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$\nu h_{11/2}$ bands in ^{113}Pd and ^{115}Pd

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Two cascades of γ rays were discovered in ^{113}Pd and ^{115}Pd in prompt γ-ray spectroscopy with Gammasphere following heavy-ion induced fission in the reaction $^{18}\mathrm{O}+^{208}\mathrm{Pb}$ at 91 MeV. Comparison with recently observed band structures in ^{109}Pd and ^{111}Pd as well as blocking arguments lead to an interpretation of these bands as $\nu h_{11/2}$ bands. This discovery, together with cranked Woods-Saxon and total Routhian surface calculations, indicates that increased rotational frequency stabilizes a prolate but still γ-soft shape in the neutron-rich, even-even Pd isotopes up to ^{116}Pd, which exhibit very γ-soft nuclear potentials in their respective ground states. [S0556-2813(99)50209-4]

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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, 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 multidetector arrays for sensitive γ-ray spectroscopy (see Ref. [2] for a recent review).

A few years ago backbends of the yrast bands in ^{112,114,116}Pd were observed and interpreted as the crossing of the ground state band by an aligned $\pi g_{9/2}$ pair [3]. This assignment was based on the prediction [4] of a prolate-to-oblate transition at ^{111}Pd together with cranked Nilsson-Strutinsky calculations [3] for oblate deformations. This interpretation was recently contested by Kutsarova *et al.* [5] after the discovery of $\Delta I = 2$ bands based on $\frac{11}{2}^-$ states in ^{109}Pd and ^{111}Pd. These bands exhibit a large signature splitting together with an initial alignment of about $5.5\hbar$ while they do not show the alignment gain around $\hbar\omega = 0.35$ MeV that is observed in the even-even neighbors. In particular this blocking of the backbend in the odd-A nuclei provides clear evidence that the ground state bands of the even-even nuclei ^{110}Pd and ^{112}Pd are crossed by an aligned $(\nu h_{11/2})^2$ configuration. Kutsarova *et al.* further argued that the apparent large signature splitting is another indication that these nuclei exhibit prolate deformation.

At the same time the low-spin level schemes of the neutron-rich Pd isotopes around $A = 110$ exhibit characteristic features of a γ-soft nuclear potential with a low-lying bandhead of the first excited $K = 2$ band (quasigamma 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 of the nucleus. Their potential is γ soft but shows some dependence on the potential in the direction of the γ-degree of freedom. Such a description is supported by the low-spin level structure of the neutron-rich even-even Pd isotopes. In particular the energy of the 2_2^+ state with respect to the 2_1^+ state and its branching ratio for the transitions to the 2_1^+ and 0_1^+ states indicate large effective γ deformations around $\gamma_{\mathrm{eff}} \approx 28°$ [6]. These are even larger than the effective γ deformations in the Xe, Ba, and Ce nuclei near midshell [7]. However, one cannot simply argue that these nuclei exhibit static traxiality at low spin, since the potential minima are very shallow in γ directions. A similar conclusion was also drawn in the investigation of the low-spin structure of the neutron-rich even-even Ru isotopes [8] and the $\nu h_{11/2}$ bands in the odd-A Ru isotopes [9].

This Rapid Communication reports on the discovery of $\Delta I = 2$ cascades in ^{113}Pd and ^{115}Pd, which are interpreted to be based on $h_{11/2}$ neutrons due to blocking arguments as well as their similarity to the bands in ^{109}Pd and ^{111}Pd [5]. These new findings, together with cranked Woods-Saxon and total Routhian surface calculations indicate that a prolate but still γ-soft shape is stabilized with increased rotational frequency in all Pd isotopes from mass 110 to 116.

Neutron-rich nuclei in the $A \approx 110$ region were produced via beam induced fission following the reaction $^{18}\mathrm{O}+^{208}\mathrm{Pb}$. 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 a forward direction were stopped within a time of about 1 ps. About 2.9×10^9 fourfold and higher fold γ-ray coincidences were detected by the Gammasphere array [11], comprising of 100 large Compton-suppressed Ge detectors. In the offline analysis the data were 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 on the high-spin structure of the even-even Pd isotopes will be published elsewhere.

