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Non-yrast states in ^{101}Pd and their rotational interpretation

Rakesh Popli, F. A. Rickey, and P. C. Simms
Tandem Accelerator Laboratory, Purdue University, West Lafayette, Indiana 47907
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Several non-yrast states of both parities in ^{101}Pd have been observed using three-detector γ-γ coincidence measurements following the reaction ^{92}Zr(^{12}C,3n)^{101}Pd. Energy levels, γ-ray mixing ratios, and branching ratios are deduced from the data and compared with the results of a rotational model calculation. Five of the newly discovered states are identified as non-yrast members of rotational bands based on the $5/2^+$ and $11/2^-$ states.

[NUCLEAR STRUCTURE ^{92}Zr(^{12}C, 3n)^{101}Pd at 48 MeV; measured $I_\gamma(\theta)$, 3-detector γ-γ coin, γ-γ DCOQ. ^{101}Pd deduced levels, J, π, γ mixing ratios. Rotational model calculations, Coriolis, recoil, calculated levels, mixing ratios, branching ratios, half-lives.]

We have previously reported the observation of collective excitations in ^{101}Pd populated using (HI, xn) reactions.[1] These studies provided information on three collective $\Delta I = 2$ bands built on the lowest $\frac{5}{2}^+$, $\frac{7}{2}^+$, and $\frac{11}{2}^-$ states, respectively. It has been demonstrated[2] that the energy levels in these bands are reproduced by a rotational model using a small deformation and a variable moment of inertia. The calculation shows that the observed states in the bands have a predominantly rotation-aligned configuration, i.e., the particle angular momentum $j=\frac{5}{2}$, $\frac{7}{2}$, or $\frac{11}{2}$ is aligned with $R = 0, 2, 4, \ldots$ units of core rotation. Less aligned members of the particle-core multiplets, which would provide a more stringent test of the model, were not observed in the previous work. Since then, the three-detector coincidence technique[3] has been developed, and it has become possible to study many states which are weakly populated in (HI, xn) reactions.

The present paper reports several weakly populated states observed in ^{101}Pd using the reaction ^{92}Zr(^{12}C, 3$n\gamma$), and their configurations as inferred from the rotational calculation. We have also performed calculations of the transition properties for states in this nucleus. In this way, we have been able to identify five non-yrast rotational states of both parities which are one step away from rotation alignment. We also find that several other non-yrast states observed in ^{101}Pd do not have a one-quasiparticle-plus-rotor character.

The details of the experimental procedures and data analysis,[1,3] and of the Coriolis calculation of energies, wave functions,[2] and transition properties[4] have already been described. The ^{12}C beam at 48 MeV was obtained from the Purdue Tandem Van de Graaff. γ-ray angular distributions and three-detector γ-γ coincidence measurements were performed. Directional correlation of radiation from oriented nuclei with respect to quadrupole transitions (DCOQ) analysis[5] was used to determine the multipolarities and mixing ratios of γ rays which are not resolved cleanly in the singles spectra.

Figure 1 shows the up-to-date decay scheme of ^{101}Pd seen in (HI, xn) reactions. The solid arrows indicate stretched $E2$ transitions, and the widths of arrows are proportional to the respective γ-ray transition intensities. The three main bands based on $\frac{5}{2}^+$, $\frac{7}{2}^+$, and $\frac{11}{2}^-$ states and some of the interband transitions between them have already been reported.[1] Ten states, marked by asterisks on the level scheme, are reported here for the first time. The spin parities of most of these states were determined unambiguously from the angular distribution and DCOQ analyses. Additional systematic arguments had to be used for the states whose spins are shown in parentheses. The decay scheme also contains new transitions between

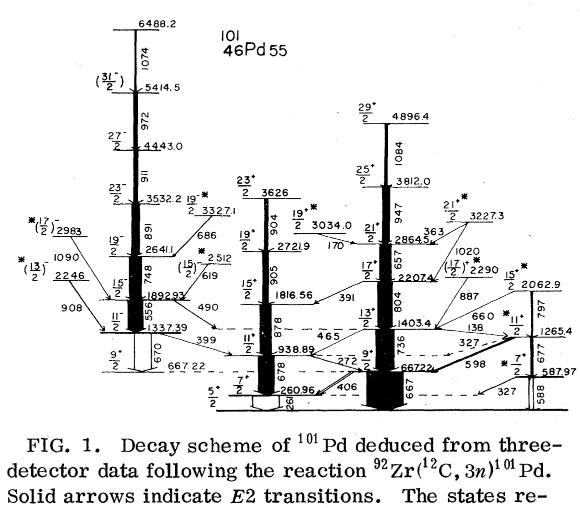

FIG. 1. Decay scheme of ^{101}Pd deduced from three-detector data following the reaction ^{92}Zr(^{12}C, 3n)^{101}Pd. Solid arrows indicate $E2$ transitions. The states reported for the first time are marked with asterisks.

