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Structural changes observed in neutron-rich A~110-120 nuclei

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Studies of prompt triple and four-fold, γ-γ-γ and γ-γ-γ-γ, coincidence data observed with Gammasphere following the spontaneous fission of ^{252}Cf have significantly expanded our knowledge and identified new features of the variety of structures in fourteen neutron-rich nuclei and traced their changes over long isotopic chains in Ru, Pd and Cd nuclei. Evolution with changing neutron number and onset of wobbling motions were observed in Ru and Pd isotopes. Evolution from chiral symmetry breaking to disturbed chirality was identified from ^{110,112}Ru to ^{112,114,116}Pd and from ^{110,112}Ru to ^{108}Ru. Quasi-particle couplings, quasi-rotations and triaxiality were suggested in Cd isotopes. A complete but complex picture of shape evolution and coexistence was revealed in Pd isotopes. Based on the systematic studies in the mass region, maximal triaxiality is reached in ^{112}Ru and ^{114}Pd, for N=68, four neutrons more than predicted in theoretical calculations. The Cd isotopes were observed to have small quadrupole deformation.

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1. Introduction

The neutron-rich nuclei with A~110-120 over long isotopic chains in Ru (Z=44), Pd (Z=46) and Cd (Z=48) are intermediate between the spherical doubly magic ^{132}Sn and the strongly deformed heavy Zr (Z=40) and Mo (Z=42) nuclei. In this transitional nuclear region rich and challenging structural phenomena were predicted and observed in their low to medium spin states mainly by means of β$^-$-decay studies. For Cd isotopes spherical-vibrational structure, quasi-particle couplings, quadruple-octupole couplings (QOC) and soft triaxial deformations were investigated (e.g. [1,2]); For Pd isotopes, anharmonic vibration, soft rotor, mixed symmetry states (e.g. [3]) and preliminary studies of high spin states (e.g. [4]) were investigated. The systematics of the lower spin members of the ground bands in even-even Ru isotopes [5], the band-crossings of the ground bands, the one- and two-phonon quasi-γ bands and triaxial deformations in Ru isotopes were studied [6,7]. Considerable disagreement in interpretations for the observed levels have been seen. For example, the QOC interpretation for the 5^- levels in Cd isotopes was challenged by a study using polarized deuteron beams [8]. The shape evolution from prolate to oblate predicted in Pd remained an open question due to the lack of reliable data at higher-spins.

To gain new insight into the nuclear structure in this transitional region, we were motivated by the predictions of chiral symmetry breaking in nuclei with well-deformed triaxiality [9,10], and by the predictions of triaxial wobbling motions [11,12]. Our systematic studies revealed a shape evolution from axial-symmetry in Y (Z=39) to near maximal triaxiality in Rh (Z=45) [e.g. [13]]. The theoretical calculations of Hartree-Fock energy surfaces for low-lying states in Ru suggested an evolution from near prolate to triaxial in ^{108,110,112}Ru [5]. The global calculations of axial symmetry breaking in nuclear ground states [14] have found the most pronounced triaxial minima centered around ^{108}Ru, and large triaxial deformations around ^{110}Pd. The Shell Correction version of the Tilted Axis Cranking model (SCTAC) [15,16] was applied for near spherical nuclei, and showed evidence for triaxiality in lighter $^{104\text{-}114}$Cd isotopes, providing a new view angle for them.

2. Experiment and data analysis

Fourteen high-spin level schemes of ^{108,110,112}Ru [17,18], $^{112,114.115,116,117,118}$Pd [19] and ^{117,118,119,120,122}Cd [20] were considerably extended and expanded by means of γ-γ-γ and γ-γ-γ-γ measurements of prompt fission γ-rays from ^{252}Cf using the Gammasphere [21]. Over 5.5 $\times 10^{11}$ triple-fold, 1.9 $\times 10^{11}$ four-fold and higher-fold coincidence events, factors of 10-100 higher than earlier measurements, were accumulated. The triple-gated 4d data with such a high event accumulation turned out to be very powerful in exploring weakly populated levels. Very weakly populated doublet bands with rich decay paths were identified in ^{108,110,112}Ru and ^{112,114,116}Pd, and assigned as odd-parity bands based on angular correlations measurements. The odd-parity doublet bands of ^{114}Pd analogous but different with those of ^{110,112}Ru manifest themselves as disturbed chirality. Wobbling motions are revealed in the extended one phonon γ-band, band 2. The important extension by one level of the ground band confirmed the absence of the second crossing. Similar level schemes were observed in ^{112,116}Pd [19]. The extensions of the ground band in ^{114,116}Pd and yrast bands in ^{115,117}Pd provide critical information for the studies of shape evolution and shape coexistence in the Pd isotopes.

