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Phase transition in odd-N Pd-isotopes*

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Abstract: Phase transition in odd-N isotopes ^{99,101,103}Pd are investigated via the E-GOS (E-Gamma Over Spin) curves, which strongly suggest a structure evolution from vibration to rotation along the yrast lines with increasing spin. Theoretical calculations have been performed for the ground state bands of ^{99,101,103}Pd in the framework of the cranked shell model (CSM) and the alignment properties observed experimentally are analyzed employing this model. The results show that the phase transition in the ground state bands of ^{99,101,103}Pd can be interpreted as the valence nucleons start to occupy the $g_{9/2}$ proton orbitals with increasing spin which would polarize the core to a small, but rigid quadrupole deformation.

Key words: structure evolution, the E-GOS curve, cranked shell model

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1 Introduction

The experimental observation of shape and phase evolution is very important for a deeper understanding of the nuclear structure. In the $A\sim100$ mass region, rapid changes in nuclear shape are known to begin as valence nucleons start to fill the $g_{9/2}$ proton or $h_{11/2}$ neutron orbitals [1]. However, the exact location of where these transitions occur and the rapidity of such transitions are still interpreted in a model-dependent way, due in part to difficulties in extracting the signs and magnitudes of static quadrupole moments through Coulomb excitation measurements. Nevertheless, details of the band-crossing in these nuclei at high spin can provide an effective way to research the nature of the states lying close to the Fermi surface, which can help us to get the shape deformations of the nuclear mean field. The odd-N Pd-isotopes with $Z=46$ and $N\sim55$ are expected to exhibit a γ-soft moderate deformation at low and medium angular momenta, and their level structure can provide important information on the Coriolis-driven alignment effect in weakly deformed nuclides.

Prior to this work, phase evolution in the even–even nuclei, such as in Mo, Ru, Pd and Cd isotopes with mass number around 110, was confirmed in Ref. [2]. For an odd-A nuclide, its high-spin states may be formed by coupling weakly the valence nucleon to the respective core excitations [3]. Therefore, the odd-A nuclei in this mass region would be expected to exhibit similar phase evolution as their neighboring even–even nuclei. In this paper, we aim to investigate the phase evolution in ^{99,101,103}Pd, and the mechanism of this phenomenon will be discussed in the framework of the cranked shell model.

2 The E-GOS curves of ^{99,101,103}Pd

The concept of the E-GOS prescription has been applied to discern the structure evolution from vibration to rotation in nuclei as increasing spin [2]. In this method, the axially symmetric rotational and harmonic vibrational modes can be distinguished by the ratio of $E_\gamma(I\rightarrow I-2)/I$ [2]. For a vibrator, this ratio decreases towards zero with increasing spin, whereas for an axially symmetric rotor case, this ratio will become to a constant value of $4[\hbar^2/2J]$ ultimately. Here J is the static moment of inertia. This prescription has been applied to the yrast cascades in the even–even nuclei and a clear signature for shape phase transition has been found [2]. For odd-A systems, the E-GOS prescriptions can be addressed by substituting the spin (I) by a normalised spin minus the bandhead spin projection on the axis of symmetry, K, such that $I\rightarrow(I-K)$. For good rotors, the E-GOS prescription for odd-A systems then becomes [4]

$$R(I)=\frac{E_\gamma}{I}\rightarrow\frac{\hbar^2}{2J}\frac{(4I-2)}{I}\rightarrow\frac{\hbar^2}{2J}\frac{[4(I-K)]-2}{(I-K)},\qquad(1)$$

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$$R(I-K)=\frac{E_\gamma-\left(4K\dfrac{\hbar^2}{2J}\right)}{I-K}=\frac{E_\gamma-KR_{K+2}}{I-K}. \qquad (2)$$

Figure 1 shows the E-GOS plots for the odd-N isotopes ^{99,101,103}Pd. The data on ^{101}Pd [5] come from our recent experiment performed at the Japan Atomic Energy Agency (JAEA) where the nuclei of interest was populated via the reaction ^{76}Ge(^{28}Si, 3n) at beams with energies of 85 and 95 MeV, respectively. The γ rays were detected using the GEMINI [6] detector array and the full experimental details can be found in Ref. [5]. The spectrum in Fig. 2 shows a summed spectrum by gating on the transitions of 657, 947, and 716 keV, which extends this structure from the ground state to the yrast spin $33/2\hbar$ level. The data on ^{99,103}Pd are taken from Refs. [7, 8]. As Fig. 1 shows, the E-GOS plots exhibit a clear evolution from vibrational to rotational excitations in the positive-parity structures of the odd-N isotopes ^{101,103}Pd. For the ^{99}Pd nucleus, the E-GOS curve shows similar behavior to ^{101}Pd at low spins, suggesting a vibr-

