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Spectroscopy of ^{112}Pd using heavy-ion–induced fission

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Abstract. High-spin states in ^{112}Pd were studied using prompt γ-ray spectroscopy with Gammasphere following heavy-ion–induced fission in the reaction ^{18}O + ^{208}Pb at 91 MeV. A new 8^+ level at 2638 keV was discovered with transitions connecting it to the yrast band and the quasi-gamma band. The three, now established, closely spaced 8^+ states indicate a mixing between the ground-state band, s-band, and quasi-gamma band. Several high-spin structures with likely negative parity have been extended to higher spin and it is proposed that they are based on the $\nu h_{11/2}(g_{7/2}d_{5/2})$ and $\nu h_{11/2}(s_{1/2}d_{3/2})$ configurations.

PACS. 23.20.Lv Gamma transitions and level energies – 25.70.Jj Fusion and fusion-fission reactions – 21.60.-n Nuclear-structure models and methods – 27.60.+j $90 \leq A \leq 149$

1 Introduction

The neutron-rich nuclei in the mass region around $A =$ 100-110 exhibit a variety of structural phenomena, which include shape coexistence, strong octupole correlations, the existence of low-lying intruder states, signs of triaxiality and γ-softness as well as vibrational excitations (see, *e.g.*, ref. [1] and references therein). The detailed study of these nuclei has only recently become feasible using the fission process for their population and the resolving power of large multi-detector arrays for sensitive γ-ray spectroscopy (see ref. [2] for a recent review).

The level structure of neutron-rich Pd isotopes has been investigated in recent years using β-delayed γ-ray spectroscopy [3–5] as well as prompt γ-ray spectroscopy following spontaneous fission [6,7] and heavy-ion–induced fission [8–10]. These studies have shown that the low-spin level schemes of the neutron-rich Pd isotopes around $A \approx 110$ exhibit characteristic features of a nuclear potential that is soft with respect to the γ-deformation. In particular, a low-lying band head of the first excited $K^\pi = 2^+$ band (quasi-γ band) and a ratio of the energies of the first excited 4^+ state to the first excited 2^+ state of about 2.5. Indeed, Nilsson-Strutinsky [1] calculations show very shallow minima with respect to the γ-deformation with some dependence of the potential in the direction of the γ degree of freedom.

In this article we report new results of prompt γ-ray spectroscopy in ^{112}Pd using heavy-ion–induced fission. The known level scheme was significantly extended and new features were established. These include an interaction between the ground-state band, s-band, and quasi-γ band as well as the discovery of a strongly coupled band possibly based on a triaxial shape.

2 Experiment

Neutron-rich nuclei in the $A \approx 110$ region were produced via beam-induced fission following the reaction ^{18}O + ^{208}Pb. The 91 MeV ^{18}O beam, delivered by the 88-Inch Cyclotron of the Lawrence Berkeley National Laboratory, was incident on a 45 mg/cm^2 isotopically enriched ^{208}Pb target in which all fission fragments recoiling in forward direction were stopped within a time of about 1 ps. About 2.9×10^9 four- and higher-fold γ-ray coincidences were detected by the Gammasphere array [11], comprising of 100 large Compton-suppressed Ge detectors. In the off-line analysis the data was unfolded into triple coincidences which were sorted into a levit8r [12] cube. Gamma rays of even-even Pd nuclei with masses from $A = 108$ to $A = 116$ were observed in the data set, with a maximum yield for $A = 112$. Results with respect to various odd-A nuclei from this experiment have been published in refs. [9,13].

