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The sudden onset of the band crossing for the aligned $\pi g_{9/2}$ orbitals: a possible transition of a triaxial shape from prolate to oblate?

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Abstract

The yrast states were observed up through both the first and second band crossings in both ^{112}Ru and ^{116}Pd using the ^{238}U(α, f) fusion–fission reaction. The rotational alignment of the $g_{9/2}$ proton-pair is responsible for the second band crossing. This assignment is based on the amount of angular momentum gained in the alignment and a similar crossing frequency is observed for the rotational band based on the $h_{11/2}$ neutron orbital in both ^{111}Ru and ^{117}Pd. The closeness of the crossing frequency between the first and second band crossings, which happens unexpectedly within a rotational frequency span of ≈ 50 keV, most likely is caused by a transition of a triaxial shape from prolate to oblate in neutron rich Ru and Pd nuclei.

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Nuclear shape degrees of freedom constitute the basis of Bohr's Hamiltonian [1] in describing the low-lying collective modes of motion in nuclei. The success of this model suggests the importance of systematic studies of nuclear shapes as a function of both neutron and proton number, where transitions from one shape to the other are expected to occur at certain locations along the nuclear landscape. Neutron-rich $A \sim 100$ nuclei, where nuclear shapes change rapidly as the valence nucleons begin to fill the $h_{11/2}$ neutron and $g_{9/2}$ proton orbitals, provide a fertile ground for studies of shape transitions, such as the transition from spherical to deformed or from prolate to oblate. The exact location where shape transitions occur is very sensitive to the model assumptions. For example, the shape transition from prolate to oblate for the Pd isotopes is predicted to occur at ^{111}Pd by the finite-range droplet model (FRDM) [2] and at ^{112}Pd by the relativistic mean-field (RMF) theory [3]. The latter cal-

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culations were only applied to even–even nuclei but both calculations were made for nuclei across the periodic table. On the other hand, calculations using the Nilsson–Strutinsky method with the cranked Woods–Saxon average potential and a monopole pairing residual interaction [4], which were applied only to even–even neutron-rich $A \sim 100$ nuclei, predict the transition occurring at ^{116}Pd. Experimental confirmation of this shape transition is important to elucidate the nuclear structure in neutron-rich nuclei.

The distinction between a prolate and an oblate shape for a quadrupole deformation is the sign of the static quadrupole moment of the state of interest. Measurement of both the sign and magnitude of the static quadrupole moments for the first 2^+ states in even–even Os and Pt isotopes using the Coulomb excitation technique, confirmed the transition from prolate to oblate shape with increasing mass for the Os to Pt isotopes [5,6]. This shape transition was predicted by Kumar and Baranger by solving Bohr's Hamiltonian using the pairing-plus-quadrupole model [7–9]. However, this experimental technique is difficult to apply for nuclei away from the valley of β stability such as the neutron-rich Pd isotopes. An alternative approach is to explore phenomena that may yield a unique signature to distinguish between the two shapes. In this Letter, we address one such opportunity by studying the band crossing phenomenon in nuclei, which is sensitive to the interplay between the single-particle and shape degrees of freedom, to produce the evidence for a prolate to oblate shape transition in both Ru and Pd isotope chains.

Recent advances in the spectroscopy of neutron-rich $A \sim 100$ nuclei have benefitted from studies of the γ-ray spectroscopy of fission fragments from either a spontaneous fission source [10–13] or charged-particle induced fusion–fission reactions [14,15]. Most of these previous experiments were performed using modern γ-ray detector arrays and a source or target sufficiently thick to stop the recoiling fission fragments. This approach was used to avoid the Doppler broadening effect for the observed γ rays in order to maximize the resulting energy resolution and resolving power for the very dense γ-ray transitions from hundreds of fission fragments.