Candidate transitions for new cascades in odd-A Pd nuclei were identified in spectra gated on the yrast transitions of the

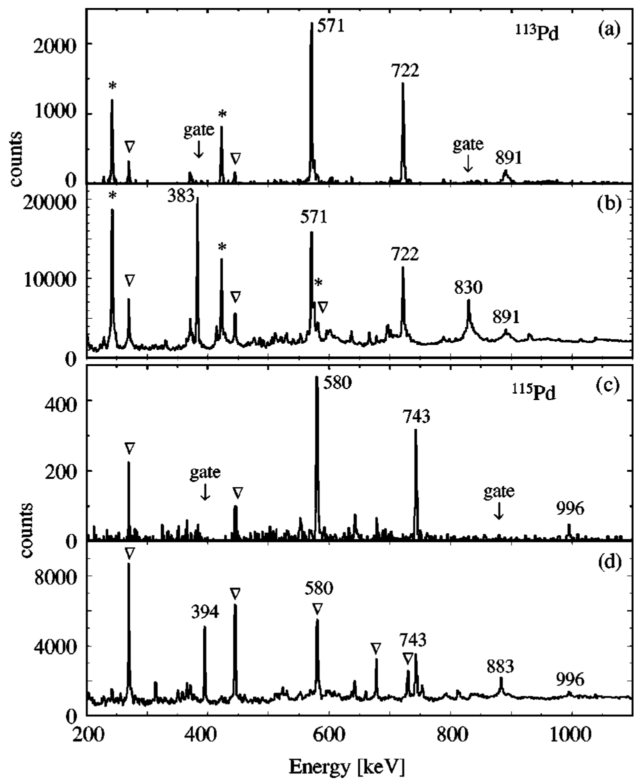

FIG. 1. Gated spectra of the new $\nu h_{11/2}$ bands in ^{113}Pd (a,b) and ^{115}Pd (c,d). Transitions in the new bands are labeled with their energy. The spectra for ^{113}Pd are obtained from triple coincidences with gates on the 383 keV and 830 keV transitions (a) and a sum of all double gates on the 383, 571, 722, 830, and 890 keV transitions (b), respectively. The spectra for ^{115}Pd are obtained from triple coincidences with gates on the 394 keV and 883 keV transitions (c) and a sum of all double gates on the 394, 580, 743, 883, and 996 keV transitions (d), respectively. Yrast transitions in the complementary fragments ^{106}Ru (∇) and ^{108}Ru ($*$) are indicated.

complementary even-even Ru isotopes. Two new cascades of γ-ray transitions were observed and Fig. 1(a)–(d) shows sample double-gated spectra of these bands. The spectra also show yrast transitions in the most abundant complementary fragments, ^{106}Ru and ^{108}Ru. ^{108}Ru is most abundant in Fig. 1(a) and 1(b) and not visible in Fig. 1(c) and 1(d). ^{106}Ru is the strongest Ru fragment in Fig. 1(c) and 1(d) while it is less abundant than ^{108}Ru in Fig. 1(a) and 1(b). The assignment of the two new cascades to ^{113}Pd and ^{115}Pd, respectively, is based on the relative yields of the even-even Ru isotopes when gated on the transitions in the new bands as compared to gates on the yrast cascades in the neighboring even-even Pd isotopes. Fig. 2 shows the proposed partial level schemes for ^{113}Pd and ^{115}Pd as well as a partial level scheme for ^{111}Pd for comparison. The remarkable similarity between the bands in ^{111}Pd through ^{115}Pd suggests that they are built on similar structures. Therefore we propose that the new bands in ^{113}Pd and ^{115}Pd are each based on a low lying $11/2^-$ state, which has been established at 89 keV in ^{115}Pd but is not known in ^{113}Pd. However, from the systematics of $11/2^-$ states across the odd-A Pd isotopes one clearly expects this state in ^{113}Pd at an excitation energy of between about 80 and 170 keV.

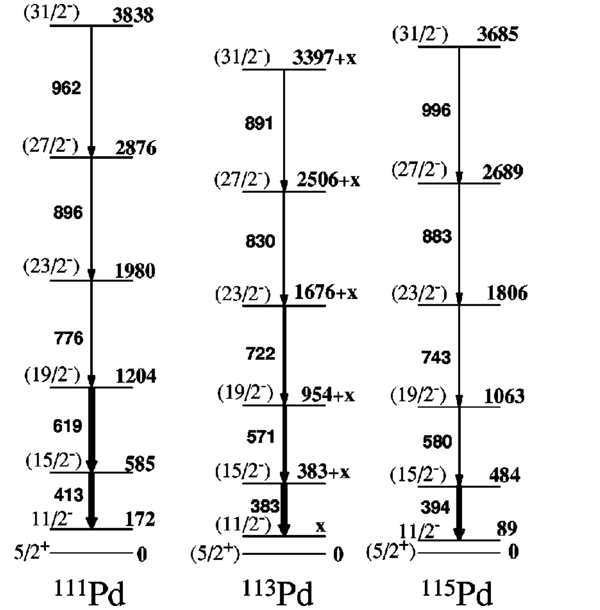

FIG. 2. Partial level scheme for ^{113}Pd and ^{115}Pd showing the ground states together with the new negative parity bands. The $\nu h_{11/2}$ band in ^{111}Pd, which is also observed in the present data, is shown for comparison.

