論文内容の要旨

論文題目：Shape evolution in neutron-rich midshell nuclei studied by γ-ray spectroscopy

（ガンマ線核分光による中性子過剰中重核の変形進化の研究）

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Atomic nuclei are finite quantum many-body systems consist of two different kinds of nucleons, protons and neutrons. The existence of two degree of freedom, proton and neutron numbers, is one of the features adding variety to the nuclear phenomena. The quantum effect in a many-body system yields shell structure. The shell effect is one other key feature driving wide variety of phenomena in atomic nuclei. The nuclear shell structure relates to a macroscopic characteristic, the shape of nucleus. The nuclei at closed shell have spherical shape. As the number of particles in unfilled shell increased, nuclei break their symmetry spontaneously and get deformed even they are in the space with spherical symmetry. Study of the nuclear deformation of midshell nuclei is important to understand how the shell effect drive macroscopic shape of nuclei to have different shapes at different proton or neutron numbers. In addition, onset of higher-order deformations such as octupole (β_3) or hexadecupole (β_4) deformations, are predicted in the neutron-rich midshell nuclei. Strong octupole correlation is expected in neutron-rich $Z \sim 56$ isotopes, and hexadecupole deformation is expected in neutron-rich $Z \sim 60$ isotopes. Octupole and hexadecupole moments have been measured in stable nuclei (β_3 in ^{138}Ba and β_4 in ^{152}Sm) and the appearance of higher-deformation itself is known. However, the number of experimental studies on higher-order deformations so far, are very limited and it is not well known how such deformation appears in nuclei and how it affects to the single particle levels. Study of neutron-rich nuclei far from the line of β stability is also important from the astrophysical point of view. It has been known that *r*-process abundance distribution has a peak at $A \sim 160$ that is smaller than the peaks due to the shell closure along the path. The origin of smaller peak at $A \sim 160$ is not yet understood but it should relevant to the nuclides with $A \sim 160$ along the *r*-process path, $Z \sim 60$, $N \sim 100$. One of the recent theoretical calculations predicts the new neutron shell gap at $N \sim 100$ and experimental investigation is necessary to confirm this. This study focuses on the neutron-rich midshell nuclei with $Z \sim 60$, $N \sim 100$ aiming at understanding how nuclear shape, including higher-order, octupole and hexadecupole, deformations evolves with the increase of proton and neutron numbers. This study will also provide important input to the calculations of *r*-process abundance.

In order to investigate the shape evolution, excited states of the deformed nuclei in neutron-rich mid-shell region with $Z \sim 60$ and $N \sim 100$ have been studied by isomer and β-γ spectroscopy. Such highly neutron-rich isotopes were produced by in-flight fission of 345MeV/nucleon ^{238}U at RI Beam Factory in RIKEN Nishina Center. The beams were separated and identified by using BigRIPS beam line. Experiments were performed with two different detector setups. The first one was aimed at isomer search of the midshell region with 4-clover type HP-Ge detectors. In the second experiment, an active stopper WAS3ABi was introduced in order to enable β-γ spectroscopy at the same time with isomer measurement. An array of 12 EUROBALL cluster Ge detector, EURICA, was employed to improve the efficiency of γ-ray detection.

23 new isomers were identified in neutron-rich midshell nuclei with $59 \leq Z \leq 67$. $K^{\pi} = 4^{-}$ isomer was systematically observed in $N = 100$ isotones (See Figure 1 (a)). $K^{\pi} = 6^{-}$ isomer was identified in $N = 98$ Pm and Nd. Isomers with proton one quasi-particle excitation was identified systematically in $100 \leq N \leq 104$ Tb isotopes. Excited levels of the ground-state band were newly identified in ^{157}Pm, ^{154}Ce and ^{150}Ba by the β-γ spectroscopy. A candidate for the negative parity state of octupole band was observed at 697 keV in the most neutron-rich Ba isotopes ever measured, ^{150}Ba (See Figure 1 (b)).

From the systematics of $\mathrm{E}(4_1^+)/\mathrm{E}(2_1^+)$ ratio in even-even nuclei, the most neutron-rich isotopes in $56 \leq Z \leq 70$ region have the value ~ 3.3 and the ground states are expected to be good rotors. From the systematics of the moment of inertia (See Figure 2), Nd isotopes ($Z = 60$) have the largest quadrupole deformation. There is a local minimum of moment of inertia at $N = 100$ in $62 \leq Z \leq 66$ isotopes which was discussed to be an indication of the new deformed shell gap predicted at $N = 100$ by a calculation.