An alternative approach is to detect the γ rays in coincidence with the detection of both fission fragments recoiling out of a source or target on a thin backing, which allows reconstruction of the fission kinematics, such as the determination of masses and velocity vectors for both fission fragments [12,13]. This allows Doppler-shift corrections to be applied to the observed γ rays, which eliminates the limitation to the study of excited states with lifetimes longer than the stopping times of the fission fragments, imposed by the thick-source or thick-target experiments. This, plus the ability to establish the identities of γ rays originating from either fission fragment, significantly improves the sensitivity of studies for neutron-rich nuclei. For example, in our early work with a ^{252}Cf fission source on a thin backing [12,13], the ground-state band of ^{104}Mo was extended from spin 14^+ at 4.114 MeV to 20^+ at 7.282 MeV and the $K^\pi = 2^+$, γ-vibrational band from spin 10^+ at 3.004 MeV to 16^+ at 5.591 MeV.

The scope of studies of neutron-rich nuclei can be extended beyond that available using spontaneous fission sources by using fusion–fission reactions, since the latter reactions can be optimized to emphasize the population of a certain region of neutron-rich nuclei. In the present study of the $^{238}\mathrm{U}(\alpha, \mathrm{f})$ fusion–fission reaction [16,17], both the population of excited states for neutron-rich $A \sim 100$ nuclei has been extended to higher spin and the mass distribution for a given isotope chain is broader than obtained using spontaneous fission sources. This experiment was carried out at the 88-inch cyclotron facility of Lawrence Berkeley National Laboratory by bombarding a thin $\approx 300\ \mu\mathrm{g/cm}^2$ ^{238}U target with an α beam at $E_{\mathrm{lab}} = 30$ MeV. Fission fragments were detected by the Rochester highly-segmented 4π heavy-ion detector array, CHICO [18], in coincidence with the detection of the deexcitation γ rays using Gammasphere [19]. A total of ≈ 600 M events, with two fragments and at least three γ rays in coincidence, were collected. The deduced masses from the measured fission kinematics have a resolution of 12 mass units, which reflects the achieved time resolution, ≈ 500 ps. The achieved position resolution, $\approx 1°$ in polar angle and 4.6° in azimuthal angle, is consistent with prior CHICO performance [20–23].

Mass-gated events with at least three γ rays were used to build the level schemes for the neutron-rich Ru and Pd nuclei. Samples of the Doppler-shift corrected γ-ray spectra for ^{112}Ru and ^{116}Pd, gated by both the mass and known γ-ray transitions, are shown in Fig. 1, where the achieved energy resolution

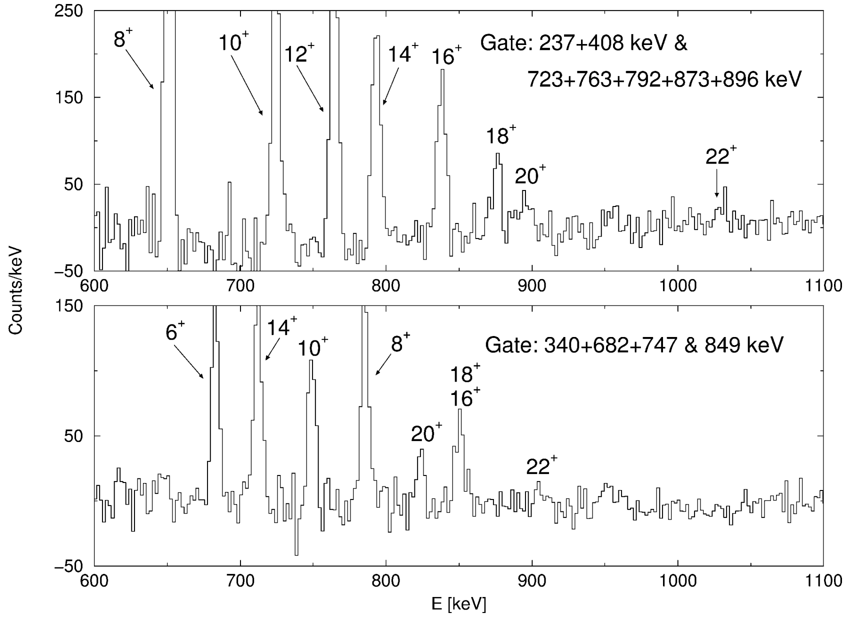

Fig. 1. Doppler-shift corrected spectrum with gates on the mass ($100 \leqslant A \leqslant 125$) and specified γ-ray transitions for ^{112}Ru (top) and ^{116}Pd (bottom). The labeled transitions are $\Delta I = 2$ transitions.

