PHYSICAL REVIEW C VOLUME 58, NUMBER 4 OCTOBER 1998

Neutron $h_{11/2}$ band structures of ^{109,111}Pd observed in heavy-ion induced fission

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(Received 12 February 1998)

The neutron-rich nuclei ^{109,111}Pd have been produced as fission fragments following the fusion reactions ^{28,30}Si+ ^{176}Yb at 145 MeV and studied with the EUROGAM2 array. Two signature branches of a new band built on the $\nu h_{11/2}$ orbital have been identified in ^{109}Pd and the favored signature of the $\nu h_{11/2}$ band has been observed for the first time in ^{111}Pd. The spectroscopic properties as well as the rotational behavior of these bands are characteristic of bands expected for a prolate nuclear shape in this mass region. The effect of blocking of the first $h_{11/2}$ quasineutron in the odd-A Pd nuclei supports the interpretation of the first crossing in the yrast bands of ^{110,112}Pd as due to a $\nu(h_{11/2})^2$ pair. [S0556-2813(98)01210-2]

PACS number(s): 23.20.Lv, 25.85.Ge, 27.60.+j

The information obtained so far shows that the nuclei in the mass region $A\approx 100$ exhibit a wide range of structural phenomena. The very sharp transition from spherical to strongly deformed shapes established in Sr and Zr isotopes becomes less dramatic when going to Mo, Ru, and Pd nuclei [1]. The low-spin collective excitations of even-even nuclei in this region indicate an increased softness of the nuclear potential energy to triaxial deformations with the increased proton number. Indeed calculations of potential energy surfaces using different types of mean field approaches such as Nilsson-Strutinski [2] or self-consistent Hartree-Fock [3] show very shallow minima characteristic of γ-soft or triaxial shapes for heavier transitional nuclei. In particular, palladium nuclei are predicted to undergo a prolate-to-oblate shape transition at ^{111}Pd [4]. Experimental evidence for a shape change or shape coexistence can be obtained by high-spin studies of these transitional nuclei. The rotational alignments in the ground bands of the lighter even-even $^{104-108}$Pd nuclei are consistent with the population of the prolate driving $\nu(h_{11/2})^2$ configuration [5]. This interpretation is supported by blocking arguments from the neighboring odd-N ^{105,107}Pd and odd-Z Ag nuclei [6]. On the other hand the first crossings in the heavier ^{112,114,116}Pd nuclei are interpreted to be the result of quasiproton $(g_{9/2})^2$ alignment [7]. As no data exist on the high-spin states in the neighboring heavier odd-N palladium or odd-Z silver isotopes, this conclusion was based exclusively on the comparison of the experimental crossing frequencies with the predictions of the cranked shell model calculations for oblate shape.

In the present study we report on the observation of unique-parity bands and band crossings in the odd-N ^{109,111}Pd nuclei. These results are important in order to understand the origin of the alignments in the predicted prolate-oblate transitional palladium region. No band structures built on the low-lying states were known in ^{109,111}Pd prior to our study. It is worth noting that high-spin states of ^{A}Pd with $A>108$ cannot be populated using fusion-evaporation reactions. On the other hand, fission has become a powerful tool to study neutron-rich nuclei when using the new generation of large arrays of escape-suppressed HpGe detectors [8]. Very neutron-rich nuclei have been studied recently from spontaneous fission of ^{248}Cm or ^{252}Cf [9,10] and less neutron-rich nuclei can be studied from heavy-ion induced fission [11].