3. Discussions

3.1 Search and studies of triaxial wobbling motions in neutron-rich Ru and Pd isotopes; the identifications of onset wobbling motions in ^{112}Ru and ^{114}Pd, the N=68 isotones, likely also in ^{114}Ru, ^{116}Pd; and the evolution of wobbling motions with neutron number

The wobbling motions in a triaxial nucleus constitute a revolving motion of J about an axis of triaxial nucleus [11,22]. Wobbling motions have been reported in ^{161,163,165,167}Lu and ^{167}Ta at high spins [e.g. [22]]. Wobbling motions are expected to occur at moderate spins if the predicted triaxial shapes lead to different moments of inertia for the three principal axes. Wobbling motion manifests itself as a fingerprint of wobbling motion is that the two-phonon wobbling (even-spin members) lies above the one-phonon wobbling (odd-spin members) [12].

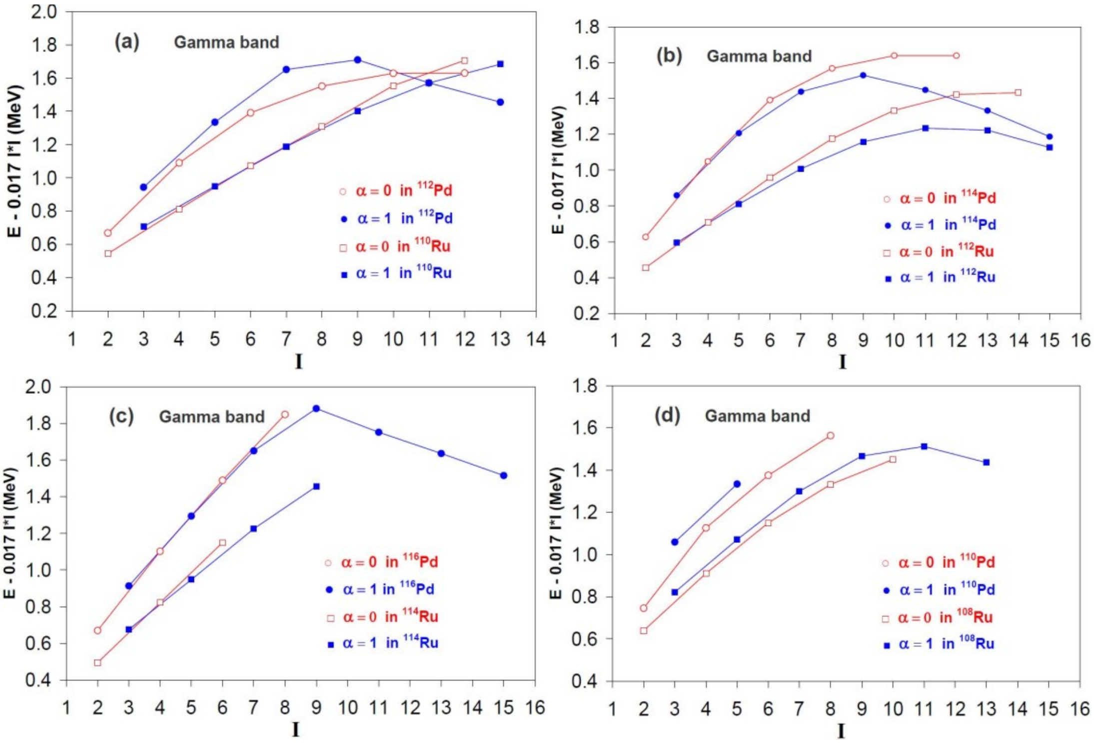

Fig. 1 Excitation energies of the γ-band plotted against spin, *I*, for *N*=66 isotones ^{110}Ru and ^{112}Pd (a); *N*=68 isotones ^{112}Ru and ^{114}Pd (b), *N*=70 isotones ^{114}Ru and ^{116}Pd (c) and, back to *N*=64 isotones ^{108}Ru and ^{110}Pd (d). Based on the relative locations, the crossing points and separations (level-staggering) of the two-phonon wobbling and the one-phonon wobbling, fingerprint of the wobbling motions is checked and the evolution and onset of the wobbling motions in Ru and Pd isotones are identified. See text.