Following the arguments of Ref. [5] we propose that the two newly observed cascades are the favored signatures of the $\nu h_{11/2}$ configuration. This is strongly supported by the alignment of the new bands when compared to the alignment of the $\nu h_{11/2}$ band in ^{111}Pd and the yrast bands of the neighboring even-even Pd isotopes, which is presented in Fig. 3. Similar to the band in ^{111}Pd the two new bands show a blocking of the backbend in the yrast bands of the even-even isotopes. The initial alignment of about 5.5$\hbar$ is also consis-

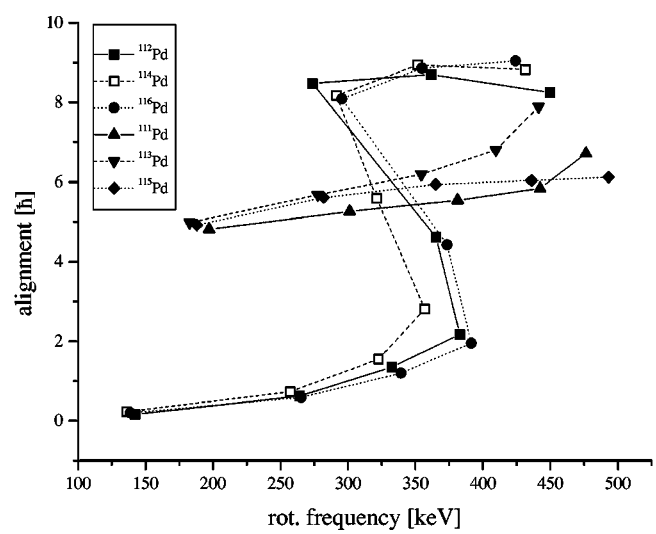

FIG. 3. Alignment of the new bands in ^{113}Pd and ^{115}Pd in comparison with that of the $\nu h_{11/2}$ band in ^{111}Pd and the yrast bands in ^{112}Pd, ^{114}Pd, and ^{116}Pd. The alignment is calculated using $\hbar\omega(I) = [E(I+1)-E(I-1)]/[I_x(I+1)-I_x(I-1)]$ with $I_x(I)=[I(I+1)-K^2]^{1/2}$. A reference with $\mathcal{J}_0 = 8\hbar^2/\mathrm{MeV}$ and $\mathcal{J}_1 = 16\hbar^4/\mathrm{MeV}^3$ was used.