Prompt γ rays in the palladium isotopes were observed following their formation as fission fragments in the fusion reactions ^{28,30}Si+ ^{176}Yb at 145 MeV bombarding energy. The experiment was performed at the Vivitron accelerator at Strasbourg. A 1.5 mg/cm^2 target of ^{176}Yb was used, onto which a backing of 15 mg/cm^2 Au had been evaporated in order to stop the recoiling nuclei. Gamma rays were detected with the EUROGAM2 array [8]. This spectrometer consisted of an array of 54 escape-suppressed germanium detectors, 30 of which were large-volume coaxial detectors positioned at backward and forward angles with respect to the beam. The remaining 24 detectors, arranged in two rings close to 90° to the beam direction, were four-element ‘‘clover’’ detectors. The data were recorded in an event-by-event mode with the requirement that a minimum of five unsuppressed Ge fired in prompt coincidence. Using the ^{28}Si beam, a total of 540 million coincidence events were collected, out of which 135 million were three-fold, 270 million four-fold and 108 million five-fold. In the reaction induced by ^{30}Si a total of 40 million events were recorded. So most of the results have been obtained from ^{28}Si data. The off-line analysis consisted of both usual γ-γ sorting and multiple gated spectra [12]. In addition we have built and analyzed a three-dimensional matrix (‘‘cube’’) using the software of Ref. [13]. The latter

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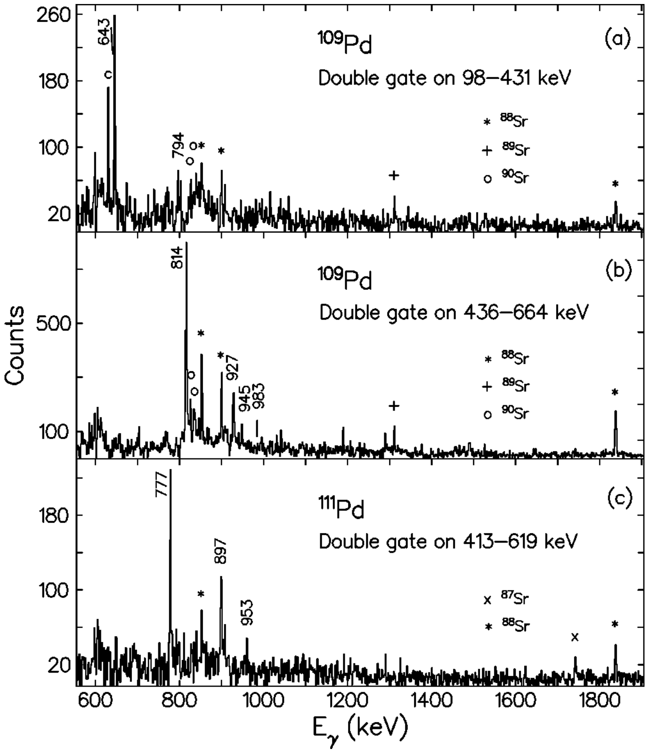

FIG. 1. Examples of spectra obtained from double gates on the lowest-lying transitions in the $h_{11/2}$ bands of ^{109,111}Pd. Peaks are labeled with the energies of the new transitions. The γ rays emitted by complementary Sr fragments are indicated.

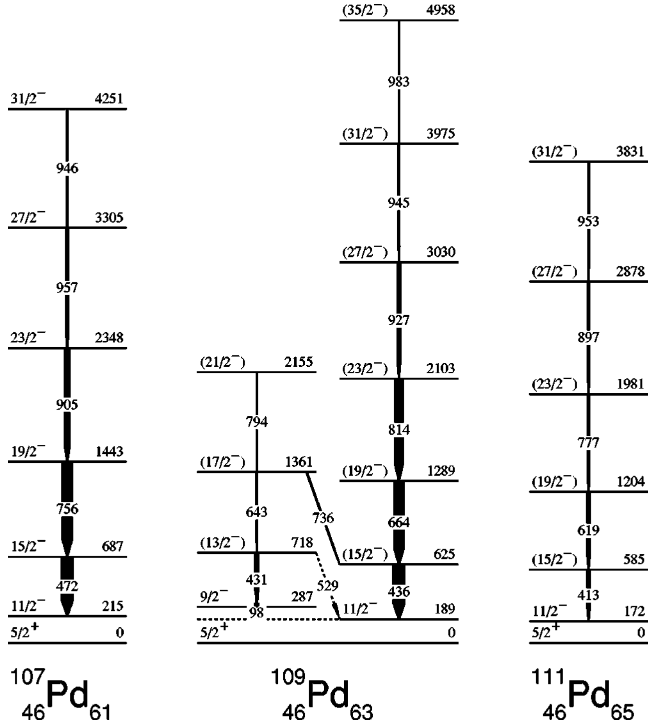

FIG. 2. The negative-parity bands of ^{109,111}Pd. For ^{107}Pd only the levels seen in the present work are shown. The relative intensities of the transitions within a given band are indicated by the thickness of the corresponding arrows. The intensities of the lowest transitions correspond to the relative production yield of the observed bands.