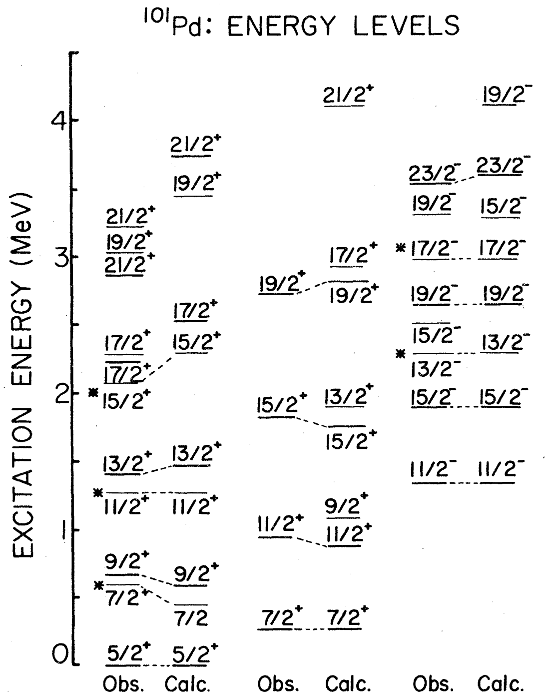

FIG. 2. Comparison of experimental and calculated energy levels in ^{101}Pd. The non-yrast states adequately described by the rotational calculation are marked with asterisks.

previously observed states. Thus branching ratios are now available to provide a sensitive test of the nuclear structure.

The experimental results are compared with a particle-plus-rotor model which uses a slightly deformed, axially symmetric rotor with a variable moment of inertia. The Hamiltonian is diagonalized in a basis consisting of strong-coupled Nilsson states. The only parts of the Hamiltonian which give off-diagonal matrix elements in this basis are the Coriolis and recoil terms, connecting $\Delta K = \pm 1$ and $\Delta K = 0$ states, respectively. The calculation of energies and wave functions is the same as that of Smith and Rickey,[2] except that an improved treatment of the recoil term suggested by Rekstad *et al.*[6] is included. This treatment explicitly includes the two-body parts of the recoil operator (j^2-Ω^2) and thereby takes into account the blocking effect. Both the Coriolis and recoil matrix elements had to be attenuated to 75% to reproduce the experimental results. Thus, a recent suggestion[7] that the inclusion of the recoil term would make a Coriolis attenuation unnecessary does not seem to be true here.

The parameters used are the same as in Ref. 2. The deformation of the core is $\delta = 0.12$. The neutron Fermi surface has been placed just below the $\frac{1}{2}^+[420]$ Nilsson state of $g_{7/2}$ parentage, corresponding to the number of neutrons (55), and the pairing gap used is 1.1 MeV. The basis for the positive-parity calculation includes all the Nilsson states of $s_{1/2}$, $g_{7/2}$, and $d_{5/2}$ parentage, whereas the negative-parity calculation has used all six Nilsson states arising from the unique-parity $h_{11/2}$ orbital.

Figure 2 shows a comparison of the observed and calculated energy levels of various states in ^{101}Pd. The calculated energies of the $\frac{7}{2}^+$ and $\frac{11}{2}^-$ bandheads have been adjusted by approximately 150 and 300 keV, respectively, to coincide with the experimental values. Such a shift is not important since our purpose here is not to reproduce exactly the bandhead energies, but to investigate the rotation-particle coupling within each band. The agreement between observed and calculated results is seen to be excellent. The calculation correctly predicts not only the energy levels in the three main bands but also energies of the non-yrast states marked with asterisks in Fig. 2. The wave functions of the non-yrast $\frac{7}{2}^+$, $\frac{11}{2}^+$, and $\frac{15}{2}^+$ states show that they have predominant $d_{5/2}$ parentage. Thus they are included in Fig. 2 as members of the $\frac{5}{2}^+$ band. Similarly the $\frac{13}{2}^-$ and $\frac{17}{2}^-$ states have been associated with the $\frac{11}{2}^-$ band. The R components indicate that whereas the yrast states in the three bands could be considered as predominantly rotation aligned, the non-yrast states of both parities mentioned above are one step away from rotation alignment, i.e., the predominant R components satisfy the relation