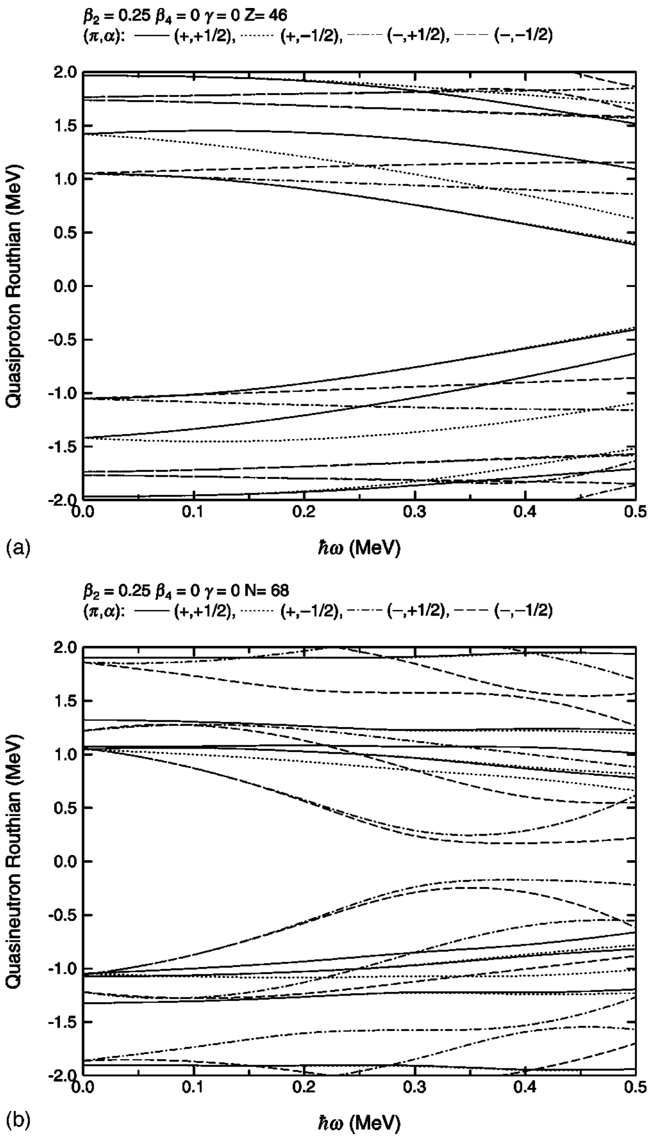

FIG. 4. Quasiproton (a) and quasineutron (b) Routhians for ^{114}Pd as a function of rotational frequency calculated in the framework of the cranked Woods-Saxon model. The parameters used were $\beta_2 = 0.25$, $\beta_4 = 0.0$, $\gamma = 0.0$, $\Delta_p = 1.0$ MeV, and $\Delta_n = 1.1$ MeV.

tent with the proposed configuration assignment. As already discussed in Ref. [5] this blocking clearly shows that the backbending in the even-even isotopes has to be due to the crossing by the aligned $(\nu h_{11/2})^2$ neutron configuration and not, as suggested by Aryaeinejad *et al.* [3], the aligned $(\pi g_{9/2})^2$ configuration. This difference is critical since the assignment of the proton configuration was based on the assumption of an oblate deformation of the even-even core while only the $\nu h_{11/2}$ crossing is expected for a prolate deformation of the core.

We have carried out total Routhian surface (TRS) calculations as a function of rotational frequency for the ground state configurations of the even-even isotopes from ^{110}Pd to ^{116}Pd using the ultimate cranker [10] as well as a normal TRS code with Woods-Saxon potential. Both calculations indicate a very γ-soft minimum at low rotational frequencies with a preference for large negative values of γ, around $-30°$, in the normal TRS calculations and a preference for prolate shapes in the ultimate cranker predictions. However, due to the softness of the potential with respect to γ this difference between the calculations may not be significant.

Figure 4 shows quasiproton and quasineutron Routhians for ^{114}Pd calculated in the framework of the cranked Woods-Saxon model for deformations of $\beta_2 = 0.25$ and $\gamma = 0$. The values for the deformation were chosen on the basis of the TRS calculations. It is apparent that the $(\nu h_{11/2})^2$ configuration exhibits a crossing at a rotational frequency of about $\hbar\omega = 0.35$ MeV, which is consistent with the observed backbend in the yrast bands in the even-even Pd isotopes.

In summary, we have found two new band structures in ^{113}Pd and ^{115}Pd in prompt γ-ray spectroscopy following the heavy-ion induced fission reaction ^{18}O+^{208}Pb. These new bands are assigned to the $\nu h_{11/2}$ configuration on the basis of the blocking of the beckbend observed in their even-even neighbors. The calculated quasiparticle Routhians lend strong support to this interpretation. The results of our calculations agree with the expectation to observe the crossing of the ground state configuration by the aligned $(\nu h_{11/2})^2$ configuration in the even-even nuclei for a prolate deformation. We conclude that there is no evidence for a prolate to oblate shape transition in the neutron-rich Pd isotopes. Further theoretical and experimental investigations are clearly needed to completely understand the structure of the neutron-rich Pd isotopes, in particular the role of the γ-degree of freedom of the nuclear deformation.

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[1] J. Skalski, S. Mizutori, and W. Nazarewicz, Nucl. Phys. **A617**, 282 (1997).
[2] J. H. Hamilton *et al.*, Prog. Part. Nucl. Phys. **35**, 635 (1995).
[3] R. Aryaeinejad *et al.*, Phys. Rev. C **48**, 566 (1993).
[4] P. Möller, J. R. Nix, W. D. Myers, and W. J. Swiatecki, At. Data Nucl. Data Tables **59**, 185 (1995).
[5] T. Kutsarova *et al.*, Phys. Rev. C **58**, 1966 (1998).
[6] A more detailed discussion of the low-spin structure of the even-even Pd isotopes will be given in a forthcoming publication.
[7] O. Vogel, P. van Isacker, A. Gelberg, P. von Brentano, and A. Dewald, Phys. Rev. C **53**, 1660 (1996).

[8] D. Troltenier, J. P. Draayer, B. R. S. Babu, J. H. Hamilton, A. V. Ramayya, and V. E. Oberacker, Nucl. Phys. **A601**, 56 (1996).
[9] N. Fotiades *et al.*, Phys. Rev. C **58**, 1997 (1998).
[10] T. Bengtsson, Nucl. Phys. **A496**, 56 (1989).
[11] I. Y. Lee, Nucl. Phys. **A520**, 641c (1990).
[12] D. Radford, Nucl. Instrum. Methods Phys. Res. A **361**, 297 (1995).