technique was useful to make fast inspection of the data which contain γ-ray cascades from about eighty fission fragments as well as from the strong fusion-evaporation channels. The problem of obtaining correct relative intensities, first exposed in Ref. [12], has been solved by creating multiple gated spectra directly from data on tape with the code FANTASTIC [12].

The chain of Pd isotopes produced as fission fragments in the ^{28}Si reaction extends from ^{104}Pd to ^{112}Pd with a maximum yield at mass $A\sim108$. The odd ^{109,111}Pd could be expected to be produced with sufficient yield to search for yrast band structures. In the prolate light odd-mass palladium isotopes ($A=101$–107) $\Delta I=2$ bands built on the $\nu h_{11/2}$ state are well established. The neutron Fermi level lies below or at the bottom of the $h_{11/2}$ subshell and these bands represent the favored sequences which are strongly populated in fusion-evaporation reactions. Due to the low-Ω value the unfavored sequence is shifted to higher energies and usually not observed in these nuclei. Weaker collective bands of positive parity have also been observed. For example, in a rather complete level scheme of ^{107}Pd populated in a fusion-evaporation reaction [6] the $h_{11/2}$ band represents more than 70% of the population. In ^{109,111}Pd the 11/2$^-$ levels are known to be low-lying isomeric states. In ^{109}Pd a 9/2$^-$ state is located 98 keV above the isomer [14].

The beginning of the search for new bands has consisted of examining various spectra conditioned by the presence of the 98 keV transition and a transition of the complementary ^{88,89}Sr fragments. A sequence of three relatively weak transitions in coincidence with the 98 keV transition has been established. Figure 1(a) shows a double-gated spectrum on the 98 and 431 keV transitions. The lowest transitions of the complementary ^{88,89,90}Sr nuclei can be clearly seen, confirming the identification of the new cascade shown in the decay scheme (Fig. 2). The identification method based on prompt coincidences between γ rays emitted by complementary fragments has been applied initially for spontaneous fission [1] and recently confirmed for heavy-ion induced fission in Ref. [11] . Candidate transitions of unknown bands were found in spectra gated on transitions in a series of the complementary Sr fragments. Subsequently, the spectra of γ rays in coincidence with the new transitions were examined for known transitions in the corresponding Sr isotopes, as well as for transitions related to the new ones. Figures 1(b) and 1(c) show examples of double-gated spectra on the candidate transitions of ^{109}Pd and ^{111}Pd. Peaks corresponding to transitions in the complementary Sr fragments are seen along with the new transitions. For each palladium isotope the average mass of the complementary Sr fragments has been deduced. In the present analyses the yields of both even-even and odd Sr isotopes have been utilized. This was possible thanks to the fact that in the odd-mass Sr nuclei the strength of the population from fission is concentrated in a single cascade of 2–3 transitions above the ground state. The mean masses of Sr fragments are plotted in Fig. 3 as a function of the known and proposed palladium masses. A smooth trend confirms our mass assignments for the new level sequences. The ^{30}Si reaction data provide an additional check of this identification. The analyses show the new transitions in coincidence with the strongest complementary channels shifted

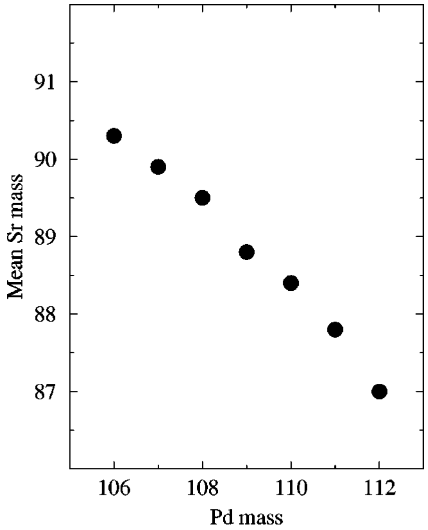

FIG. 3. A plot of average mass of the complementary Sr fragments observed in coincidence with each of the Pd isotopes.