$$I = R + j - 1,$$

where I, R, and j are the quantum numbers corresponding to the angular momenta of the nucleus, the core rotation, and the quasiparticle, respectively.

The systematic difference between the three bands observed in ^{101}Pd can be understood by considering the position of the Fermi surface for the nucleus. When the Fermi surface is near or below Nilsson states with $\Omega \ll \langle j \rangle$, the nuclear states with maximum alignment have less energy than the corresponding states which are one step away from alignment. The energy order is reversed when the Fermi surface is near Nilsson states with $\Omega \sim \langle j \rangle$; the aligned states have more energy than the less aligned states.

The Fermi surface for ^{101}Pd lies well below the $\Omega = \frac{1}{2}$ state of $h_{11/2}$ parentage. Therefore the less-aligned $\frac{13}{2}^-$ and $\frac{17}{2}^-$ states in the $\frac{11}{2}^-$ band have higher energies than the corresponding aligned $\frac{15}{2}^-$ and $\frac{19}{2}^-$ states. A similar pattern would be expected in the $\frac{7}{2}^+$ band. The less-aligned states were not observed in the experiment; hence these states are probably above the yrast line, in agreement

TABLE I. Transition properties in ^{101}Pd calculated using Coriolis-mixed wave functions and compared with experimental results.

I_i^π	I_f^π	E_γ (keV)	Mixing ratio[a] obs	Mixing ratio[a] calc	Branching ratios obs	Branching ratios calc	Predicted half-life (psec)
$\frac{7}{2}^+$	$\frac{5}{2}^+$	261	$-0.01 \leq \delta \leq 0.03$	0.03			653
$\frac{9}{2}^+$	$\frac{7}{2}^+$	406	$0 \leq \delta \leq 0.1$	−0.01	0.07	0.30	5.1
	$\frac{5}{2}^+$	667			0.93	0.70	
$\frac{11}{2}^+$	$\frac{9}{2}^+$	272	$0.05 \leq \delta \leq 0.13$	0.01	0.06	0.01	5.1
	$\frac{7}{2}^+$	678			0.94	0.99	
$\frac{13}{2}^+$	$\frac{11}{2}^+$	465	$-0.08 \leq \delta \leq 0$	0.01	0.04	0.14	2.6
	$\frac{9}{2}^+$	736			0.94	0.76	
	$(\frac{11}{2}^+)_2$	138		−0.02	0.02	0.10	
$\frac{15}{2}^+$	$\frac{13}{2}^+$	414		−0.03	0.00	0.01	1.3
	$\frac{11}{2}^+$	878			1.00	0.99	
$\frac{17}{2}^+$	$\frac{15}{2}^+$	391	$-0.06 \leq \delta \leq 0$	0.03	0.07	0.05	1.7
	$\frac{13}{2}^+$	804			0.93	0.86	
	$(\frac{15}{2}^+)_2$	145		−0.01	0.00	0.09	
$\frac{19}{2}^+$	$\frac{17}{2}^+$	515		0.02	0.00	0.01	1.1
	$\frac{15}{2}^+$	905			1.00	0.99	
$(\frac{7}{2}^+)_2$	$\frac{7}{2}^+$	327	$-0.03 \leq \delta \leq 0.1$	0.03	0.25	0.19	6.8
	$\frac{5}{2}^+$	588	$-1.4 \leq \delta \leq -0.8$	−1.0	0.75	0.81	
$(\frac{11}{2}^+)_2$	$\frac{11}{2}^+$	327		0.01	0.07	0.08	2.6
	$\frac{9}{2}^+$	598	$-0.4 \leq \delta \leq -0.25$	−0.44	0.36	0.48	
	$(\frac{7}{2}^+)_2$	677			0.57	0.44	
$(\frac{15}{2}^+)_2$	$\frac{15}{2}^+$	247		0.01	0.00	0.02	1.3
	$\frac{13}{2}^+$	660		−0.33	0.12	0.33	
	$(\frac{11}{2}^+)_2$	797			0.88	0.65	
$(\frac{19}{2}^+)_2$[b]	$\frac{21}{2}^+$	170		−0.01	1.00	0.05	0.5
	$\frac{17}{2}^+$	827		−0.31	0.00	0.19	
	$(\frac{17}{2}^+)_2$	744		−0.12	0.00	0.17	
	$(\frac{15}{2}^+)_2$	970			0.00	0.59	
$\frac{11}{2}^-$	$\frac{11}{2}^+$	399			0.06	0.04	240
	$\frac{9}{2}^+$	670			0.94	0.96	
$\frac{13}{2}^-$	$\frac{15}{2}^-$	353		−0.05	0.00	0.12	0.2
	$\frac{11}{2}^-$	908		0.20	1.00	0.88	
$\frac{15}{2}^-$	$\frac{11}{2}^-$	556			0.94	0.97	12.8
	$\frac{13}{2}^+$	490			0.06	0.03	
$\frac{17}{2}^-$	$\frac{19}{2}^-$	342		0.19	0.00	0.10	0.2
	$\frac{15}{2}^-$	1090		−0.03	1.00	0.85	
	$\frac{13}{2}^-$	736			0.00	0.05	
$\frac{19}{2}^-$	$\frac{15}{2}^-$	748			1.00	1.00	2.8
	$\frac{17}{2}^+$	434			0.00	0.00	