is better than 1%, limited primarily by the finite size of the Ge detectors. The derived yrast level schemes for both ^{112}Ru and ^{116}Pd are shown in Fig. 2, where states were extended to spin 22^+ at 7.746 and 7.819 MeV, respectively. The achieved sensitivity from this technique has led to the observation of the second band crossing and beyond in ^{112}Ru and ^{116}Pd as well as the band crossing for the $h_{11/2}$ neutron band in ^{111}Ru and ^{117}Pd, where states with spin up to $47/2^-$ at 7.496 MeV and $35/2^-$ at 4.632 MeV, respectively, were populated.

The spectroscopy of the neutron-rich Ru and Pd nuclei has been studied extensively, and the existence of the low-lying $K^\pi = 2^+$, γ-vibrational band was recognized for the even–even isotopes. The significant role of the γ deformation on the structure of these nuclei is evident from the latter observation. The typical γ value, derived from the measured branching ratios for the decay of the $I_K^\pi = 2_2^+$ state, assuming a simple triaxial rotor model, is $\approx 25°$ (or $35°$) for ^{112}Ru and $\approx 27°$ (or $33°$) for ^{116}Pd, where $0°$ represents a prolate shape and $60°$ an oblate shape. For the yrast states, the first band crossing was observed for most neutron-rich Ru and Pd isotopes [11–13] and the onset of the second band crossing

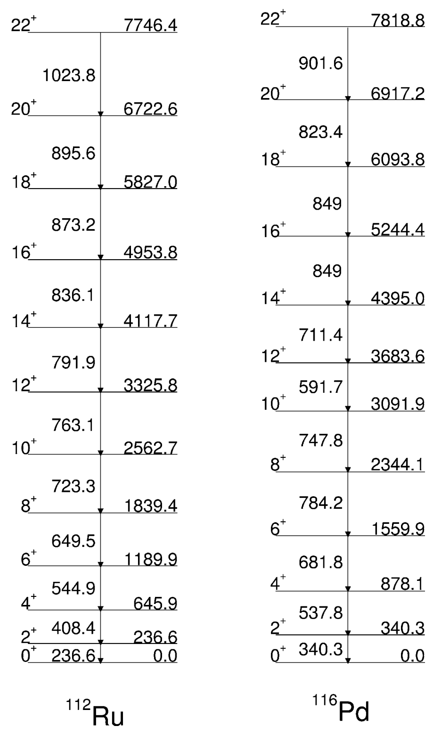

Fig. 2. The yrast states for both ^{112}Ru and ^{116}Pd. Energies are in keV.

