EXOTIC ISOMERS EXPLORED AT THE NEW GENERATION IN-FLIGHT-SEPARATOR FACILITY RIBF*

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(Received November 19, 2018)

The development of in-flight separators has opened up fascinating opportunities for studying exotic nuclei in isomeric states. At the Radioactive-Isotope Beam Factory (RIBF) in RIKEN Nishina Center, which has come online in 2007 as the first 3$^{\rm rd}$-generation in-flight separator facility, more than 400 species of rare isotopes have been explored in experimental programs dedicated to radioactive-decay measurements performed in the last decade. Some selected topics relevant to characteristic isomers, such as seniority, spin-trap, and K isomers, are presented.

DOI:10.5506/APhysPolB.50.641

1. Introduction

Since the late 1980s, when dedicated radioactive isotope (RI) beam facilities started their operation, the in-flight method using intermediate/high-energy heavy-ion beams has become the dominant means of producing new RIs, particularly those on the neutron-rich side of the β-stability line, due both to the increased beam intensities and to the improvement and upgrade of the particle-separation/identification techniques compared to the previous ones [1]. As such, the characteristic features of in-flight separators, *i.e.*, *physical separation*, *fast transportation*, and *unambiguous identification* of fragments, are beneficial also to decay studies of short-lived rare isotopes. Physical separation allows for better access to exotic nuclei of essentially all the elements up to uranium, making it possible to conduct systematic studies for a wide range of isotopic/isotonic/isobaric chains. Using inverse kinematics with intermediate/high-energy heavy-ion beams can realize fast

* Presented at the Zakopane Conference on Nuclear Physics "Extremes of the Nuclear Landscape", Zakopane, Poland, August 26–September 2, 2018.

separation and transportation of RI beams to a stopper in a short time, typically ranging from several hundred nanoseconds to one microsecond, depending on the transit time through an in-flight separator. This feature, as well as unambiguous particle identification, enables one to investigate short-lived exotic nuclei, not only in the ground state, but also in metastable states, so-called *nuclear isomers*, that are populated in the production process. Gamma rays following the decay of isomeric states with half-lives ranging from several tens of nanoseconds to several hundred microseconds can be observed in delayed coincidence with each individual stopped fragment that is identified in terms of atomic number (Z) and mass-to-charge ratio (A/q) through the preceding in-flight separator. The detection of such delayed γ rays on an event-by-event basis allows for a firm assignment of isomeric states to specific isotopes. Meanwhile, the identification of long-lived isomers in the millisecond range often relies on the detection of internal-conversion electrons that are emitted in the decay cascades from the isomers. It should be emphasized that for the study of rare isotopes, especially when the nucleus of interest lies at the boundaries of availability for spectroscopic studies, such isomeric-decay measurements are likely to provide a powerful technique to investigate excited levels under the condition of low backgrounds. In this contribution, recent highlights of isomeric-decay spectroscopy carried out at the RI-Beam Factory (RIBF) are introduced, with particular focus on exotic isomers in the vicinity of ^{78}Ni, ^{100,132}Sn, and ^{170}Dy.

2. 3$^{\mathrm{rd}}$-generation RI-beam facility: RIBF

The RI-beam facilities that are equipped with in-flight separators can be classified into three generations depending on the development of heavy-ion accelerators, improvement of particle-separation/identification techniques, and upgrade of RI-beam intensities [1]. In 2007, a 3$^{\mathrm{rd}}$-generation facility has come online for the first time at RIBF with the installation of three new ring cyclotrons, fRC (K = 570 MeV), IRC (980 MeV), and SRC (2,600 MeV), as well as the large-acceptance in-flight separator BigRIPS [2, 3]. Heavy-ion beams, including ^{238}U, can be boosted up to 345 MeV/u with high intensities (goal is 1 pμA $\approx 6 \times 10^{12}$ particles/s) by a cascade acceleration mode of RILAC-RRC-fRC-IRC-SRC, where RILAC and RRC represent a variable-frequency heavy-ion linac (linear accelerator) and a K540-MeV ring cyclotron, respectively, both of which are located in the existing (old) facility at RIBF.