Although the calculations predicted the $N = 100$ also in $Z < 62$ isotopes, our result showed no local minimum of moment of inertia at $N = 100$ in Nd ($Z = 60$) isotopes. We showed that the disappearance of the $N = 100$ shell gap can be explained by the large hexadecupole deformation in Nd isotopes. The $\nu 1/2[651]$ orbital that have large hexadecupole interaction will get lower as hexadecupole moment of the nucleus increased, and can get as low as the level around $N = 100$ gap. The appearance and disappearance of the $N = 100$ shell gap were also observed in odd mass nuclei. Tb ($Z = 65$) isotopes showed local minimum of moment of inertia at $N = 100$, while Pm ($Z = 61$) isotopes did not. The increase of the excitation energy of $K^{\pi} = 4^{-}$ isomer in $N = 100$ isotones and the change of isomer configuration from $K^{\pi} = 5^{-}$ to 6^{-} in $N = 98$ isotones from Sm to Nd can also be explained by assuming large hexadecupole deformation in Nd isotopes.

We have carried out self-consistent RPA calculation and obtained $J^{\pi} = 3^{-}$ state with octupole collectivity at low excitation energy ~ 0.77 MeV, which left the possibility of the new 697 keV excitation in ^{150}Ba is the 3^{-} state systematically known in other neutron-rich Ba isotopes. It suggests that ^{150}Ba also have some octupole collectivity.

There are many isomers in neutron-rich midshell nuclei. Figure 3 is a distribution of isomers in $Z \sim 60, N \sim 100$ region. Nuclides colored in orange or green have an isomer with half-lives longer than 100 ns. Distribution of the *K* isomer indicates how well the nucleus is deformed with axial symmetry. There are a lot of isomers observed in Nd and Sm isotopes, while no isomer was observed in $\mathrm{Z} \leq 58$ isotopes. Life of a *K* isomer will get shorter when quadrupole deformation is decreased or the nucleus break axial symmetry and deformed triaxial way, and will not be observed by delayed γ-ray spectroscopy. Appearance of middle *K* state below the excitation of high-*K* quasi-particle states can also shorten the half-life of high-*K* isomer by making decay path with smaller ΔK transitions. The reason for the disappearance of *K* isomer in $\mathrm{Z} \leq 58$ isotopes has not become clear yet, but it is an indication of some change in nuclear shape.

This study investigated the nuclear shape in neutron-rich midshell nuclei with $A \sim 160$ and observed experimental evidence for the $N = 100$ shell gap in $62 \leq Z \leq 66$ isotopes and its disappearance at $Z = 60$. The deformation maximum or neutron shell gap around $N = 100$ are expected to be responsible for the sub peak around $A = 160$ in *r*-process abundance. From Figure 2, $N \sim 100$ nuclei have large deformation but the maximum points are different for the proton number. The shell gap at $N = 100$ probably play an important role on the $A \sim 160$ peak in *r*-process abundance. The theoretical calculation which predicts $N = 100$ shell gap does not predict the disappearance of the gap at $Z = 60$. Hexadecupole deformation may be responsible for the disappearance. Further theoretical and experimental investigation on $N = 100$ isotones with $Z < 60$ is required for precise calculation of *r*-process abundances. Octupole deformation is also expected to be significant in $Z < 60$ nuclei and further study of such higher-order deformations is also important.

The next step of this study is to improve experimental setups to measure the lifetime of the excited states for more direct measurement of β_2. Application of Coulomb excitation technique to unstable nuclei will give us more exclusive information on higher-order deformations for wide range of neutron and proton numbers.

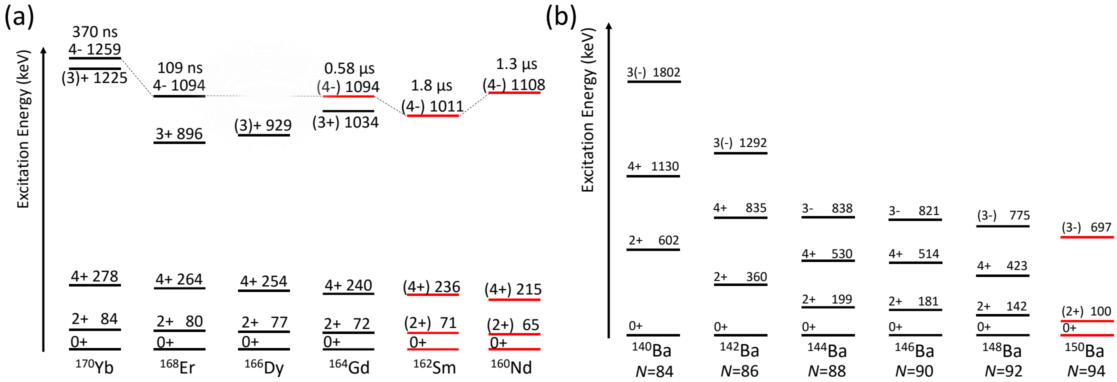

Figure 1 Systematics of the excitation energies of (a) isomers in $N = 100$ isotones and (b) negative parity bands in Ba isotopes.