3 Results

The level scheme of ^{112}Pd was extended using the levit8r program [12] by establishing new transitions in coinci-

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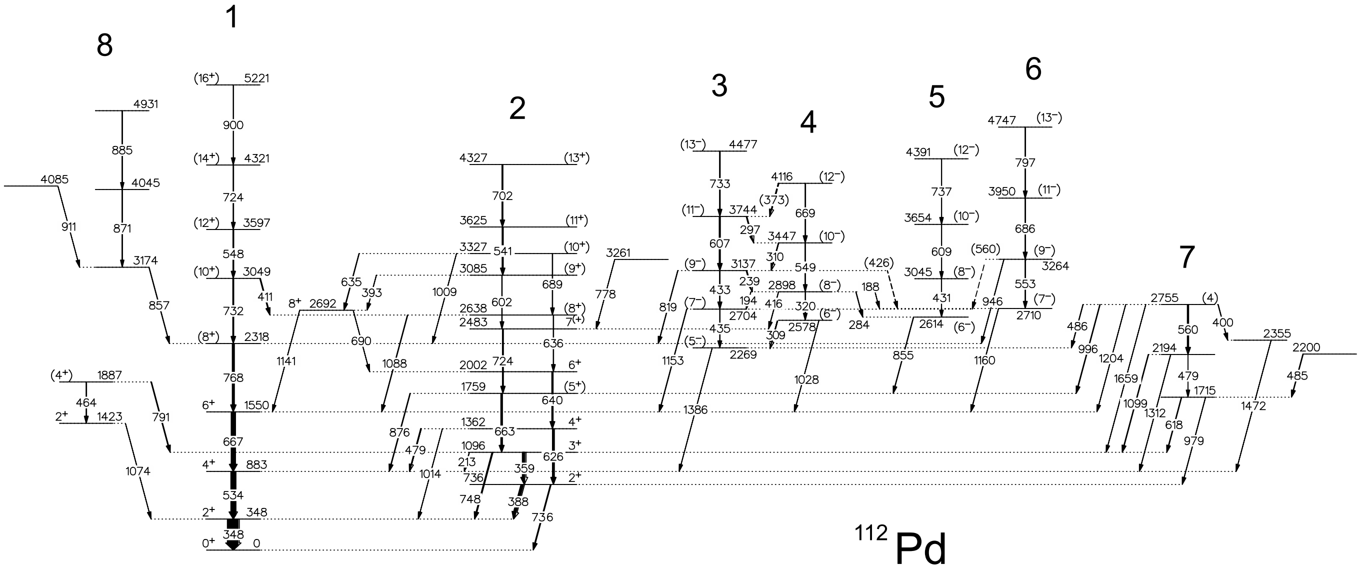

Fig. 1. Level scheme of ^{112}Pd obtained in the present work.

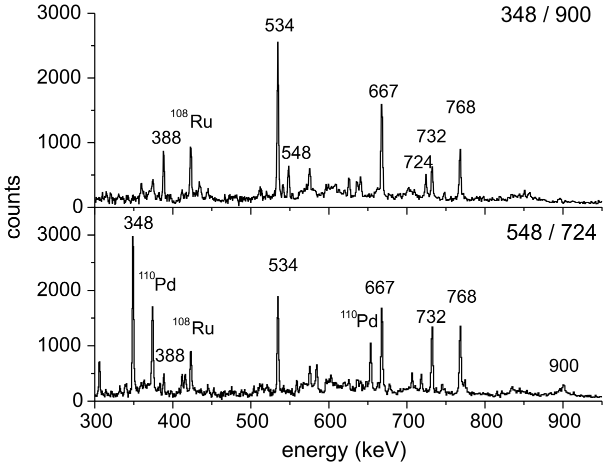

Fig. 2. Double-gated spectra that establish the 900 keV transition on top of the yrast band (band 1). The bottom spectrum shows the 900 keV transition in a gate on the 548 keV and 724 keV transitions in the yrast band. The top spectrum shows the transitions of the yrast band when a gate is placed on the 900 keV transition together with the 348 keV ground state transition. The transitions used for the gates are indicated at the top right corner of each panel. The ^{110}Pd transitions in the bottom spectrum are due to a gate contamination. Transitions in ^{108}Ru are due to the fact that ^{108}Ru is the complementary fragment to ^{112}Pd with the strongest population.

dence with the known transitions in ^{112}Pd. The coincidence relationships for a number of gating conditions as well as intensity relations were used to firmly establish the new transitions. Spin assignments are tentative due to the lack of directional alignment of the fragments with respect to the beam axis. The level scheme obtained in this work is shown in fig. 1.