3. Isomeric-decay spectroscopy at RIBF: the EURICA project

In order to expand research opportunities for decay spectroscopy at RIBF, a new project, referred to as EURICA (EUROBALL-RIKEN Cluster

Array), has been launched in 2012 with the approval of the EUROBALL Owners Committee [4]. This was an ambitious project dedicated mainly to β-delayed and isomeric γ-ray spectroscopy covering a wide range of exotic nuclei both on the neutron-rich and on the proton-rich sides of the β-stability line, which could be reached using the world's strongest RI beams available at RIBF, in conjunction with highly efficient EUROBALL-Cluster γ-ray detectors [5, 6]. The 12 seven-element cluster detectors (corresponding to 84 HPGe crystals) were mounted on the support frame that was designed previously for the RISING stopped-beam experiments at GSI [7] and installed at the end of the BigRIPS-ZeroDegree spectrometer. The active-stopper system placed at the center of the EURICA array was developed with the so-called WAS3ABi (wide-range active silicon-strip stopper array for beta and ion detection), which consisted of several layers of DSSSD [8].

The EURICA project operated until 2016 with more than 100 days of data taking in 18 experimental programs. In total, more than 400 species of rare isotopes have been explored during the whole EURICA campaign. Some selected results relevant to the study of isomeric states are highlighted in the following subsections.

3.1. Seniority scheme in $N = 82$ isotones and $_{28}$Ni, $_{50}$Sn isotopes

The concept of seniority symmetry was adopted for many like nucleons in a single-j shell for the classification and characterization of excitation spectra. Here, the seniority quantum number υ represents the number of nucleons that are not in pairs coupled to $J = 0$. In a many-nucleon system, where seniority is conserved as a good quantum number, all the eigenstates can be uniquely specified by υ in addition to J^{π}. One important embodiment of the seniority conservation is that, for an n-particle (or n-hole) system in a single-j shell, the level energies with identical J and υ are independent of n. Another well-known feature is that the highest energy/spin state in a given seniority multiplet can have a relatively long lifetime because, in addition to a small energy spacing with respect to the lower-lying level, the matrix elements of E2 transitions connecting the same υ multiplet members are close to zero near the middle of the valence subshell, giving rise to so-called seniority isomers, which manifest themselves with half-lives typically in the microsecond range in single closed-shell nuclei. The characterization of such seniority states is useful for testing interaction matrix elements whether they conserve symmetry or induce admixtures of states with different seniorities. Furthermore, probing the seniority isomers in semi-magic nuclei where either only proton or neutron is active, a significant insight into the underlying shell closures can be obtained.

As a good example of the seniority scheme, the excitation energies of the $J^\pi = 2^+$–8^+ states in ${}^{128}_{46}$Pd studied at RIBF [9] are compared with those in the $N = 82$ isotone ${}^{130}_{48}$Cd [10] in Fig. 1. These level sequences can be interpreted in terms of the $\upsilon = 2$ coupling in the $\pi 1g_{9/2}$ subshell, which lies just below the $Z = 50$ spherical shell gap. Similar level properties, including the $J^\pi = 8^+$ isomers, were observed for the even $N = 50$ isotones from ${}_{42}$Mo to ${}_{48}$Cd [11]. In the right panel of Fig. 1, a set of measured $B(\mathrm{E2}; 8^+ \to 6^+)$ values for the $N = 50$ isotones exhibits a parabolic-shape distribution as a function of the proton number, due to the seniority cancellation of the quardupole matrix element when the $\pi 1g_{9/2}$ subshell is close to half-filled. This is an indirect evidence for an inert $N = 50$ core. For the $N = 82$ isotones, it can be seen that the $B(\mathrm{E2}; 8^+ \to 6^+)$ value is much smaller in ^{128}Pd than in ^{130}Cd, as expected in the exact seniority classification, namely, $B(\mathrm{E2}; \upsilon = 2, n = 4) = \frac{1}{9} B(\mathrm{E2}; \upsilon = 2, n = 2)$. This observation indicates that both the $J^\pi = 8^+$ and 6^+ states in the $N = 82$ isotones, as well as in the $N = 50$ nuclei, have good seniority $\upsilon = 2$ in the well-isolated $\pi 1g_{9/2}$ subshell, in consequence of the robust neutron shell closure.