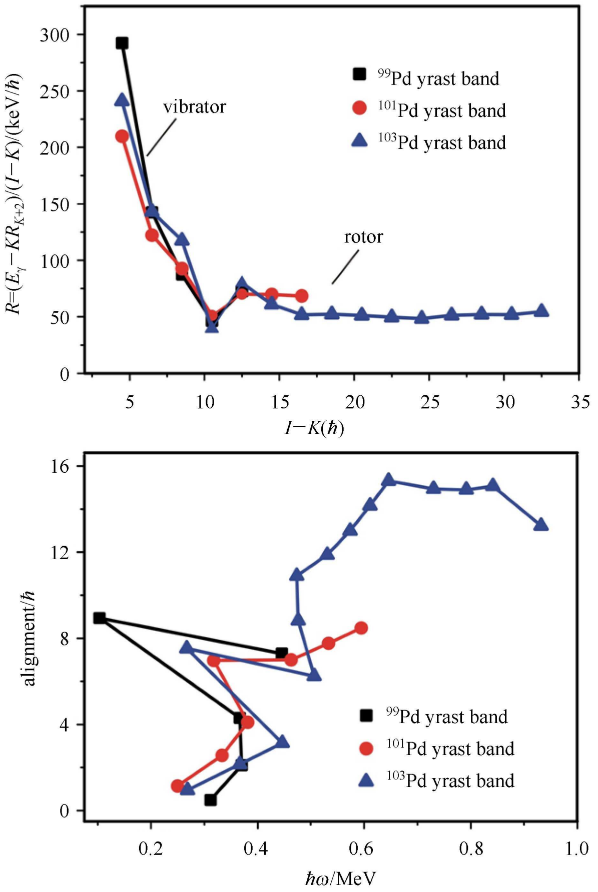

Fig. 1. (color online) (top) E-GOS plots for the odd-N Pd-isotopes; (below) Deduced quasiparticle alignments for the odd-N Pd-isotopes, using the Harris parameters of J=7.0 $\hbar^2$MeV and J_1=15.0 $\hbar^4$MeV^3.

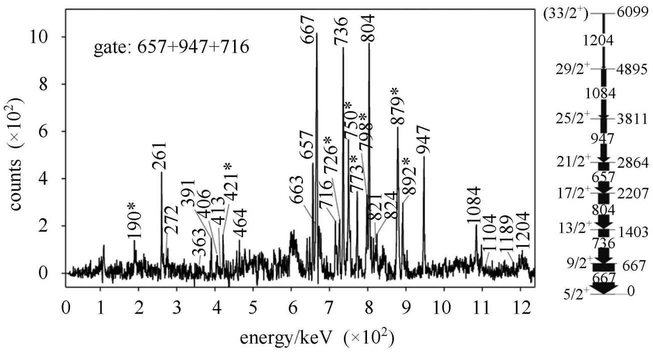

Fig. 2. Summed spectrum showing the yrast sequence for ^{101}Pd in the current work. The asterisks indicate contaminations mainly from ^{100}Pd.

