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Abstract Collective properties of neutron-rich Ru, Pd, and Cd isotopes are reviewed, combining the original results from the IGISOL β-decay experiments with recent experimental and theoretical progress. The transitional nature of Ru and Pd nuclei is discussed via the low-lying level systematics, including the low-lying 0^+ states. Although the role of an anharmonic quadrupole vibrator in Cd nuclei was recently questioned, level systematics for the three-phonon quintuplet in ^{116,118,120}Cd are presented, and an outlook of the spectroscopic methods for the level lifetime or $B(E2)$ values is given.

Keywords Collective structure · Ru, Pd and Cd nuclei · IGISOL · β decay

1 Introduction

The structure of neutron-rich Ru, Pd, and Cd isotopes has been the subject of many experimental and theoretical works in recent years. While Ru and Pd nuclei have been predicted to show transitional features from an anharmonic vibrator to a γ-soft rotor when approaching the neutron midshell [1], the general character of Cd nuclei has long been regarded as a good example of an anharmonic quadrupole vibrator with the observation of candidates for complete sets of multi-phonon states [2, 3]. For neutron-rich Ru and Pd nuclei, traditional high-spin studies by prompt γ spectroscopy were carried out by several groups using spontaneous or

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heavy-ion-induced fission, for example, $^{108-112}$Ru in [4–12], ^{114}Ru in [4, 13] as well as ^{112}Pd in [14], ^{114,116}Pd in [9, 15], ^{118}Pd in [16], and ^{120}Pd in [17]. These investigations highlight the nuclear shape degree of freedom of neutron-rich Ru and Pd nuclei by analyzing the rotational band structures, and a possible shape transition from a triaxial prolate to a triaxial oblate has been intensively explored. The absolute transition probabilities for the first 2^+ states in ^{110,114}Pd have also been measured using the recoil distance Doppler shift technique following projectile Coulomb excitation at intermediate beam energies [18], and a sizable deformation of $\beta = 0.24(1)$ in ^{114}Pd has been determined, consistent with systematic Interacting Boson Model (IBM) calculations [1]. Towards very neutron-rich Ru and Pd nuclei relevant to the astrophysical rapid neutron capture process, β-decay half-lives and β-delayed neutron emission branchings for $^{120-122}$Pd isotopes and half-lives for $^{114-118}$Ru isotopes have recently been measured [19].

The Cd nuclei span a full shell from $N = 50$ to $N = 82$, which provides an ideal test-bed for structure evolution in the context of varying valence neutron number. Therefore, numerous experimental investigations have been carried out on even-mass Cd nuclei by using various spectroscopic methods. A striking feature revealed in these studies has been the coexistence of the anharmonic quadrupole vibrator and intruder excitations at low excitation energies [20]. Experimental methods on stable and neutron-rich Cd nuclei include neutron inelastic scattering [21–24], high-spin studies [17, 25–27], and β decay [28–34]. These experimental works have generated a wealth of data on detailed level schemes and transition probabilities in even-mass Cd nuclei.

At IGISOL, systematic studies of neutron-rich even-mass Pd isotopes by β decay started at its inauguration in the 1980's [35, 36], followed soon by similar studies of Ru isotopes [37]. Later on, the constant improvement of the ion guide technique enabled more detailed studies of ^{110}Ru [38] and $^{110-118}$Pd [39–44] isotopes. These experimental studies resulted in the identification of many new γ transitions and excited levels in the daughter Pd and Cd nuclei. The systematics of the low-lying collective and two-quasineutron levels in even Pd nuclei was also extended up to ^{118}Pd. In the experiments of neutron-rich Rh decay studies, the Ag isotopes from the same mass chain were delivered to the spectroscopic station in large quantities and therefore the β decays of neutron-rich Ag to Cd nuclei were studied simultaneously. This led to more detailed decay schemes of $^{116-120}$Ag isotopes and to the identification of many new low-lying collective levels. The complete three-phonon quadrupole vibrational quintuplet was proposed for the ^{116}Cd nucleus for the first time [45], and later extended to ^{120}Cd nuclei [46]. Recently, the utilization of the JYFLTRAP Penning trap setup as a high-resolution mass filter enabled the first study of the ^{114}Tc β decay to ^{114}Ru.

