Yet isomeric states have not been identified in ^{168}Dy.

The octupole vibrational excitations have been identified in the doubly midshell region at relatively low energy, for example, $^{164}_{66}$Dy (976.9 keV, $K^\pi = 2^-$) [6], $^{166}_{66}$Dy (1029.9 keV, $K^\pi = 2^-$) [6], $^{170}_{66}$Dy (861 keV, $K^\pi = 2^-$) [7] and $^{172}_{70}$Yb (1154.9 keV, $K^\pi = 1^-$) [6]. Thus the aforementioned K isomers with negative parity are probably mixed with the rotational band-members built on such low-lying octupole vibrations. On the other hand, the $K^\pi = 3^+$ states have been identified in $^{170}_{68}$Er (1217.5 keV) [1] and $^{172}_{70}$Yb (1172.4 keV) [4]. In $^{174}_{72}$Hf, the $K^\pi = 3^+$ state has the possibility that the hexadecapole vibrational excitation may also have a contribution, which has already been studied before [8].

2 Experimental Procedure

In order to study the level structure of the neutron-rich rare-earth nuclei around double midshell, an experiment was performed in November 2014 at the RI-Beam Factory (RIBF) at RIKEN [9]. The ^{238}U^{86+} primary beam was accelerated up to 345 MeV/u by a sequential acceleration system consisting of a linac injector (RILAC) and four ring cyclotrons (RRC-fRC-IRC-SRC). The secondary beams were produced by in-flight fission of the U beam incident on a Be target with a thickness of 5 mm. The nuclei of interest were separated and identified through the BigRIPS spectrometer [10]. In this experiment, the secondary beams were transported with two different settings of the slits on the beam line; one is optimized for ^{170}Dy^{66+}, and the other for ^{172}Dy^{66+}. The respective particle identification spectra are shown in Fig. 1. About 1.2×10^4 ions and 1.0×10^4 ions were collected for ^{168}Tb^{65+} and the sum of ^{168}Dy$^{65+,66+}$, respectively.

The identified particles were implanted into the WAS3ABi active stopper [11] which was comprised of two layers of double-sided silicon-strip detectors (DSSSD). Each DSSSD had a thickness of 1 mm with an active area of 60×40 mm^2 with 2400 segmentations of 1 mm^2 pitch. The WAS3ABi was placed at the end of the beam line for the measurement of heavy-ion implantation and electrons following β-decay and internal conversion processes.

Gamma rays emitted from the implanted RIs were detected by the EUROBALL-RIKEN Cluster Array (EURICA) [12] that had a full energy-peak efficiency of about 10 % for 1 MeV γ ray. The EURICA array consisted of 84 HPGe crystals arranged in nearly 4π geometry in the form of twelve 7-element CLUSTER-type detectors. The γ rays emitted from the implanted RIs were detected within a coincidence time window of 100 μs with respect to the trigger signals generated either when the heavy ions passed through a plastic scintillator mounted ∼1 m upstream of the WAS3ABi stopper or when the DSSSDs were fired by the decay electrons.

The beam, electron, and γ-ray events were time-stamped and recorded by independent data-acquisition systems. Isomeric states with (sub)microsecond lifetimes were identified by delayed coincidence between γ-ray and beam signals on an event-by-event basis. Meanwhile, all the data sets containing beam, electron and γ-ray events were needed for electron-γ coincidence analyses, in which the ion implantation of an identified particle was associated with the subsequent electron events that were detected in the same or neighboring DSSSD pixels where the beam particle was implanted.

3 Preliminary results

Figure 2 shows the β-delayed γ-ray spectrum measured within 20 s after the implantation of ^{168}Tb. Before the present work, the excited states of ^{168}Dy had been studied by the β decay of ^{168}Tb [13] and multi-nucleon transfer reactions with a ^{82}Se beam incident on an ^{170}Er target [14]. The γ rays at energies of 75 and 173 keV, which were previously assigned as $2^+_1 \rightarrow 0^+_1$ and $4^+_1 \rightarrow 2^+_1$, respectively, have been confirmed in the present work. In addition to the transitions reported previously, several new γ rays are clearly visible at 216, 322, 915 and 1131 keV in the present work.

Figure 3 shows the γ-ray spectrum measured within 350 ns ∼ 3 μs after the implantation of ^{168}Dy. New γ rays at 236 and 348 keV are clearly visible. Note that in Fig. 3, the γ-ray at 405 keV is a contaminant from an isomeric state in ^{174}Ho, which could not be separated from the hydrogen-like component of the ^{168}Dy ions in terms of Z on the particle identification plot due to the poor resolution of the ion chamber. Based on the present work, we

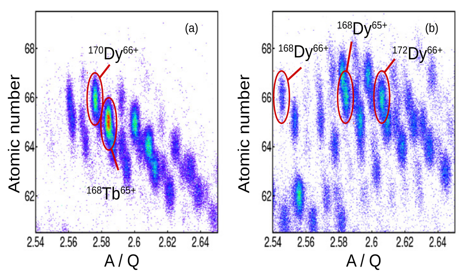

Figure 1. Particle identification spectra obtained with two different setting optimized for (a) ^{170}Dy^{66+} and (b) ^{172}Dy^{66+} ions.

have established a new level scheme of ^{168}Dy, the details of which will be presented elsewhere along with the discussion about the spin-parity assignment, transition hinderances, multi-quasiparticle configurations, and so on.

4 Summary

Decay spectroscopy experiment of ^{168}Dy has been carried out as part of the EURICA experimental campaign at RIBF, RIKEN. Following the production of neutron-rich isotopes by in-flight fission of ^{238}U, the nuclei relevant to the present work were separated and identified through the BigRIPS spectrometer. The nuclei of interest were implanted into the WAS3ABi array, which also served as a detector for β rays and internal conversion electrons accompanying the decay of the implanted radioactive isotopes. The heavy-ion implantation was associated with the subsequent decay electrons based on the position correlation in WAS3ABi. Gamma rays following β decay were measured by the EURICA array in coincidence with electrons detected by WAS3ABi. Meanwhile, isomeric states with half-lives ranging from several tens of nanoseconds to (sub)microseconds could be unambiguously identified by taking delayed coincidence between γ-ray and identified particles on an event-by-event basis. New results obtained in the present work include a number of γ rays following the β decay from ^{168}Tb and the isomeric decay in ^{168}Dy. The detailed analysis including evaluation of γ-ray intensities, feeding patterns, coincidence relationship, and transition strengths will allow us to establish a level scheme of ^{168}Dy, which will be presented elsewhere.

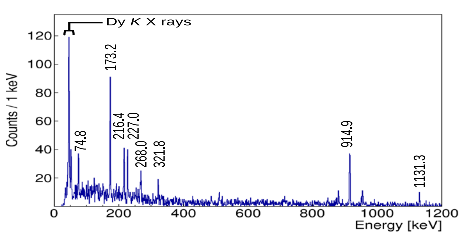

Figure 2. γ-ray energy spectrum measured in coincidence with electrons within 20 s after the implantation of ^{168}Tb.

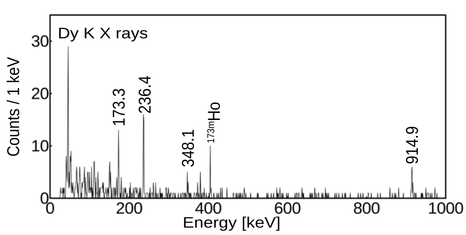

Figure 3. γ-ray energy spectrum measured in EURICA after the implantation of ^{168}Dy ions within a time range of $0.35 - 3$ μs.

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