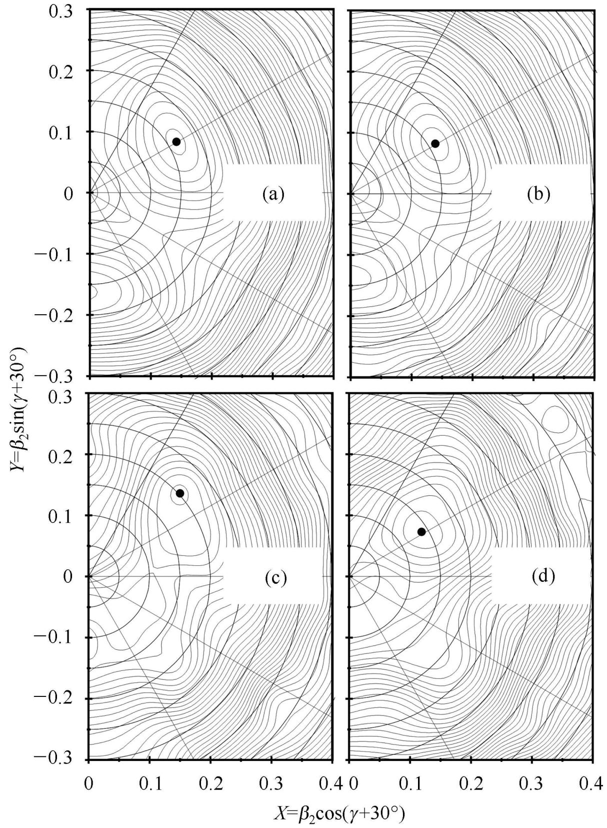

Fig. 3. Calculated total Routhian surfaces for the lowest (π, α)=(+, +1/2) configuration of ^{103}Pd. The energy contours are at 200 keV intervals. The deformation parameters for the individual minima are: (a) $\hbar\omega$=0.0 MeV, β_2=0.164, β_4=0.007, and γ=0.300°; (b) $\hbar\omega$=0.20 MeV, β_2=0.161, β_4=0.006, and γ=0.457°; (c) $\hbar\omega$=0.40 MeV, β_2=0.202, β_4=0.033, and γ=12.226°; (d) $\hbar\omega$=0.60 MeV, β_2=0.140, β_4=0.032, and γ=1.611°.

ational character. Unfortunately, experimental information on the high spin states for this band is not currently available.

The comparison of experimental alignment properties from ^{99,101,103}Pd allows the identification of the chief orbitals responsible for the structural changes frequently observed in this mass region. The resultant quasiparticle aligned angular momentum is obtained from the subtraction of a reference angular momentum, $\omega J_0+\omega^3 J_1$, from the total angular momentum along the rotational axis [9]. Harris parameters of J_0=7.0 $\hbar^2$MeV and J_1=15.0 $\hbar^4$MeV^3 [10] were used for the ground state bands of ^{99,101,103}Pd in the present analysis. As shown in Fig. 1, ^{99,101,103}Pd exhibit a backbend around the same crossing frequencies. This seems to indicate that the same orbital may be responsible for the observed alignment in these isotopes. In particular, the phase changes seem to occur at a frequency of about 0.4 MeV in the yrast bands of ^{99,101,103}Pd, although this critical crossing frequency may be shifted with increasing neutron number. It is indicated that the quasiparticles may polarize the core to a quadrupole deformation after the band crossings.

3 Theoretical calculations

In order to obtain a general description of shape transitions and understand systematically the microscopic origin of these interesting phenomena, cranked shell model calculations with nonaxial deformed Woods–Saxon potential [11] for the ground bands of ^{99,101,103}Pd were made and compared with available experimental data. It was known that the deformation properties of the nuclei depend not only on the neutron numbers but also on the collective rotation. The nuclear shapes are susceptible to the increased angular momentum. In this work, the effect of collective rotation on the nuclear deformation is also considered. Such calculations were performed by means of total-Routhian-surface (TRS) methods in a three-dimensional deformation space (β_2, γ, β_4) [12]. Both monopole and quadrupole pairings were included [13, 14]. At a given frequency, the deformation of a state is determined by minimizing the calculated TRS.

An advantage of the TRS calculations is to allow the proton and the neutron contributions to the total aligned angular momentum to be decomposed separately, such that the experimental data on a specific nucleus can be