3.1 Yrast and quasi-gamma band

The yrast band has been extended by a 900 keV transition to spin 16^+. Figure 2 shows double-gated spectra that clearly establish this transition at the proposed position in the level scheme. This transition already exhibits a visible Doppler lineshape indicating a short level lifetime. This indicates that even higher-spin states were populated in this experiment but are not visible due to their broad Doppler lineshapes. The 900 keV transition is in disagreement with the 793 keV transition reported in ref. [10]. We do not see any evidence for a 793 keV transition in coincidence with the 724 keV $(14^+)\rightarrow(12^+)$ transition in band 1.

Previous to the present work, two different, mutually exclusive, assignments have been made for the 8^+ member of the quasi-gamma band [7,10]. Reference [7] reports an 8^+ level at 2691 keV attributed to the quasi-gamma band on the basis of a cascade 689–640–625 keV to the 2^+ band head of the quasi-gamma band. Reference [10] reports an 8^+ level at 2638 keV attributed to the quasi-gamma band on the basis of a cascade 636–620–645 keV to the 2^+ state, which we were unable to confirm. However, we were able to clearly establish 8^+ levels at 2638 keV and 2692 keV and have thus solved the previous inconsistencies. Figure 3 shows double-gated spectra that establish these states in the level scheme. The spectra on the left establish a 411–636–640–626 keV cascade from the 10^+ yrast state at 3049 keV through the 2638 keV 8^+ state to the 6^+, 4^+ and 2^+ states in the quasi-gamma band. The spectrum at the top right of fig. 3 establishes a 393–690–640–626 keV cascade from the 9^+ member of the quasi-gamma band to the 2692 keV 8^+ state and to the 6^+, 4^+ and 2^+ members of the quasi-gamma band. The lower right spectrum confirms the additional decay of the 2692 keV level to the yrast band. Both of these 8^+

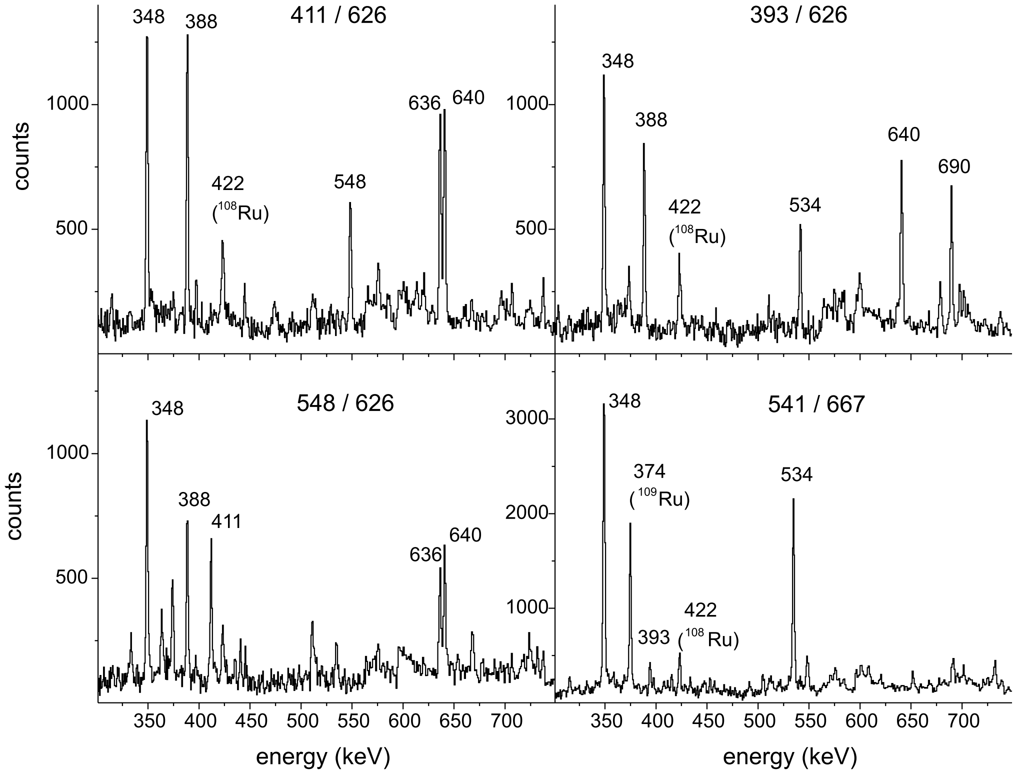

Fig. 3. Double-gated spectra that clearly show the coincidence of the 411 keV and 393 keV transitions with transitions in the yrast band (band 1) and the quasi-gamma band (band 2). The transitions used for the gates are indicated at the top of each panel.