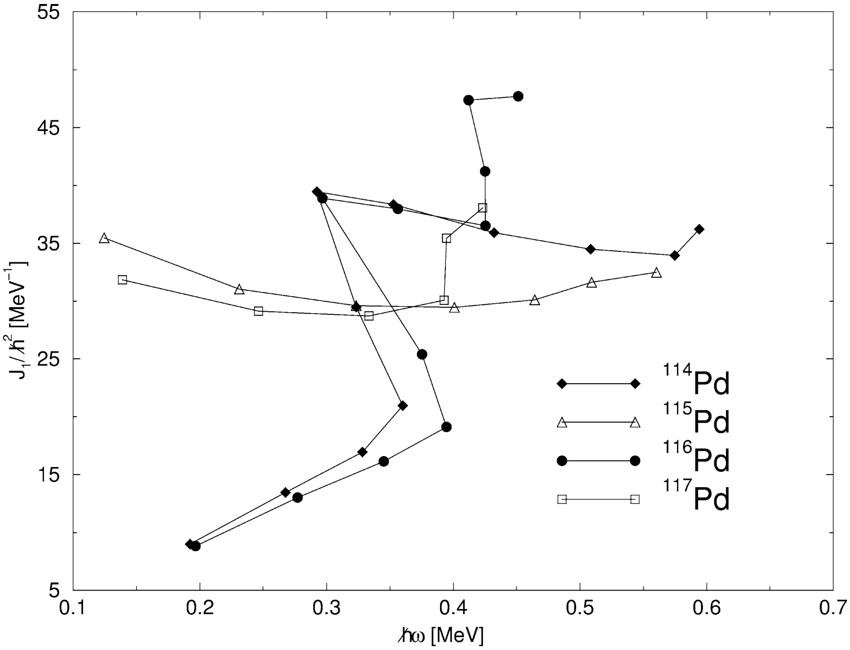

Fig. 3. The kinematical moment of inertia as a function of the rotational frequency for the yrast states of $^{114–117}$Pd.

also was observed in ^{112}Ru and ^{116}Pd [12,13,24]. An initial suggestion that the $g_{9/2}$ proton-pair alignment is responsible for the observed first band crossing in the Pd isotopes [11] was based on the calculation that the crossing frequency is lower for the $g_{9/2}$ proton-pair alignment than that for the $h_{11/2}$ neutron-pair alignment if an oblate shape is assumed. The latter assumption is predicted by the FRDM [2]. The blocking effect observed for the $h_{11/2}$ neutron band in ^{111,113,115}Pd [13–15,25] contradicts the above conclusion and supports that the alignment of a pair of $h_{11/2}$ neutrons is responsible for the first band crossing for the even Pd isotopes, implying a prolate shape for these nuclei.

Contrary to the behavior of yrast states in ^{114}Pd, where no indication of a second band crossing was observed at least until the rotational frequency ≈ 600 keV, the second band crossing was observed in ^{116}Pd at the rotational frequency only ≈ 50 keV above that of the first band crossing, as shown in Fig. 3. The angular momentum gained in the alignment process was determined to be $\approx 9\ \hbar$ and $\approx 6\ \hbar$ for the first and second band crossings, respectively, using the Harris parameters [26] $\mathcal{J}_0 = 5\ \hbar^2/\text{MeV}$ and $\mathcal{J}_1 = 16\ \hbar^4/\text{MeV}^3$ adapted from Ref. [25], as shown in Fig. 4. For the odd-A Pd isotopes, the band crossing was observed for the $h_{11/2}$ neutron band in ^{117}Pd, but not in ^{115}Pd, at a rotational frequency ≈ 400 keV similar to that for the second band crossing in ^{116}Pd. Evidence from both the angular momentum gained and the observed band crossing in ^{117}Pd justifies that the $g_{9/2}$ proton-pair alignment is responsible for the observed second band crossing in ^{116}Pd.

The sudden onset of the band crossing for the $g_{9/2}$ proton-pair alignment in ^{116}Pd cannot be explained by the sudden drop of the pairing energy since the crossing frequency for the $h_{11/2}$ neutron-pair is nearly the same for those neutron-rich Pd isotopes. The most likely explanation for this sudden onset of the band crossing is that it is due to a transition of a triaxial shape from prolate to oblate occurring at ^{116}Pd. According to the cranked shell model calculation, the band crossing shifts to a lower rotational frequency for the $g_{9/2}$ proton-pair alignment but remains relatively unchanged for the $h_{11/2}$ neutron-pair alignment if a transition from a prolate to oblate shape occurs [13]. Similar results were obtained from calculations described in Ref. [4,11]. A quantitative discus-