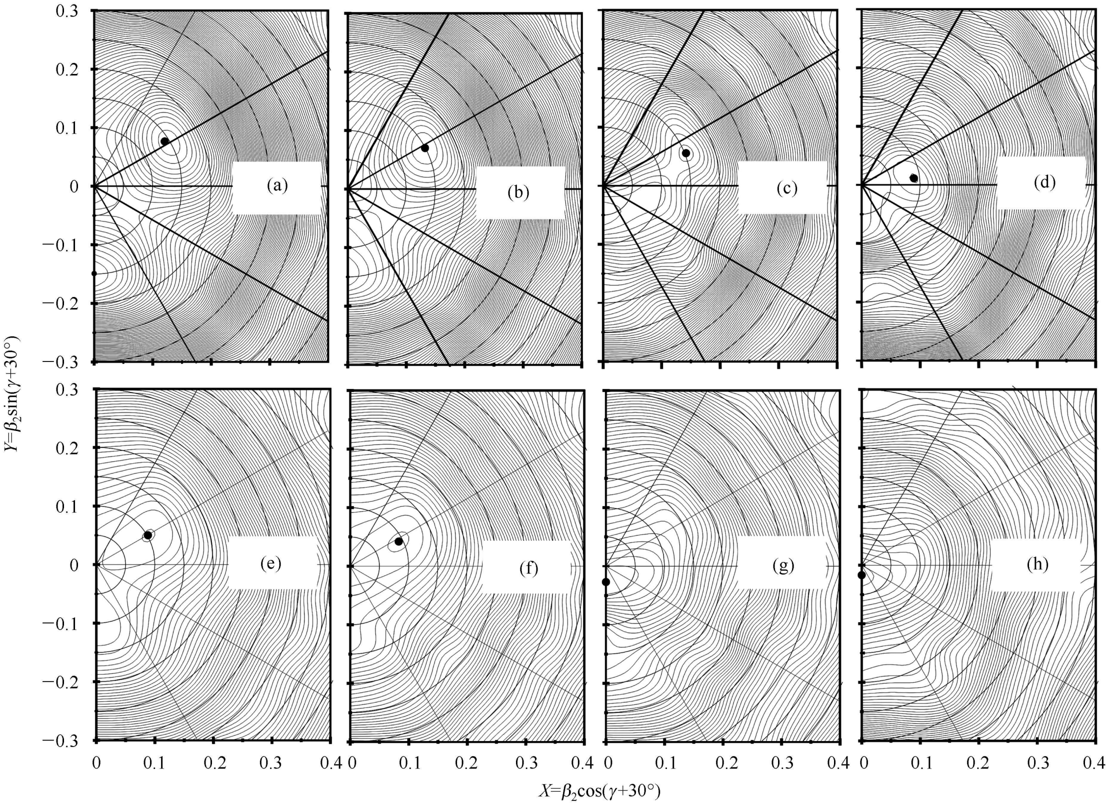

Fig. 4. Calculated total Routhian surfaces for the lowest (π, α)=(+, +1/2) configuration of ^{101}Pd (top) and ^{99}Pd (bottom). The energy contours are at 200 keV intervals. The deformation parameters for the individual minima are: (a) $\hbar\omega$=0.0 MeV, β_2=0.149, β_4=0.020, and γ=0.175°; (b) $\hbar\omega$=0.20 MeV, β_2=0.149, β_4=0.020, and γ=−0184°; (c) $\hbar\omega$=0.40 MeV, β_2=0.152, β_4=0.0226, and γ=−9.2°; (d) $\hbar\omega$=0.60 MeV, β_2=0.091, β_4=0.001, and γ=24.4°; (e) $\hbar\omega$=0.0 MeV, β_2=0.101, β_4=0.012, and γ=−0.440°; (f) $\hbar\omega$=0.20 MeV, β_2=0.093, β_4=0.010, and γ=−0.391°; (g) $\hbar\omega$=0.40 MeV, β_2=0.027, β_4=0.007, and γ=−120°; (h) $\hbar\omega$=0.60 MeV, β_2=0.017, β_4=0.017, and γ=−120°.