Based on the extended γ-bands, band 2, in the *N*=64-70 Ru and Pd isotones, excitations of the levels are plotted against spins, *I*, in Fig. 2(a) in ^{110}Ru and ^{112}Pd (*N*=66 isotones) no wobbling motion is seen until *I*~6 and 10, respectively. Fig. 1(b) indicates onset of wobbling motion takes place in ^{112}Ru and ^{114}Pd (*N*=68 isotones) (see Fig. 1(c)). ^{112}Ru [11] and ^{114}Pd [19] (*N*=68 isotones) were thus found to be even-even wobblers. Wobbling motions are likely also seen in ^{114}Ru and ^{116}Pd (*N*=70 isotones) (Fig. 1(c)) although the separations of the two curves of ^{114}Ru and ^{116}Pd in the plot are smaller than those of ^{112}Ru [11] and ^{114}Pd [19], which may imply smaller triaxial deformations in ^{114}Ru and ^{116}Pd than those in ^{112}Ru and ^{114}Pd, respectively. While going back to lighter, *N*=64 isotones ^{108}Ru and ^{110}Pd (see Fig. 1(d)), no fingerprints of wobbling motions are observed. The studies of the *N*=64-70 Ru and Pd isotones thus indicate an evolution and onset of wobbling motions in *N*=66-70 Ru and Pd isotones: For *N*=64, no wobbling motions; for *N*=66, no wobbling motions until spin ~6 and 10, respectively; for *N*=68, onset of wobbling motions takes place; and for *N*=70, wobbling motions are likely also seen but with smaller separations (level-staggering).

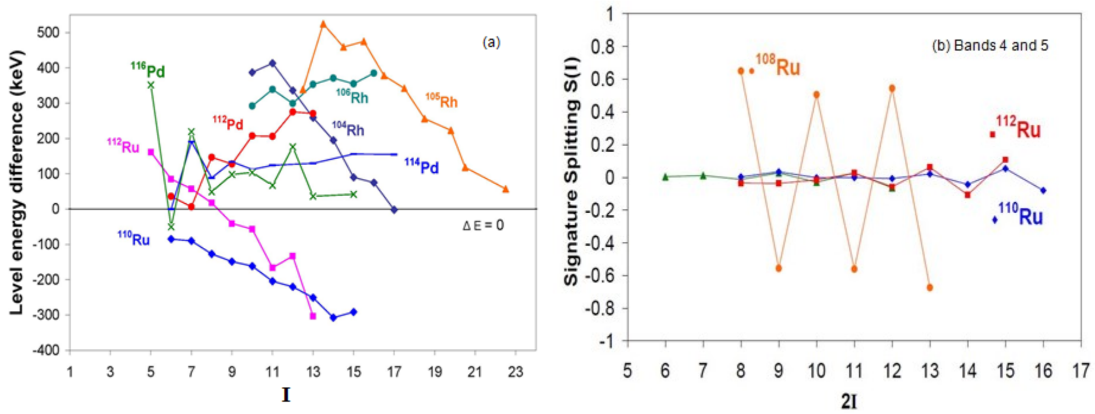

Fig. 2 (a) Energy degeneracy of the partner levels of the doublet bands in ^{110,112}Ru and ^{112,114,116}Pd and (b) Singature splitting in ^{108,110,112}Ru.