[a] The sign convention of Krane and Steffen has been used.
[b] Agreement between observed and calculated results is not good. Discussed in text.

with the general characteristic of the model.

The Fermi surface lies between the $\Omega = \frac{3}{2}$ and $\Omega = \frac{5}{2}$ Nilsson states arising from the $d_{5/2}$ orbital. Thus the less aligned $\frac{7}{2}^+$ and $\frac{11}{2}^+$ states are predicted to have lower energies than the $\frac{9}{2}^+$ and $\frac{13}{2}^+$ states in the $\frac{5}{2}^+$ band, as observed in the experiments.

The interpretation of the higher states in the $\frac{5}{2}^+$ band is more complicated. There is a break in the band near the $\frac{17}{2}^+$ state because the energy of the 657-keV transition is smaller than the next lower transition. The calculated energies of the $\frac{17}{2}^+$ and $\frac{21}{2}^+$ states in the band are considerably higher than those of the observed yrast states with these angular momenta. This compression of energy and the observation of pairs of $\frac{17}{2}^+$ and $\frac{21}{2}^+$ states suggest a band crossing, probably between one-quasiparticle and three-quasiparticle bands. Such a band crossing is consistent with the systematics of this region. In the neighboring even-even nucleus ^{102}Pd (and in other Pd and Cd nuclei), 6^+ and 8^+ bandheads have been observed at excitation energies similar to these $\frac{17}{2}^+$ and $\frac{21}{2}^+$ states and interpreted as Coriolis-mixed two-quasiparticle states.[5] The pairs of states at the band crossing probably contain mixtures of three-quasiparticle and one-quasiparticle components. A detailed interpretation of the states is not possible, since three-quasiparticle components were not included in the calculation.

The other three new states ($\frac{19}{2}^+$ at 3034 keV, $\frac{15}{2}^-$ at 2512 keV, and $\frac{19}{2}^-$ at 3327 keV) do not fit into the one-quasiparticle interpretation. The $\frac{19}{2}^+$ state has an energy similar to a calculated state, but it does not have appropriate transition properties, as will be discussed below. The $\frac{15}{2}^-$ and $\frac{19}{2}^-$ states have much less energy than calculated states with the same spins and parities.