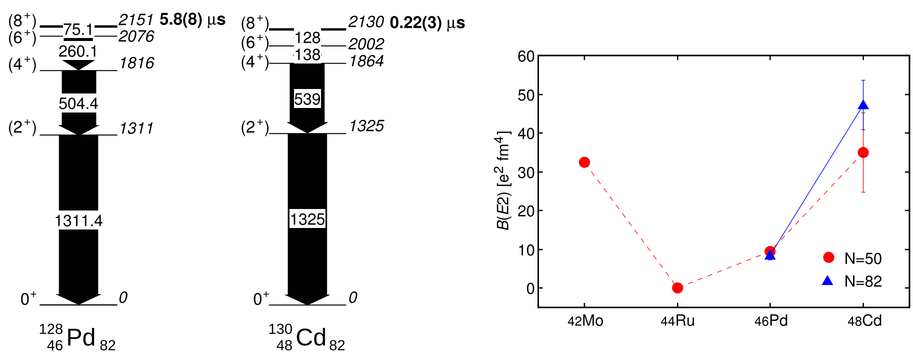

Fig. 1. (Color online) Left: Partial level schemes of ${}^{128}_{46}$Pd$_{82}$ [9] and ${}^{130}_{48}$Cd$_{82}$ [10]. Right: Reduced transition probabilities $B(\mathrm{E2})$ for the $8^+ \to 6^+$ transitions in $N = 50$ (red circles) and 82 (blue triangles) isotones.

In a simple seniority-coupling scheme, the yrast levels up to $J^\pi = 6^+$ in even-A ${}_{50}$Sn isotopes with $82 < N < 90$ are expected to be formed by the $\upsilon = 2$ configurations in the $\nu 2f_{7/2}$ orbit, which is located above the $N = 82$ shell gap. Simpson *et al.* [12] have observed delayed γ-ray cascades following the implantation of ^{136,138}Sn$_{86,88}$ fragments produced by in-flight fission of a ^{238}U beam at RIBF. The near constancy of the observed energies for the $J^\pi = 6^+$, 4^+, and 2^+ levels in ^{134,136,138}Sn is characteristic of a pure $\upsilon = 2$ scheme. On the contrary, the experimental $B(\mathrm{E2}; 6^+ \to 4^+)$ value in ^{136}Sn significantly deviates from the prediction of the simple seniority scheme with the $\nu 2f_{7/2}$ subshell, as well as from a shell-model calculation based on the realistic $V_{\text{low}-k}$ effective nucleon–nucleon interaction. This situation is in contrast to the aforementioned examples of the $N = 50$ and 82 isotones, but is analogous to what is happening in $^{70-76}$Ni, where valence neutrons predominantly occupy the $1g_{9/2}$ orbit, as is discussed in the next paragraph.

The seniority isomerism is supposed to be sensitive to the nature of the underlying closed cores. It has been known that there are $J^\pi = 8^+$ isomers with half-lives of the order of several hundreds of ns in $^{70,76}_{\ \ 28}\text{Ni}_{42,48}$ [13, 14], which arise from fully aligned $\nu 1g^{\pm 2}_{9/2}$ configurations with $\upsilon = 2$, while analogous seniority isomers have never been identified in $^{72,74}\text{Ni}_{44,46}$ [15]. Theoretically, the absence of seniority isomers in the mid-shell Ni isotopes with four neutron particles/holes in the $1g_{9/2}$ subshell was interpreted as being ascribed to the presence of the $6^+_{\upsilon=4}$ state below the $8^+_{\upsilon=2}$ level, resulting in a fast E2 transition between the states with different seniority [16–18]. In order to clarify this long-standing issue experimentally, Morales *et al.* [19, 20] have scrutinized the detailed structure of low-lying levels in ^{72,74}Ni populated by the β-decay from ^{72,74}Co as part of the EURICA project at RIBF. New results obtained in their works include the candidates for the 8^+_1, 6^+_2, and 4^+_2 states in ^{72,74}Ni, having complemented the energy systematics of the positive-parity seniority states in the Ni isotopes, as illustrated in Fig. 2. In both nuclei, the (8^+_1) states have turned out to decay toward the respective (6^+_1) states, but neither of the $(8^+_1) \to (6^+_2)$ transitions has been observed. Based on the absence of $\upsilon = 2$ isomerism in the (8^+_1) states and the predicted quasi-degeneracy of the $6^+_{\upsilon=2,4}$ states using a seniority-conserving interaction [17, 18], the experimental (6^+_1) and (6^+_2) states were assumed to have $\upsilon = 4$ and 2, respectively. More detailed discussion in comparison with a variety of shell-model calculations is given in Refs. [19, 20].