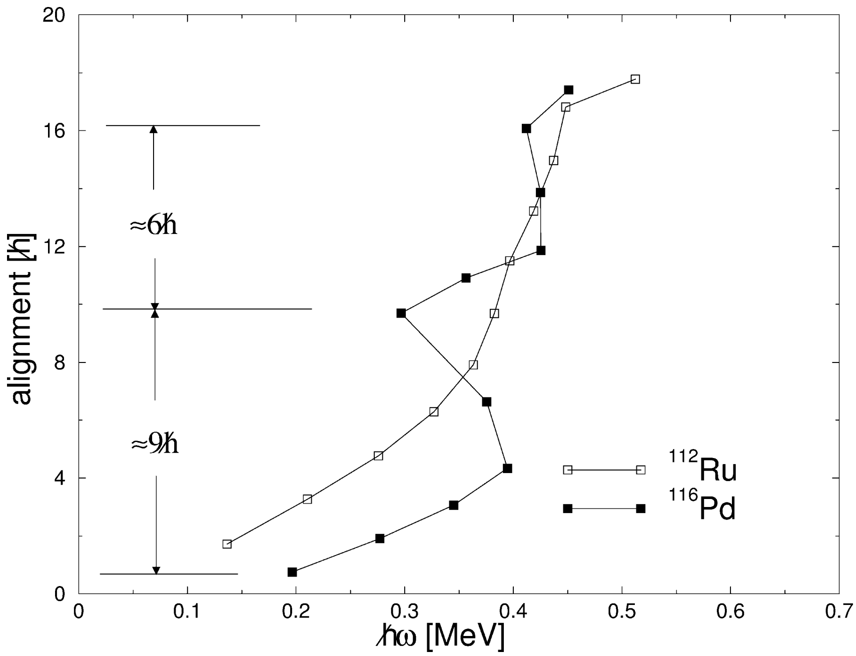

Fig. 4. The aligned angular momentum vs. the rotational frequency is plotted for the yrast states for ^{112}Ru and ^{116}Pd using the Harris parameters specified in the text.

sion for this possible shape transition of a triaxial deformation will be made for the Ru isotopes, where the calculations are available [4]. The transition of a triaxial shape from prolate to oblate occurring at ^{116}Pd is consistent with the prediction of the macroscopic–microscopic calculations of Ref. [4] but different from the calculations of FRDM [2] and RMF theory [3].

The closeness of the crossing frequency between the first and second band crossings also was observed in ^{112}Ru, shown in Fig. 5, where both the kinematic and dynamic moments of inertia are plotted as a function of the rotational frequency for $^{109–112}$Ru. The belief that the second band crossing is caused by the alignment of a pair of $g_{9/2}$ protons is justified by evidence from both the angular momentum gained in the alignment process, shown in Fig. 4, and a similar crossing frequency observed for the $h_{11/2}$ neutron band in ^{111}Ru. According to the cranked shell model calculation [4], the crossing frequency for the $h_{11/2}$ neutron-pair alignment, which is ≈ 350 keV for the neutron-rich nuclei ranging from Zr to Ru isotopes, is rather insensitive to the γ degree of freedom. This is consistent with the crossing frequency observed for the first band crossing in both Ru and Pd isotopes. By contrast, the crossing frequency for the $g_{9/2}$ proton-pair alignment is very sensitive to the γ degree of freedom. For example, it drops from ≈ 550 keV for a prolate shape of ^{102}Zr to ≈ 450 keV for a triaxial shape of $\gamma = -30°$ of ^{108}Ru [4]. A significant change in triaxiality appears to explain qualitatively the observation of sudden onset of the band crossing for the $g_{9/2}$ proton-pair alignment in ^{112}Ru. However, it is not clear that the observed difference of the crossing frequency, ≈ 50 keV, between the two configurations can be reproduced by assuming a triaxial shape of $\gamma = -30°$, where the calculated value, ≈ 120 keV, is more than twice of the observed frequency difference. Obviously, further theoretical investigations are needed to assure if a possible transition of a triaxial shape from prolate to oblate occurs in ^{111,112}Ru. This is near to the predicted location, ^{110}Ru, by both the FRDM [2] and the macroscopic–microscopic calculation of Ref. [4] and ^{108}Ru by the RMF theory [3].