2 IGISOL experiments

The IGISOL facility utilizes a universal technique for the production of radioactive ion beams with extraction times as short as sub-ms. The use of a fast helium-filled ion guide combined with proton-induced fission provides very effective access to various fission fragments in their ground and isomeric states regardless of their chemical properties. In the following series of β-decay works, very similar β and

γ spectroscopic setups were used. The mass separated beam was implanted into a collection tape, which was periodically moved at a preset time interval to reduce the background radiation emitted from the long-lived isobaric contaminants. The ions-of-interest were implanted in the center of a cylindrical 2-mm-thick BC408 plastic scintillator, which was viewed by several Ge detectors placed in close geometry. This kind of setup enabled conventional β-γ and γ-γ coincidence studies. The time stamping of events defined by the period of the tape movement also enabled half-life analyses. In most cases, separate decay schemes were built for the ground state and high-spin isomeric states, respectively. The β feedings and log *ft* values were computed according to the constructed level schemes and γ intensities.

3 Results and discussion

The original results obtained from IGISOL β-decay experiments have been reported in several publications. Here we present some selected level systematics for discussion.

3.1 Ru nuclei

The Ru isotopes show evidence of undergoing a shape transition from a spherical to a γ-soft prolate shape around $N \approx 60$–70 [37, 38, 47–52] and therefore they have been described as transitional nuclei in the Interacting Boson Approximation (IBA) model [47, 48, 51] with increasing rigidity when going towards more neutron-rich species [49–51]. Another shape transition, from γ-soft prolate to γ-soft oblate has been predicted to take place around $N \approx 70$ [53]. Therefore the Ru isotopes have been under detailed investigation, both experimentally and theoretically. Despite many studies on this topic, the exact location of the second shape transition has not been unambiguously identified and more work is certainly needed.

The level structures of the even $^{110-114}$Ru isotopes have been studied at IGISOL via β decays of $^{110-114}$Tc isotopes in three different investigations. In the first one, the ^{110,112}Ru nuclei were studied [37] resulting in new β-decay schemes for the mother nuclides and emphasizing the importance of triaxiality in interpreting the experimental results. The second study concentrated on the level structure of ^{110}Ru resulting in a remarkably extended decay scheme [38]. The experimental results were also compared to a variety of nuclear models. In the third study the β decay of very neutron-rich ^{114}Tc was studied with the help of a Penning trap as a mass selective filter. The level structure of ^{114}Ru populated by the β decay revealed the existence of two beta-decaying states in ^{114}Tc.

The level systematics of even Ru isotopes is presented in Fig. 1. One can observe how the energies of the first 2^+ states are decreasing as a function of neutron number up to $A = 108$, which indicates an increase of collectivity for these nuclei. Near the neutron mid-shell ($N = 66$) the decreasing trend levels off and the energies of the lowest 2^+ states in $^{108-112}$Ru isotopes are rather similar, which is the case also for the other ground state band members. This behaviour has been suggested to correlate with the negative-parity excitations in odd-A Ru nuclei [54]. The energies of the second 2^+ states also have a decreasing trend reaching a clear minimum at $A = 112$, two neutrons above the mid-shell. This trend is the same as in the Pd isotopes, where

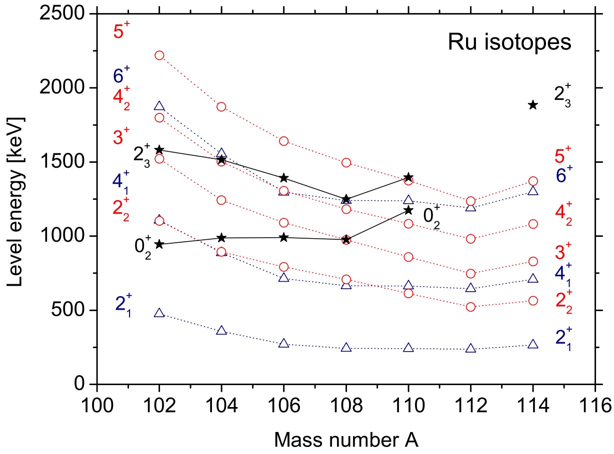

Fig. 1 Systematics of low-lying excited levels in even-mass Ru isotopes. The levels in the ground-state band (*open triangles, blue*) and in the γ-band (*open circles, red*) are connected with *dotted lines*. The first excited 0^+ levels and the third 2^+ levels (*solid stars, black*) are connected by *solid lines*. See text for more details

the energies of the 2^+_2 levels have a minimum at $N = 68$. The level energies in the ground state and gamma bands start to increase again at $A = 114$. The sum rule of $2^+_1 + 2^+_2 \approx 3^+_1$ as well as having the second 2^+ state below the first 4^+ state and the characteristic gamma band indicates that the Ru isotopes have triaxial shapes, which has been supported also by several theoretical calculations [50, 55, 56].