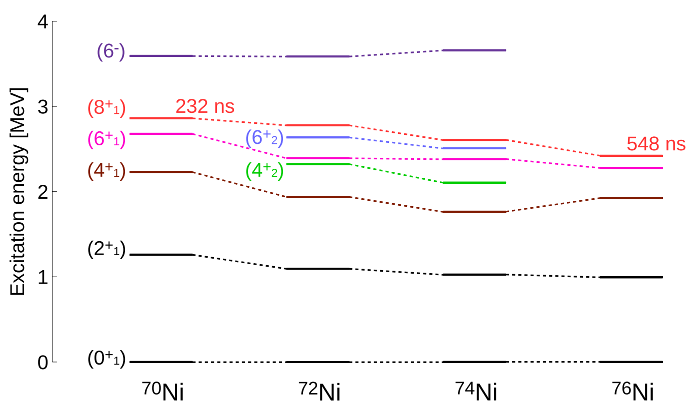

Fig. 2. Partial level schemes of even Ni isotopes with $A = 70$–76. The data are taken from Refs. [19–21].

3.2. Spin-trap isomers in the vicinity of ^{100}Sn and ^{132}Sn

The transition multipolarity λ, which is required to satisfy the spin selection rule for the initial and final states, $|I_\mathrm{i} - I_\mathrm{f}| \leq \lambda \leq I_\mathrm{i} + I_\mathrm{f}$, is one of the key quantities to determine the lifetime of nuclear excited states. An electromagnetic decay that is compelled to proceed with a high-λ transition is likely to be retarded, leading to spin-trap (or spin-gap) isomerism.

The well-known magic numbers 50 and 82 emerge as a result of the lowering in energy of the $1g_{9/2}$ and $1h_{11/2}$ orbitals, respectively, due to the strong spin–orbit coupling. In the vicinity of ^{100}Sn and ^{132}Sn, these orbitals play an essential role to form excited states including characteristic isomers, not only within the major shells, but also through particle–hole excitations across the shell gaps. The strong proton–neutron interaction between the high-j orbits can give rise to spin-trap isomers at high spin, which often have lifetimes long enough to generate significant β-decay branches.

A β-decaying isomer in the self-conjugate nucleus ^{96}Cd has been identified for the first time at GSI using projectile fragmentation of a ^{124}Xe beam [22]. Based on the observation of γ rays de-exciting the known (15^+) isomer in the β-decay daughter nucleus ^{96}Ag, as well as on the measured β-decay half-life ($0.29^{+0.11}_{-0.10}$ s) being consistent with the GT transition, this isomer was proposed to have a spin and parity of 16^+ predominantly with a fully aligned configuration comprising two $1g_{9/2}$ proton holes and two $1g_{9/2}$ neutron holes relative to the doubly magic ^{100}Sn core. To find β-delayed proton emission through the GT-resonance states, a follow-up experiment for the 16^+ isomer of ^{96}Cd has been carried out at RIBF using the EURICA setup [23], in which the number of collected ^{96}Cd ions were about 27 times larger than in the previous work at GSI [22]. The measured γ-ray spectrum in coincidence with β-delayed proton events correlated with the ^{96}Cd implantation clearly exhibited four γ rays that were reported previously as the de-excitation from the $23/2^+$, $25/2^+$, and $29/2^+$ states in ^{95}Pd [24]. This observation is the first evidence for the β-delayed proton emission from the 16^+ spin-trap isomer in ^{96}Cd: the βp branching ratio was determined to be 11(3)% together with a half-life with better precision of $T_{1/2} = 0.45^{+0.05}_{-0.04}$ s. The analysis of the efficiency-corrected γ-ray intensities indicates that the $25/2^+$, and $29/2^+$ states in ^{95}Pd are favorably populated by the βp decay from the 16^+ isomer in ^{96}Cd.

Similar types of spin-trap isomers are expected to be formed in the vicinity of ^{132}Sn with $Z < 50$, $N < 82$, where the $1h_{11/2}$ neutron orbital is a substitution for $\nu 1g_{9/2}$ in the $N \approx Z$ case, for instance, 18^+ in ^{128}Cd and $27/2^-$ in ^{129}Cd, both of which are most likely to decay toward high-spin states in the respective daughter nuclei via β decay. However, these long-lived high-spin isomers could not be identified during the EURICA experimental campaign at RIBF and, therefore, their explorations will be a future experimental challenge at RI-beam facilities.