states are also populated from the newly established 10^+ member of the quasi-gamma band at 3327 keV.

Two additional levels have been established at 3625 keV and 4327 keV, which have been tentatively assigned as the 11^+ and 13^+ members of the quasi-gamma band, respectively. Additionally a new 876 keV transition from the 5^+ member of the quasi-gamma band to the 4^+ member of the yrast band has been established.

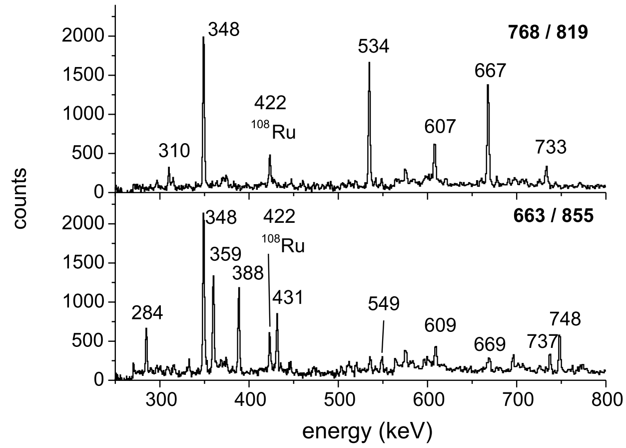

Fig. 4. Top: Double-gated spectrum with gates on the 768 keV (band 1) and 819 keV (band 3 to band 1) transitions. Transitions in bands 3 and 4 are visible. Bottom: Double-gated spectrum with gates on the 663 keV (band 2) and 855 keV (band 5 to band 2) transitions.

3.2 New high-spin structures

The band structures based on top of the 5^- level at 2269 keV and the 6^- level at 2578 keV [7,10] (bands 3 and 4 in fig. 1) were extended to spins (13^-) and (12^-), respectively. Additionally several cross-over transition (194, 239, 310, 297, (373) keV) (see top of fig. 4) between these bands were established, lending additional support to the assumption of $E2$ sequences in each of the bands. Under the assumption that the parity of both bands is, as suggested in refs. [7,10], indeed the same the cross-over transitions are of $M1$ character and the $B(M1)/B(E2)$ ratio is about 0.5 $\mu_N^2/(eb)^2$.

A new cascade (band 5) of three transitions (431 keV, 609 keV, and 737 keV), presumably of $E2$ character, built on a new 2614 keV level was discovered. This band decays to the 5^+ level in the quasi-γ band by a 855 keV transition. Two new transitions (686 keV and 797 keV) were observed on top of the known [7] 553 keV transition in band 6. The 2710 keV level in band 6 decays via a 1160 keV transition to the 6^+ yrast level. The next level in this band, at 3264 keV, decays via a 946 keV transition to the 8^+ yrast level.

Transitions with energies of 284 keV (see bottom of fig. 4) and 188 keV were established between the (8^-) level of band 4 and the respective band heads of bands 5 and 6, suggesting that there is significant mixing between