The energies of the first excited 0^+ states are increasing whereas those of the 2^+_3 states are decreasing smoothly as a function of mass number up to $A = 108$. The sudden kink at $A = 110$ suggests a possible change in the nature of the 0^+ states from a β-band-like structure to an intruder excitation. These structures exhibit different behaviours in the level systematics of odd Pd isotopes, see Fig. 2 for a comparison. Unfortunately, the excited 0^+ states have not been observed for the most neutron-rich Ru isotopes ($A = 112, 114$).

3.2 Pd nuclei

The systematics of low-lying levels in neutron-rich doubly-even Pd nuclei is shown in Fig. 2. The series of IGISOL β-decay experiments enabled identification of a large number of new levels in $^{110-118}$Pd isotopes that substantially extend the level systematics for these isotopes. Low-spin levels or band-heads of different origins have been observed enriching the spectroscopic information of Pd nuclei. As already mentioned, Pd nuclei are predicted to exhibit transitional features of triaxiality and γ softness when approaching the neutron midshell [1]. While vibrational degrees of freedom are important for lower mass ^{106,108}Pd isotopes [57], the gradual decrease of excitation energies of yrast states indicates the increase of deformation up to ^{114}Pd followed by a smooth transition towards diminishing deformation in ^{116}Pd and ^{118}Pd isotopes. The systematics of $B(E2, 0^+_1 \rightarrow 2^+_1)$ values in Pd nuclei is presented in [18], which shows a smooth development of collectivity when approaching to the neutron midshell. A $B(E2, 0^+_1 \rightarrow 2^+_1) = 51(9)$ W.u. in ^{114}Pd is close to the value in ^{110}Pd. A relatively large deformation $\beta = 0.24(1)$ in ^{114}Pd indicates that the rotational collectivity reaches its maximum around the neutron midshell, which is consistent with the theoretical predictions [1].

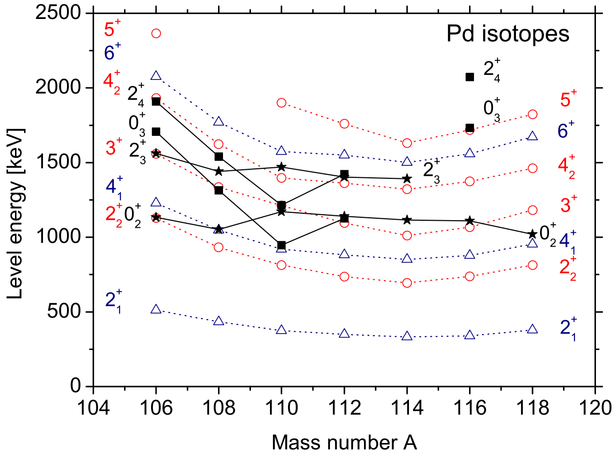

Fig. 2 Systematics of low-lying excited levels in even-mass Pd isotopes with the ground-state band (*open triangles, blue*) and the γ-band (*open circles, red*). Two pairs of 0^+ and 2^+ levels that are indicative of the β band (*solid stars, black*) and the intruder band (*solid squares, black*) are also shown

There are two sets of low-lying 0^+, 2^+ pairs in neutron-rich Pd nuclei, which are populated in the decays of 1^+ states of Rh isotopes. One pair of 0^+, 2^+ excited states exhibits very smooth energy systematics in the 1.0–1.6 MeV range. The 2^+–0^+ energy difference is only slightly lower than the first 2^+ level energies and shows the same decreasing trend with increasing neutron number. Therefore, this pair of 0^+–2^+ levels can probably be associated with a β-band-like structure. The energy systematics of the other pair of 0^+, 2^+ excited levels forms a V-shape versus neutron number, which is characteristic of an intruder excitation. The energy of this $(0^+, 2^+)$ pair is lowest in ^{110}Pd and then moves upwards with larger N. It is interesting to note that the energy minimum occurs at $N = 64$, two neutrons before the midshell. On the other hand, the gamma band energies have a minimum at $N = 68$, two neutrons above the mid-shell. The V-shape behaviour has also been observed for the $K = 1/2$ band in odd-mass Rh isotopes [58, 59], and it has been interpreted as originating from the $\pi 1/2^+[431]$ Nilsson orbital with a prolate deformation.