3.3. K isomers in the doubly mid-shell rare-earth region

The K quantum number is defined as the projection of the total nuclear spin on the symmetry axis of the deformed nucleus. In addition to the spin selection rule, $\lambda \geq |J_{\mathrm{f}} - J_{\mathrm{i}}|$, an electromagnetic transition connecting the states with different K values (ΔK) is required to fulfill a selection rule that the multipole order of the transition λ is equal to or greater than ΔK, *i.e.*, $\lambda \geq \Delta K$. However, this K-conservation law is often violated due to various sources of symmetry breaking, such as Coriolis effects, shape softness in terms of the γ (axially-asymmetric) degree of freedom, random state mixing, and so on [25]. Hence, strongly hindered transitions are forced to take place for $\Delta K > \lambda$. Such K-forbidden transitions are evaluated practically in terms of a reduced hindrance $f_\nu = F^{1/\nu}$, where $F = T_{1/2}(\gamma)/T^{W}_{1/2}$ represents a hindrance relative to the Weisskopf single-particle estimate of the decay half-life, with the degree of K-forbiddenness defined by $\nu = \Delta K - \lambda$. Namely, the value of f_ν can serve as a measure of *the hindrance per degree of K forbiddenness*. It is empirically known that the f_ν value ranges typically from 30 to 200 when K is well-sustained for both the initial and final states. Thus, large changes in K are prohibited, leading to long-lived states, so-called K isomers.

As part of the EURICA experimental campaign at RIBF, neutron-rich rare-earth (RE) nuclei around $A = 170$ have been produced by in-flight fission of a $^{238}\mathrm{U}^{86+}$ beam at 345 MeV$/u$ with an average intensity of 12 pnA, and the nuclei of interest were separated/identified through the BigRIPS separator. The level scheme of ^{172}Dy established in Ref. [26] is displayed in Fig. 3 (right). A state at 1278 keV was assigned as a $K^\pi = (8^-)$ isomer with $T_{1/2} = 0.71(5)$ s, which feeds the 8^+ level in the ground-state (g.s.) rotational band via a hindered E1 transition, consistent with what was observed for the heavier $N = 106$ isotones from $_{68}$Er to $_{82}$Pb [27]. The energies of the $K^\pi = 8^-$ isomers, which were interpreted as arising from the same neutron two-quasiparticle (2qp) configuration, $\nu 7/2^-[514] \otimes \nu 9/2^+[624]$ [28], decrease when the proton number decreases to $_{70}$Yb and subsequently rise towards ^{172}Dy, as shown in Fig. 4 (middle). The isomerism is essentially ascribed to the large difference in the K quantum number between the isomer and the states to which the isomer decays. For the E1 transition from the $K^\pi = 8^-$ isomer to the 8^+ state in the g.s. rotational band, which has $\nu = \Delta K - \lambda = 7$, the reduced hindrances f_ν increase from 28 in ^{188}Pb to 98 in ^{174}Er. The present result of ^{172}Dy, $f_\nu = 133(8)$, follows the upward trend in the $N = 106$ isotones.

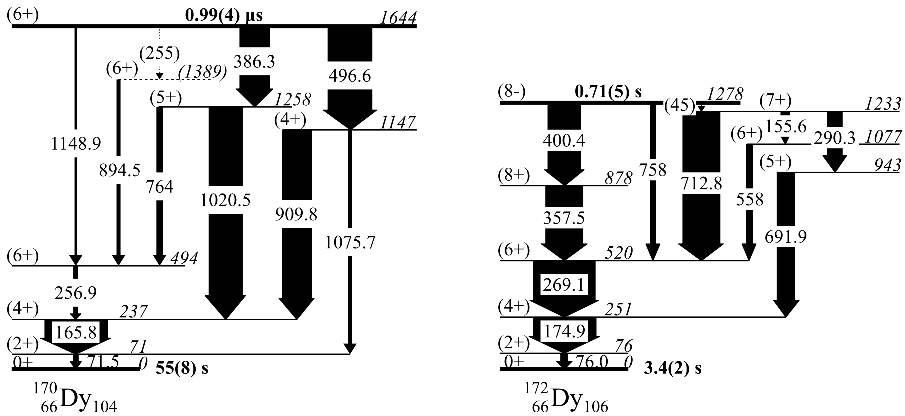

Fig. 3. Partial decay schemes from $K^\pi = 6^+$ and 8^- isomers in ^{170}Dy [29] and ^{172}Dy [26], respectively, including their ground-state rotational and γ-vibrational bands. The widths of arrows are proportional to the γ-ray relative intensities measured for each isomeric decay, except for tentative transitions at 255 keV in ^{170}Dy and 45 keV in ^{172}Dy.