3.2 Search and studies of chiral symmetry breaking in Ru and Pd isotopes; the evolution from disturbed chirality in $^{112,114.116}$Pd with less-pronounced triaxiality to chiral ^{110,112}Ru with rigid triaxiality, as also seen from γ-soft ^{108}Ru to chiral ^{110,112}Ru

^{110,112}Ru fulfill the characteristic conditions for generating chirality, and all the fingerprints for chiral symmetry breaking are fulfilled in the doublet bands. The partner levels (levels with the same spin/parity) are nearly degenerate in energy (see Fig. 2(a)). The partner levels have very similar electromagnetic properties, their *B(E2)/B(M1)* ratios being consistent to each other in error range. Their energy staggering, denoted by S(I) values are nearly equal and constant with spin (Fig. 2(b)). These features were explained by TAC calculations [11]. The doublets are zero- and one-phonon chiral vibrational bands built on a $\nu h_{11/2} \times (d_{5/2}g_{7/2})^{-1}$ configuration, giving odd-parity. However, while the odd-parity doublet bands observed in ^{112,114,116}Pd exhibit good energy degeneracy (see Fig. 2(a)), they show dramatic level staggering, as also observed in the doublet bands of ^{108}Ru. One can see the large staggering in ^{108}Ru in Fig. 2(b) and those of ^{112,114,116}Pd in Fig. 3, not fulfilling the S(I) criterion, implying disturbed chirality in ^{112,114,116}Pd and ^{108}Ru. Also shown in the figure are those of the previously reported chiral nuclei [11]. In Fig. 2 (b) in contrast to the small and nearly constant S(I) with spin in ^{110,112}Ru, as expected for chiral symmetry breaking, the doublets of the γ-soft ^{108}Ru show large level staggering, not fulfilling the S(I) criterion for chirality.

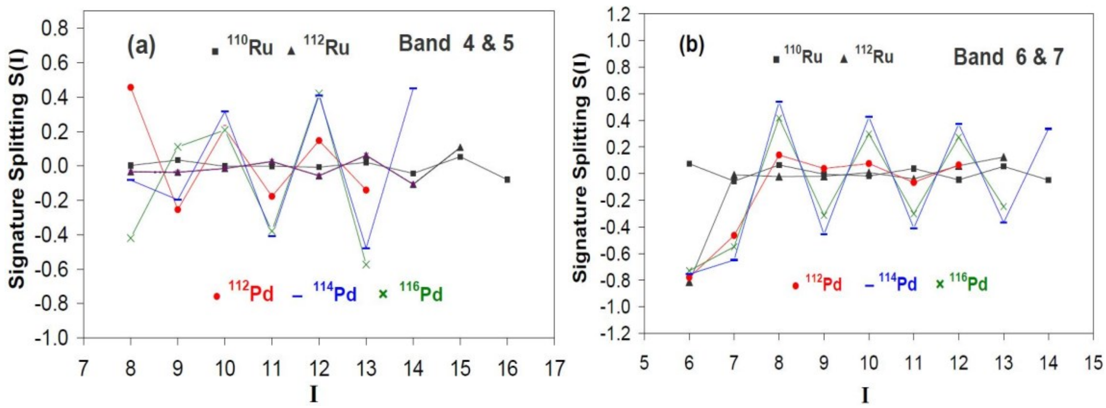

Fig. 3 Large level staggering observed in the doublets of ^{112,114,116}Pd, as seen in ^{108}Ru.

Based on the calculations in [12,14] the triaxial minimum has an energy gain of 0.67 MeV in ^{108}Ru and 0.32 MeV in ^{110}Pd, implying large but less pronounced triaxiality in Pd. The fits by the standard IBM1 model and the rigid-triaxial version IBM1-V3 [23] suggested γ-softness in SU(6) ^{108}Ru, and rigid triaxial deformations in ^{110,112}Ru. The less pronounced triaxiality in Pd and the γ-softness in ^{108}Ru may have disturbed the chirality in these nuclei, revealing an evolution from disturbed chirality in ^{112,114,116}Pd with less pronounced triaxiality to chiral ^{110,112}Ru with maximal triaxiality, and an evolution from the γ-soft ^{108}Ru to chiral ^{110,112}Ru.

The investigations of wobbling motions and chiral symmetry breaking in Ru and Pd isotopes have implied that the maximal triaxial deformations in Ru and Pd isotopes are reached in *N*=68, ^{112}Ru and ^{114}Pd, which is four neutrons more than the calculations [12,14].