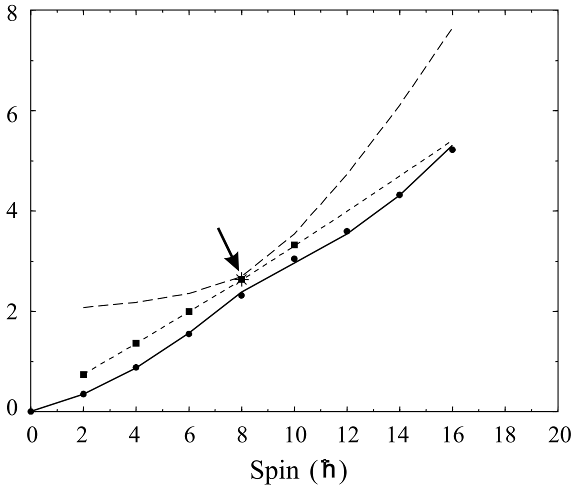

Fig. 5. Calculated yrast band (solid line), quasi-gamma band (short-dashed line) and yrare band (dashed line) in ^{112}Pd after mixing of the ground state band, *s*-band and quasi-gamma band. The experimentally known levels for the yrast band (filled circle) the *s*-band (asterisc) and quasi-gamma band (filled square) are shown for comparison. The asterix for the 8^+ level of the *s*-band is indicated by an arrow since it poorly visible. (See text for details of the mixing calculations.)

the lowest observed levels in the two new structures and the (6^-) and (7^-) levels in bands 3 and 4, respectively. Thus we tentatively assign the spins (6^-) and (7^-) to the 2614 keV and 2710 keV in bands 5 and 6, respectively. The 188 keV transition was already observed in ref. [10].

The levels at 3174 keV, 4045 keV, and 4931 keV (structure 8) observed in ref. [10] are confirmed and an additional level at 4085 keV was observed.

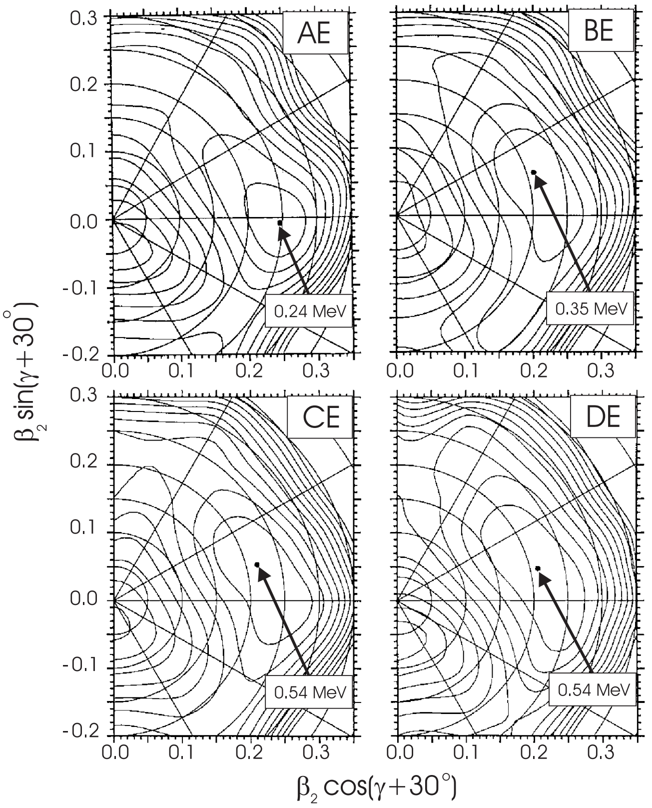

Fig. 6. Total routhian surface calculations [15] for the two signatures of the $\nu h_{11/2}(s_{1/2}d_{3/2})$ (AE, BE) and the $\nu h_{11/2}(d_{5/2}g_{7/2})$ (CE, DE) configurations at a rotational frequency of $\hbar\omega = 0.248$ MeV. The energy of the minimum is indicated and it can be clearly seen that there is no signature splitting for the configurations CE and DE while a 110 keV signature splitting is predicted between AE and BE.