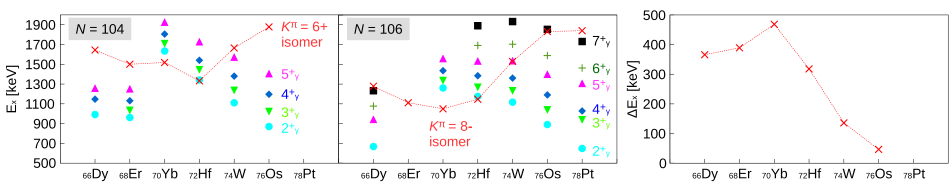

Fig. 4. Energy systematics of the γ-vibrational levels (denoted by J^π_γ), and $K^\pi = 6^+$ and 8^- isomers (connected by the dashed lines) for $N = 104$ and 106 isotones, respectively. Note that both the 6^+ and 8^- isomeric states, respectively, in ^{176}Hf and ^{178}Hf are strongly mixed between the neutron and proton 2qp configurations, which are located in energy close to each other [30, 31]. The energy differences between the $K^\pi = 6^+$ and 8^- isomers are plotted in the right panel, where the unperturbed neutron 2qp levels deduced previously are used for the Hf isotopes.

The level structure of the doubly mid-shell nucleus ^{170}Dy has been investigated in the same experiment as that for ^{172}Dy. A number of γ rays have been observed for the first time in delayed coincidence with ^{170}Dy ions within a μs-range time window [29]. A new isomer with $T_{1/2} = 0.99(4)$ μs has been identified at 1644 keV, as shown in the level scheme of ^{170}Dy in Fig. 3 (left). The isomer was tentatively assigned a spin and parity of 6^+ based on the systematics of the $K^\pi = 6^+$ isomers in the heavier $N = 104$ isotones, which are interpreted as being ascribed to the neutron 2qp configuration, $\nu 7/2^-[514] \otimes \nu 5/2^-[512]$ [27]. The (6^+) isomer in ^{170}Dy mainly decays into the 5^+ and 4^+ states assigned to the γ-vibrational band (see Fig. 3), while a weak branch toward the 6^+ level in the $K^\pi = 0^+$ g.s.-rotational band results in $f_\nu = 80(12)$ assuming a pure M1 multipolarity (*i.e.*, $\nu = 5$) for the 1149-keV transition [29]. Similar decay patterns have been observed for the neighboring even–even isotone ^{172}Er, in which the corresponding M1 transition proceeds with $f_\nu = 56(2)$ [32]. As argued in Ref. [29], the M1 transition from the 6^+ isomer to the 6^+ g.s.-band member is much less hindered in ^{170}Dy and ^{172}Er compared to the expectation based on an extrapolation from the reduced hindrances available in the heavier $N = 104$ isotones and Hf isotopes as a function of the valence-nucleon product N_pN_n, see Fig. 3 in Ref. [29]. The reduction in hindrance, as well as the preferred decay to the γ-band levels in ^{170}Dy and ^{172}Er, is ascribed to mixing with the $K^\pi = 2^+$ γ-vibrational component, as discussed using the triaxial projected shell model in Ref. [33].

Comparing the level schemes of ^{170,172}Dy shown in Fig. 3, one can notice that the excitation energy of the $K^\pi = 6^+$ isomer is 366 keV higher than that of the 8^- state. Since these K isomers are formed by the neutron 2qp excitations as mentioned above, their energy difference can be associated partly with the variation between the energy gaps at $N = 104$ and 106 in a deformed potential. Figure 4 (right) exhibits the isotope dependence of the $K^\pi = 6^+$ energy relative to the 8^- state. It can be seen that the energy differences for Er and Yb are as large as the Dy isotopes have, implying the presence of a more sizable gap at $N = 104$ than at $N = 106$. On the other hand, the downward trend beyond Yb may be due either to a diminishment of the $N = 104$ gap or to an enhancement of the $N = 106$ one, or both, with increasing the proton number toward $Z = 82$.

4. Summary

The RIBF in RIKEN Nishina Center has opened up a new era in rare isotope science after having started its operation in 2007 as the first 3$^{\rm rd}$-generation in-flight-separator facility. As part of the EURICA project, seniority schemes in the Sn and Ni isotopic chains and in the $N = 82$ isotones below $Z = 50$, β-delayed proton emission from the (16^+) spin-trap isomer in ^{96}Cd, and K isomers in ^{170,172}Dy have been investigated.

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