3.3 Band-crossings, shape evolution and coexistence in neutron-rich Pd isotopes

The extended level schemes of the Pd isotopes provided systematic data for the complicated multiple band-crossings in Pd, namely the observation and/or absence of the first/second crossings in the even-*N* and odd-*N* Pd isotopes as can be seen in Fig. 4. The interpretations of the systematic data by our systematic Total Routhian Surface (TRS) calculations threw light upon the long-sought shape evolution and shape coexistence in the Pd isotopes.

Our TRS calculations predicted pronounced driving effects of the $(\nu h_{11/2})^2$ alignment (first crossing) and $(\pi g_{9/2})^2$ alignment (second crossing). The second crossings caused by $(\pi g_{9/2})^2$ alignments accompany dramatic changes of triaxial shape deformation parameter γ toward nearly oblate shape or more negative γ-value.

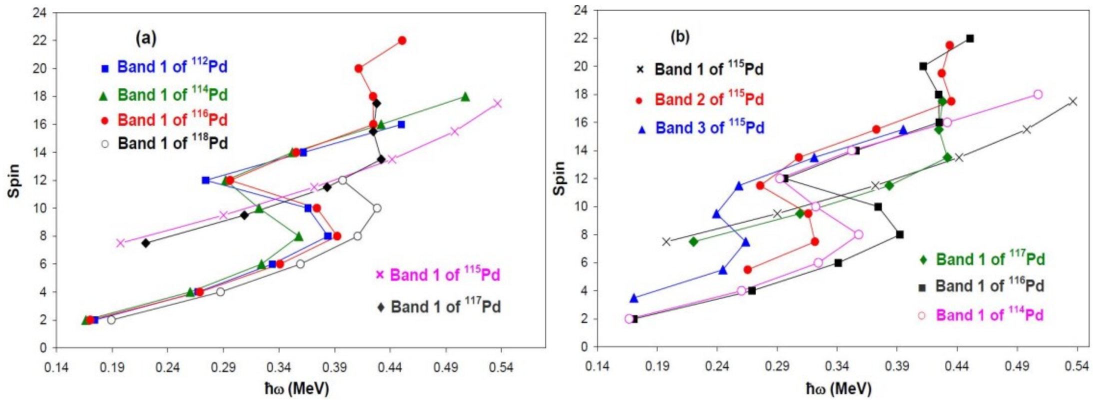

Fig. 4 Intriguing band-crossings observed in even-*N* (a) and in odd-*N* (b) Pd isotopes. For comparison, bands in odd-*N* Pd isotopes and some in even-*N* Pd isotopes are also shown in (a) and (b), respectively.

With good agreement between the experiment and TRS calculations, the first crossings in the even-*N* Pd isotopes in Fig. 4 were interpreted as $(\nu h_{11/2})^2$ alignments. The second crossings in ^{116}Pd, the crossings with similar crossing frequencies in ^{115,117}Pd, and the absence of (delayed, most likely) second crossing in ^{114}Pd are all interpreted as $(\pi g_{9/2})^2$ alignments, showing different shape evolutions with increasing rotational frequency in neighboring Pd isotopes. Based on the interpretations for the band-crossings of the bands 1-3 of ^{115}Pd, shape coexistence was revealed in the nucleus. Our systematic TRS calculations have well reproduced the intriguing data, thus have given an answer to the long-sought shape evolution, that is with increasing neutron number $^{110\text{-}118}$Pd undergo an overall shape evolution from triaxial-prolate via triaxial-oblate to nearly oblate, and then back to less negative γ-value, with shape coexistence identified in ^{115}Pd, which is a more complete but complex picture than the previous prediction. Furthermore, shape evolution with increasing rotational frequency is also suggested by reproducing the data by TRS calculations. Interested readers are referred to [19] for detailed discussions.