3.3 Cd nuclei

A three-phonon multiplet had been reported in even-even $^{108-114,118}$Cd isotopes before the IGISOL β-decay experiments. However, information on ^{116}Cd and ^{120}Cd isotopes were lacking in order to fill in the gap in the three-phonon multiplet systematics. Based on the β-decay works at IGISOL, we identified a new 4^+_2 level at 1869.7 keV in ^{116}Cd, and proposed candidates for the complete three-phonon quintuplet along with other four known levels near 2 MeV. The relative $B(E2)$ branching ratios were deduced, which showed strongly preferred decays to the two-phonon triplet [45]. The three-phonon multiplet in ^{118}Cd was previously studied by Aprahamian et al. [28] and the IGISOL experiment modified their interpretation by the substitution of the 1915.8 keV 2^+_3 state with a newly identified 2023.0 keV (2^+_4) state in accordance with the intruder systematics [26, 30]. In ^{120}Cd, we pointed out that the 1899.0-keV (3^+), 1920.5-keV (2^+_3), 1997.9-keV (4^+_2), and 2032.8-keV 6^+ levels can be candidates for the three-phonon multiplet members. The relative $B(E2)$ branching ratios were studied whenever possible to verify the preferred decay to the

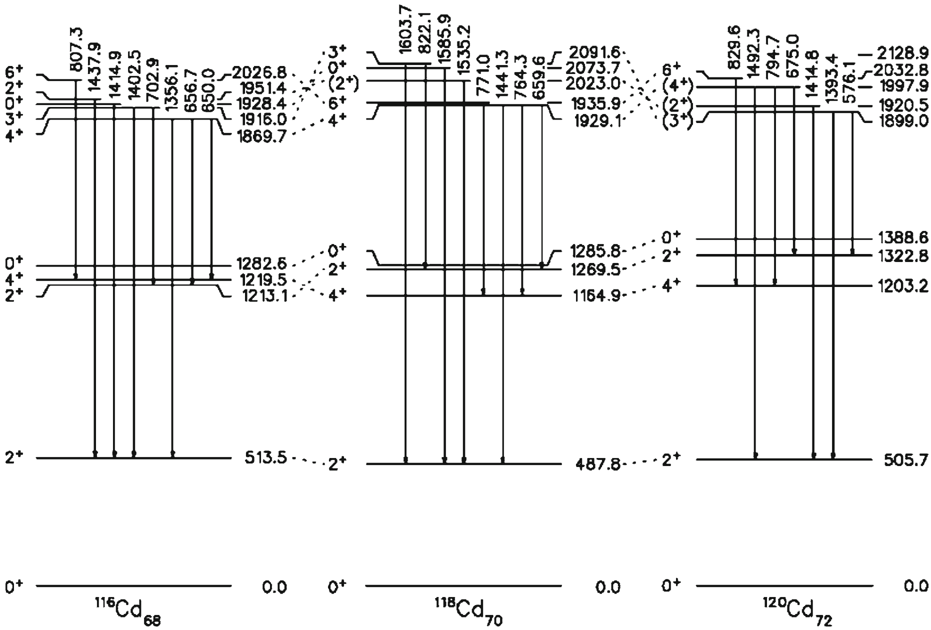

Fig. 3 Comparison of the three-phonon states in ^{116,118,120}Cd isotopes

$N = 2$ states. The comparison of the suggested three-phonon states in ^{116,118,120}Cd isotopes is shown in Fig. 3.

Recently, Garrett et al. made a systematic study of the $^{110-116}$Cd isotopes by using the available experimental data and the IBM calculations incorporating both normal vibrational levels and intruder excitations [60, 61]. For the two-phonon levels, the calculations appear to reproduce the data reasonably well in $^{110-114}$Cd nuclei. However, systematic deviations in low-spin states at the three-phonon levels have been found. A quasi-rotational structure, with the $K = 0$ and $K = 2$ bands built on the ground state has been suggested for $^{110-116}$Cd isotopes [61].

4 Summary and outlook

Many studies with various spectroscopic methods have provided detailed information on even-mass Ru, Pd, and Cd nuclei, thus rendering the possibility to check the mixing of different excitation modes at low excitation energies. However, the level lifetime or $B(E2)$ values that allow for the insight into the intrinsic quadrupole moment are usually available only for stable Pd and Cd nuclei around the neutron midshell. Therefore, it is crucial to apply various spectroscopic studies to more neutron-rich species to extend the $B(E2)$ systematics.

For less neutron-rich Pd and Cd nuclei, fast timing studies with a $\beta - \gamma - \gamma$ coincidence technique have been intensively performed by Mach et al. at ISOL facilities with sources produced by neutron- or proton-induced fission. As shown in the case of ^{116,118,120}Cd isotopes [29], the $B(E2)$ values are very useful to distinguish between the vibrational or intruder nature of narrowly separated 0_2^+ and 0_3^+ states. A better precision may be achieved for such kind of fast timing measurements with the use of high-resolution $LaBr_3$ scintillation detectors [62]. On the other hand, since the very neutron-rich isotopes can be produced now by projectile fragmentation at intermediate beam energies [19, 63], measurements of the Coulomb excitation cross sections or level lifetimes by the Doppler shift technique are promising ways to determine the absolute transition probabilities in the near future [18].

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