The calculated transition properties in ^{101}Pd, including $M1$, $E2$, and $E1$ modes, are compared with the experimental results in Table I. There are many interesting patterns of branching among the states, which are reproduced by the calculation. The second $\frac{15}{2}^+$, $\frac{11}{2}^+$, and $\frac{7}{2}^+$ states are connected by $E2$ transitions, and less intense transitions to other states are also observed. These weaker branchings favor the yrast states in the $\frac{5}{2}^+$ band over those in the $\frac{7}{2}^+$ band. There are weak interband transitions between the two main positive-parity bands, indicating some mixing of the $g_{7/2}$ and $d_{5/2}$ single-particle configurations. There are also weak $E1$ transitions connecting the rotation-aligned negative-parity states to the $\frac{5}{2}^+$ and $\frac{7}{2}^+$ bands. The nonaligned $\frac{13}{2}^-$ and $\frac{17}{2}^-$ states decay by $\Delta I = -1$ transitions to $\frac{11}{2}^-$ and $\frac{15}{2}^-$ states, and not by $\Delta I = +1$ transitions to states having the same amount of core rotation as the respective initial states. Although less aligned states in the $\frac{5}{2}^+$ band are connected by $E2$ transitions, the corresponding transition between the less aligned $\frac{17}{2}^-$ and $\frac{13}{2}^-$ states is not observed. All these features are reproduced by the calculation.

The $E2/M1$ mixing ratios of all the interband transitions between the main positive-parity bands are observed to be small, whereas those for the transitions depopulating the positive-parity nonaligned states are of considerable magnitudes and negative sign. These results are in agreement with the calculations. It should be emphasized that here we are dealing with a complex situation where there is substantial mixing not only between different Nilsson states arising from the same shell-model orbital, but also between different orbitals, $d_{5/2}$ and $g_{7/2}$. The contributions to an $M1$ amplitude from various pairs of Nilsson states come in both signs, resulting in large cancellations. Thus, the overall agreement between the predicted and observed values of the mixing ratios and branching ratios is remarkable.

The calculation predicts relatively long half-lives for the yrast $\frac{7}{2}^+$ and $\frac{11}{2}^-$ states (0.65 and 0.25 nsec, respectively). It would be interesting to measure these half-lives experimentally.

As mentioned previously, the transition properties of the second $\frac{19}{2}^+$ state at 3034 keV do not support assignment of this state as a member of the $\frac{5}{2}^+$ band, although the energy of the state is consistent with the calculation. It is seen in Table I that the observed transition should be the weakest of four possible transitions if this state were a non-yrast member of the $\frac{5}{2}^+$ band. This illustrates the advantage of including transition properties to improve the reliability of nuclear structure analysis. Since the $\frac{19}{2}^+$ state is in the energy region of the band crossing, it probably has strong three-quasiparticle components.

The second $\frac{15}{2}^-$ and $\frac{19}{2}^-$ states, which have much less energy than the corresponding calculated states, have the spin, parity, and energy expected for an $h_{11/2}$ quasiparticle coupled to the second 2^+ and 4^+ states in the neighboring even-even nucleus. However, if this interpretation were correct, an $E2$ transition between them would be expected and none was observed.

In conclusion, we have observed several non-yrast states in ^{101}Pd, weakly populated in (HI, xn) reactions. Three of these, the second $\frac{7}{2}^+$, $\frac{11}{2}^+$, and $\frac{15}{2}^+$ states, have been identified by their energies and transition properties as non-yrast members of the $\frac{5}{2}^+$ band. A similar interpretation applies to the $\frac{13}{2}^-$ and $\frac{17}{2}^-$ members of the $h_{11/2}$ band. These states further illustrate the appropriateness of using a slightly deformed symmetric rotor to interpret transitional nuclei.

[1]P. C. Simms, G. J. Smith, F. A. Rickey, J. A. Grau, J. R. Tesmer, and R. M. Steffen, Phys. Rev. C 9, 684 (1974).

[2]Hastings A. Smith, Jr. and F. A. Rickey, Phys. Rev. C 14, 1946 (1976).

[3]F. A. Rickey, J. A. Grau, L. E. Samuelson, and P. C. Simms, Phys. Rev. C 15, 1530 (1977).

[4]Rakesh Popli, J. A. Grau, S. I. Popik, L. E. Samuelson, F. A. Rickey, and P. C. Simms, Phys. Rev. C 20, 1350 (1979).

[5]J. A. Grau, L. E. Samuelson, F. A. Rickey, P. C. Simms, and G. J. Smith, Phys. Rev. C 14, 2297 (1976).

[6]J. Rekstad, T. Engeland, and E. Osnes, Nucl. Phys. A330, 367 (1979); E. Osnes, J. Rekstad, and O. K. Gjotterud, Nucl. Phys. A253, 45 (1975).

[7]A. J. Kreiner, Phys. Rev. Lett. 42, 829 (1979).