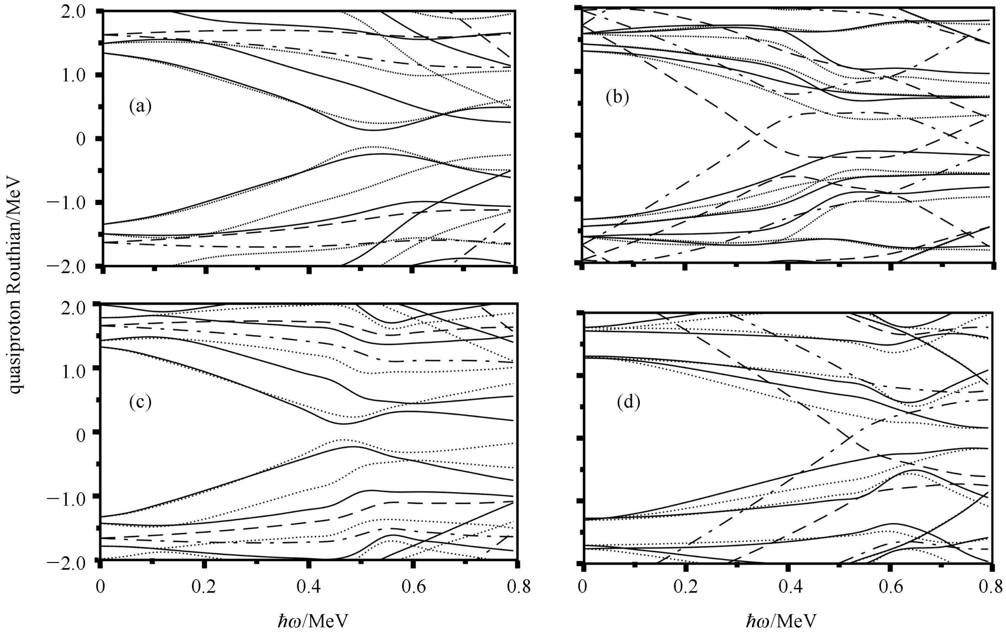

Fig. 5. Calculated quasiproton and quasineutron Routhians as a function of the rotational frequency in ^{103}Pd (top) and ^{101}Pd (bottom). In the calculations, the static deformation parameters are set, for top panels, as β_2=0.164, β_4=0.007, and γ=0.3°; and, for bottom panels, as β_2=0.145, β_4=0.021, and γ=−7.0°. The parity and signature (π, α) of the Routhians are represented as follows: (+, +1/2) solid lines, (+, −1/2) dotted lines, (−, +1/2) dashed-dotted lines, and (−, −1/2) dashed lines.

analysed with respect to the changes in both proton and neutron configurations. Figs. 3 and 4 present the results of TRS calculations for the ground state band of ^{103}Pd and the ground state bands of ^{99,101}Pd, respectively. The calculations indicate that the lowest-lying positive-parity configurations in ^{99,101,103}Pd develop gradually a triaxial shape as the rotational frequency increases. At higher rotational frequency ($\hbar\omega \geqslant 0.5$ MeV), a distinct decrease in the quadrupole deformation is predicted by the calculations. This is consistent with a reduction in collectivity due to band terminations. The CSM calculations were performed with the deformations predicted by the TRS calculations for the given configurations. In Figs. 5 and 6, we plot quasiproton and quasineutron Routhians. The results show that the band-crossing frequencies are susceptible to the deformations, and the protons align first.

4 Discussion

As shown in Fig. 1, the ground state band in ^{103}Pd experiences a band crossing at $\hbar\omega\approx 0.46$ MeV. At higher frequencies of ∼0.60 MeV, the ^{103}Pd nucleus shows signs of a second alignment. This behaviour might be explained by the $g_{9/2}$ protons crossing followed at slightly higher frequency by the $g_{7/2}$ neutrons crossing, since the proton Fermi surface lies lower in the $g_{9/2}$ shell and has no Pauli Blocking effect [15]. Cranked shell model calculations have been performed in an attempt to understand the alignment properties observed in ^{103}Pd. In Fig. 5, the CSM calculations for the ground state band of ^{103}Pd predict the alignment of $g_{9/2}$ protons at $\hbar\omega\approx 0.48$ MeV, which reproduce the experimental observation well, whereas the predicted neutron alignments occur at higher frequencies, consistent with the crossing behaviours observed in this mass region [16]. In Fig. 3, the present TRS calculations indicate that ^{103}Pd has stable prolate shapes at the ground states, which can stay yrast up to the completion of the first $g_{9/2}$ proton-pair alignment in the vicinity of rotational frequency ∼0.40 MeV. Beyond the first band crossing, a distinct increase in the quadrupole deformation is predicted by the calculations, and the shape of ^{103}Pd changes from prolate to a large triaxial prolate ($\gamma \sim 12°$) deformation. This phenomenon can be ascribed to the $g_{9/2}$ protons aligning their angular momentum with the rotational axis and causing the minimum in the potential energy surface to move from $\gamma=0°$ to $\gamma\approx 12°$ at $\hbar\omega\approx 0.40$ MeV.