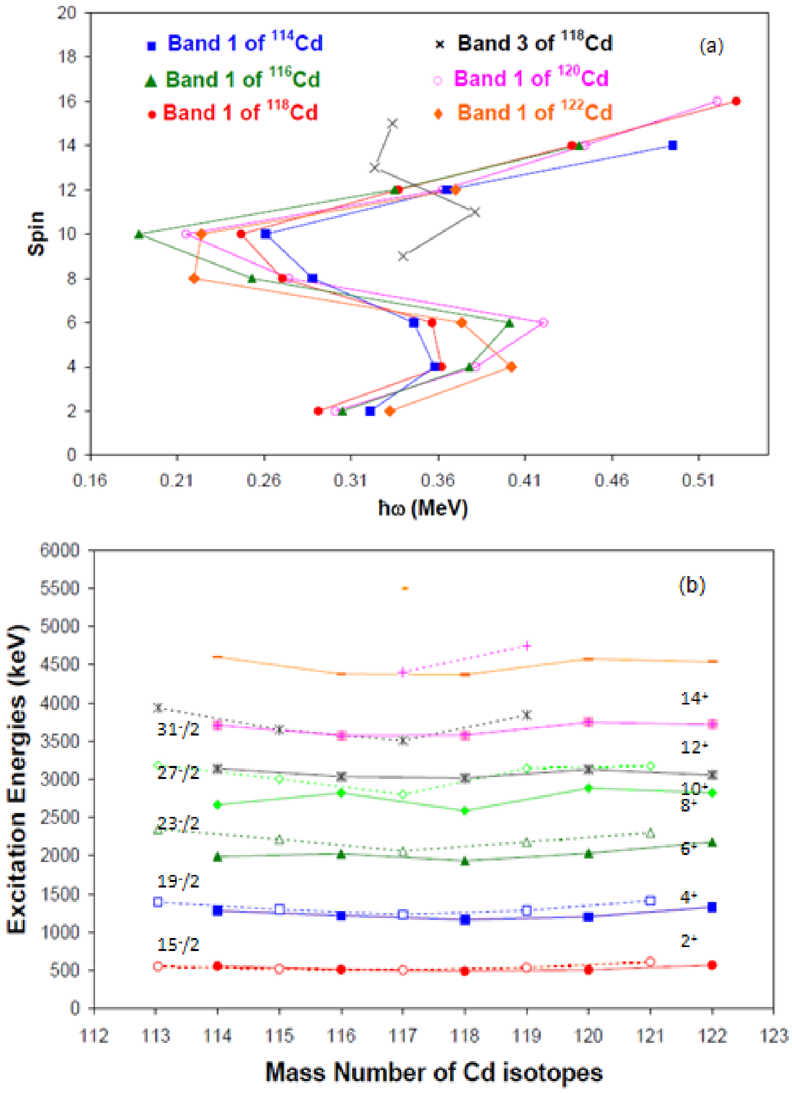

Fig. 5 (a) Weakening of the stretch-coupling with increasing spins, and (b) the sharp band-crossings in quasi-rotations of even-*N* Cd isotopes. See text.

3.4 Quasi-particle couplings, quasi-rotations and triaxiality in Cd (*Z*=48) isotopes section

Figure 5(b) shows the comparison among the excitations of 2^+, 4^+, 6^+, 8^+, 10^+ in $^{114\text{-}122}$Cd (solid-symbols) with those above the $11/2^-$ state of $15/2^-$, $19/2^-$, $23/2^-$, $27/2^-$, $31/2^-$ in $^{113\text{-}121}$Cd (open-symbols). Below the 6^+ (and $23/2^-$) levels, the transition energies $^{113\text{-}121}$Cd are quite similar to those of their neighboring $^{114-122}$Cd isotopes, showing stretch-coupling of the odd-neutron's 11/2 spin to the band members of the even-even neighbors. However, more and more deviations are seen with increasing spin, which may imply weakened coupling and increasing role of the quasi-rotational degree of freedom.

The Shell Correction version of SCTAC using slightly deformed shape parameters (β=0.1-0.2, $\gamma=-10^0$ to -15^0) [15,16] well reproduced the J versus $\hbar\omega$ of the ground bands of $^{104\text{-}114}$Cd. Our plots of experimental Spin versus Rotational frequency of even-*N* ^{116,118,120,122}Cd exhibit the same variations as seen in $^{104\text{-}114}$Cd (Fig. 5(a)), showing evidence for slightly deformed shapes with triaxiality and $(\upsilon h_{11/2})^2$ crossings in these heavier even-*N* Cd isotopes [20]. Triaxiality was also suggested for odd-*N* ^{113,115,117}Cd by triaxial-rotor-plus-particle model reproductions.

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