According to the cranked shell model calculation [4], the $(\nu h_{11/2})^2 \otimes (\pi g_{9/2})^2$ configuration is predicted to become yrast at spin between 19 and 26 for $^{102–110}$Ru, where a significant triaxiality has developed for the heavier Ru isotopes. This description may

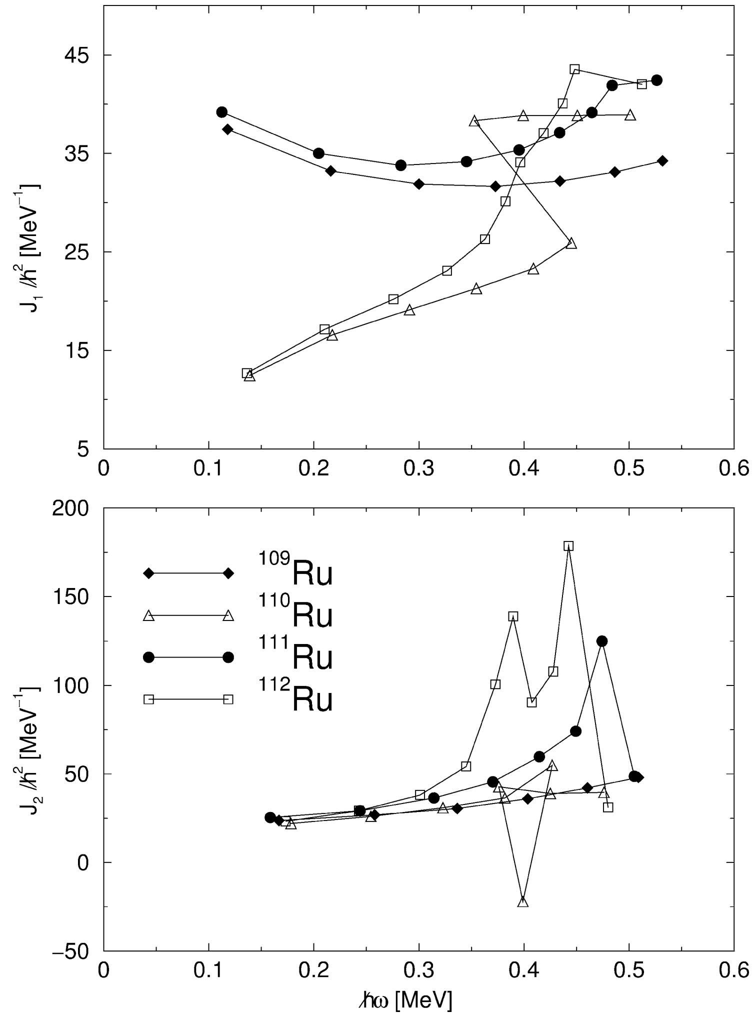

Fig. 5. The kinematical (top) and dynamical (bottom) moments of inertia as a function of the rotational frequency for the yrast states of $^{109-112}$Ru.

be consistent with the observation of the sudden onset of the observed band crossing for the $g_{9/2}$ proton-pair alignment. However, the quantitative comparison cannot be made without additional calculations.

In summary, the spectroscopy of neutron-rich Ru and Pd nuclei has been studied using the ^{238}U(α, f) fusion–fission reaction. The deexcited γ rays from fission fragments were detected by Gammasphere in coincidence with the detection of both fission fragments by CHICO. The sensitivity achieved using this technique has extended the spectroscopic study beyond the second band crossing in these nuclei. Evidence from the characteristics of the first and second band crossings in ^{112}Ru and ^{116}Pd, and the band crossing in ^{111}Ru and ^{117}Pd suggests that a possible transition of a triaxial shape from prolate to oblate occurs in neutron-rich Ru and Pd isotopes at ^{111}Ru and ^{116}Pd, respectively. Further theoretical work is needed to confirm this possible shape transition.

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