The TRS calculations for the ground state bands of ^{99,101}Pd are shown in Fig. 4. The prolate to triaxial shape transition in these structures is also predicted to occur at around $\hbar\omega \approx 0.40$ MeV. The results of CSM calculations as presented in Fig. 5 and Fig. 6 indicate that the $g_{9/2}$ proton alignments also occur at $\hbar\omega\approx 0.40$ MeV, whereas the predicted first neutron alignments occur at much higher frequencies ($\hbar\omega>0.50$ MeV). Therefore, we could conclude that the band crossings in the ground

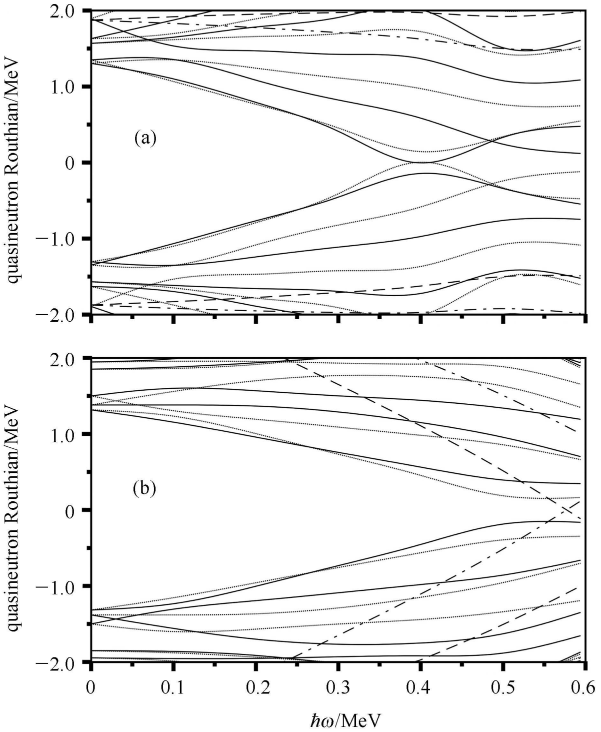

Fig. 6. Calculated quasiproton and quasineutron Routhians as a function of the rotational frequency in ^{99}Pd. In the calculations, the static deformation parameters are set as β_2=0.101, β_4=0.012, and γ=−0.4°. The parity and signature (π, α) of the Routhians are represented as follows: (+, +1/2) solid lines, (+, −1/2) dotted lines, (−, +1/2) dashed-dotted lines, and (−, −1/2) dashed lines.

state bands of ^{99,101}Pd can be ascribed to the $g_{9/2}$ proton-pair alignment. Thus, the phase transition observed in the yrast line of ^{101}Pd can be explained microscopically. After band crossing, the wave functions of the excited states predominantly consists of maximally aligned quasiparticle orbitals. Since the alignable orbitals reside low in the subshell, they have large components of angular momentum along the rotation axis. These quasiparticles might polarize the core to a small, but rigid quadrupole deformation, and thus collective rotational motion would develop. For the ^{99}Pd nucleus, the predicted nuclear shapes of the ground states change from a small prolate deformation to non-collective structure while increasing spin (see Fig. 4), which is in good agreement with the recent experimental observation [7]. This phenomenon can be interpreted as the band termination at high spins.

5 Conclusions

The E-GOS prescription was used to investigate the phase transition in the odd-A nuclei ^{99,101,103}Pd as a function of spin. The characteristics of E-GOS curves for the ground state bands of ^{101,103}Pd suggest that these nuclei undergo a clear evolution from vibrational to rotational structure with increasing angular momentum. For the ^{99}Pd nucleus, a vibrational character was inferred in the ground state band at low spins. Furthermore, we have applied the cranked shell model with nonaxial deformed Woods–Saxon potential to the analysis of shape evolution occurring in ^{99,101,103}Pd. Comparison with the experimental data provides a consistent picture of the shape evolution in these nuclei in terms of angular momentum. The predicted crossing frequency of the $g_{9/2}$ proton-pair alignment in ^{99,101,103}Pd is in good agreement with the experimental observations. The analyses of E-GOS curves and TRS calculations highlight the role of the low-Ω $g_{9/2}$ proton orbital in stabilising the quadruople deformation in ^{101,103}Pd.

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