4 Discussion

The observation of the three close-lying 8^+ states at 2318 keV, 2638 keV, and 2692 keV, together with the various cross-over transitions from and to the yrast and quasi-gamma band, indicate a three-band mixing between the quasi-gamma band, the ground state band and the $\nu h_{11/2}$ *s*-band, which crosses the ground state band just around spin $8\hbar$. The energies and branching ratios can be consistently described by three-band mixing calculations. Since neither unperturbed nor perturbed absolute $B(E2)$ values are known there are too many free parameters to firmly establish mixing amplitudes or the correct interaction strength. Figure 5 shows, as an example, the resulting energies of three-band mixing calculations in which interaction strengths of 150 keV, 10 keV, and 10 keV were used between the *s*-band (s.b.) and the ground state band (g.s.b.), the s.b. and the quasi-gamma band (q.g.b.), and the g.s.b. and q.g.b., respectively. The unperturbed energies were determined by fitting an anharmonic vibrator formula [14] to the states up to 6^+ for the ground state and quasi-gamma band and states above the 10^+ for the *s*-band. These interactions reproduce the experimental energies to better than 3% and give reasonable results for the branching ratios, although only assumptions could be made for the unperturbed absolute $B(E2)$ values. The results shown in fig. 5 are not unique due to the many parameters which are experimentally not known. However, the calculations lend strong support to the three-band mixing description. The calculations shown in fig. 5 indicate that the yrast 8^+ level at 2318 keV contains about 70% of g.s.b wave-functions and about 30% of the s.b. wave function, while the q.g.b. contribution is only about 1%. The 2638 keV 8^+ level contains about 65% of the q.g.b. wave-function and a 29% g.s.b. contribution. Therefore, we have assigned this level to the quasi-gamma-band. Finally, the 2692 keV level contains about 90% s.b. wave-function.

The strongly coupled bands 3 and 4 are apparently signature partners with almost no signature splitting. The negative parity assignment is based on the level systematics of neighboring nuclei and is most reasonable when all the decay properties of the states are taken into account. Total routhian surface (TRS) calculations based on a Woods-Saxon nuclear potential [15] suggest a $\nu h_{11/2}(g_{7/2}d_{5/2})$ configuration for this band. The TRS for the two signatures (CE and DE) of this configuration is shown in the bottom of fig. 6 for a rotational frequency of $\hbar\omega = 0.248$ MeV. The minimum for this configuration occurs at a deformation of $\beta = 0.24$ with significant triaxiality. The TRS calculations show that there is no signature splitting for this configuration, consistent with the experimental observation. Additionally the experimental $B(M1)/B(E2)$ ratio of 0.5 $\mu_N^2/(eb)^2$ is consistent with this assignment.

While band 5 is almost identical to band 3 within a few keV, band 6 deviates increasingly from band 4 with increasing spin. Although we have not observed any cross-over transitions between bands 5 and 6, we suggest that they are also signature partners with an increasing signature splitting at higher rotational frequencies. The signature splitting at the band heads is about 100 keV. The TRS calculations suggest that this configuration is most likely based on the $\nu h_{11/2}(s_{1/2}d_{3/2})$ configuration for which such a signature splitting is expected (see top of fig. 6).

If the spin and parity assignments are indeed correct there remains one open question, for which the current scenario does not provide an answer. The (6^-) levels in bands 4 and 5 are only separated by 36 keV and the (7^-) levels in bands 3 and 6 are as close as 6 keV. It is not clear to us why there does not seem to be a significant interaction between these configurations. However, different spin and parity assignments seem very unlikely. It is interesting to note that a similar situation exists for the 0^+ levels at 1124 and 1140 keV as well as the 2^+ levels at 1403 and 1423 keV [4,5].

5 Summary

In summary, we have extended the level scheme of ^{112}Pd by means of prompt γ-ray spectroscopy following heavy-ion–induced fission. We have established a three-band mixing between the ground-state band, the $\nu h_{11/2}$ s-band and the quasi gamma-band around spin 8 $\hbar$. The small interaction strength between the quasi-gamma band and the other two bands ($\approx$ 10 keV) indicates that the mixing is simply due to an accidental degeneracy of the 8^+ levels. We have also extended the previously observed negative parity bands and have proposed that these bands are most likely based on the $\nu h_{11/2}(g_{7/2}d_{5/2})$ and $\nu h_{11/2}(s_{1/2}d_{3/2})$ configurations, respectively. TRS calculations indicate that these configurations are most likely leading to a triaxial shape of the core.

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