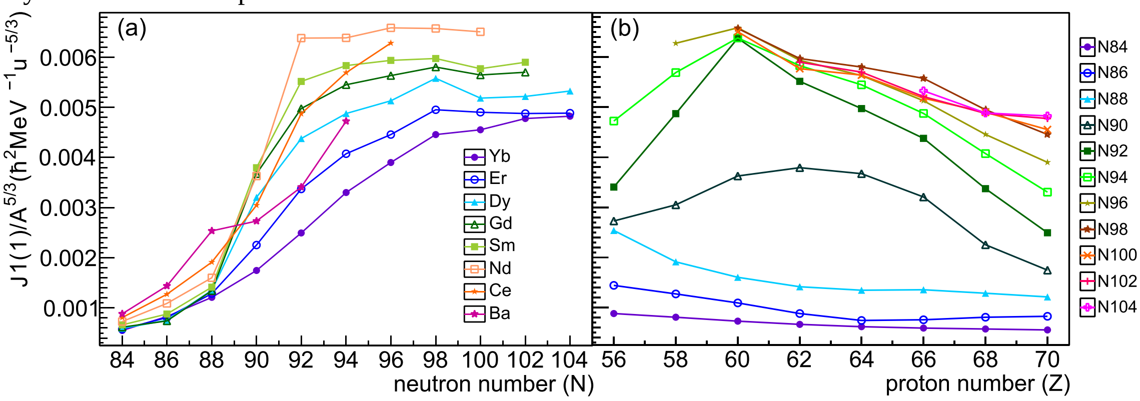

Figure 2 Systematics of the moment of inertia scaled by $A^{5/3}$ obtained from $E(2_1^+)$ values ($\Im^{(1)}(1)$). (a) is plotted by isotopes and (b) is plotted by isotones.

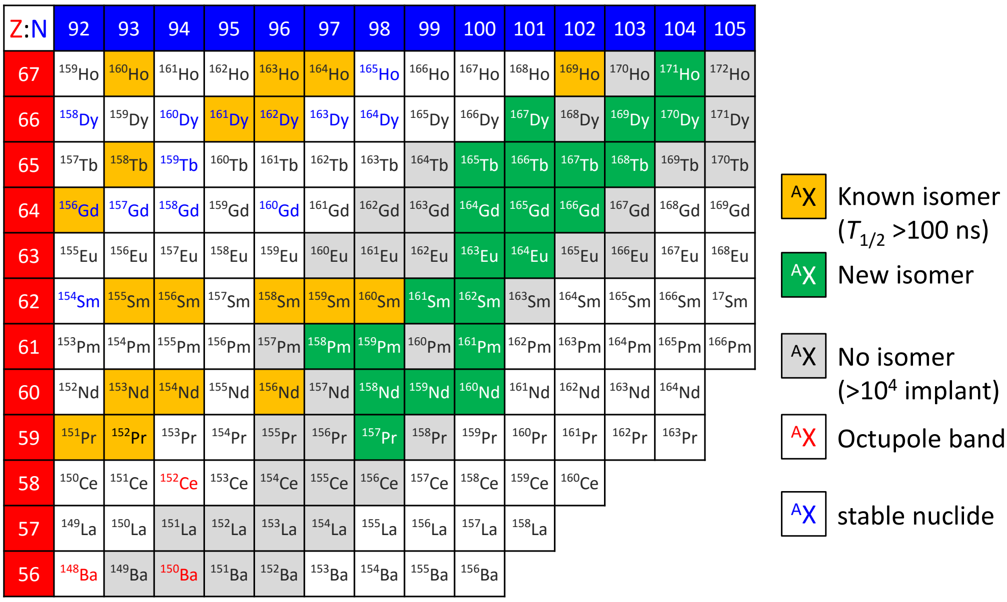

Figure 3 A part of the chart of nuclides showing disappearance of isomers in $Z < 58$ nuclei. The nuclides colored in green have isomers newly observed in this work. The nuclides colored in orange have known isomers and those with red character shows that an octupole band is observed in the nuclide.