by 2 mass units upward as observed for other pairs of complementary fragments [15]

The partial level schemes of ^{109,111}Pd are shown in Fig. 2 together with the levels of the yrast sequence of ^{107}Pd which were observed in the present experiment. The relative intensities were obtained for the low part from spectra gated on transitions in the strongest complementary fragments and for the higher part from spectra gated on the lowest transitions in each band. Spin assignments are tentative. They are based upon (i) the known spins of the base states, (ii) the assumption that in the yrast decays spins increase with excitation energy, and (iii) on the analogy with the level structure of the decoupled $h_{11/2}$ band in ^{107}Pd. In ^{109}Pd the strongest band is associated with the favored signature of the $\nu h_{11/2}$ structure. The level spacings follow the trend observed in the ground state band of ^{108}Pd core which is similar to the structure observed for the decoupled bands in the lighter odd mass palladium isotopes when compared to the even–even cores. The sequence of 3 transitions in coincidence with the 98 keV $9/2^- \rightarrow 11/2^-$ transition is identified as the unfavored signature of the $\nu h_{11/2}$ band. It is about 5 times weaker than the favored signature. A weak transition of 736 keV connecting the two branches confirms the identification of the two cascades. The weak sequence of 5 transitions identified in ^{111}Pd is most probably the favored signature of the band built on the $11/2^-$ isomeric state.

The observation of $\Delta I = 2$ bands with large signature splittings in ^{109,111}Pd suggests that these nuclei have prolate shapes in the $\nu h_{11/2}$ configuration. If orbitals with large Ω values of $h_{11/2}$ subshell were occupied, as expected for oblate shape, strongly coupled bands with small signature splitting and strong $\Delta I = 1$ transitions would emerge. In ^{109}Pd in addition to the $9/2^-$ state located at 287 keV, a possible $7/2^-$ member of the $h_{11/2}$ multiplet is located only 56 keV above the $11/2^-$ band head [14]. This small relative spacing of the low-spin negative-parity states indicates a shift of the Fermi level to the middle of the $h_{11/2}$ neutron shell. For a prolate nucleus of moderate deformation ($\beta_2 \approx 0.22$) the Fermi level is expected to lie between the $\frac{3}{2}^-[541]$ and $\frac{5}{2}^-[532]$ Nilsson orbitals. In ^{111}Pd one can expect further bunching of the low-spin members of the $h_{11/2}$ multiplet considering the systematics of these states in its isotones ^{109}Ru [16] and ^{113}Cd [17]. While the $7/2^-$, $9/2^-$, and $11/2^-$ levels are ordered by increasing energy in the well deformed ^{109}Ru, the $11/2^-$ level becomes the lowest in the more spherical nucleus ^{113}Cd, the $7/2^-$ and $9/2^-$ levels lying above it in an energy interval of ~400 keV. The intermediate situation at ^{111}Pd would cause these three levels to come closer to each other (probably even more than in ^{109}Pd). When comparing the $^{109,111}_{46}$Pd nuclei to their isotones $^{117,119}_{54}$Xe [18] a similar level compression is observed for the three low-lying negative parity states. Figure 4 shows the systematics of the negative parity levels in the $N = 63$ isotones. The only difference lies in the order of the low-spin states. In palladium nuclei the $11/2^-$ levels remain lowest in energy. At higher spins the behavior of the two signature branches of the $h_{11/2}$ bands in ^{109}Pd and ^{117}Xe is very similar displaying a large signature splitting with unfavored signature levels lying above the favored ones up to $I^\pi = 21/2^-$. These features can be understood by noting that Pd and Xe isotones differ only in the character of the four valence protons relative to $Z = 50$ shell (being holes or particles, respectively). According to the interpretation given in Ref. [19] the negative parity bands in Xe nuclei result from coupling the $h_{11/2}$ neutron to the prolate even-even core. In this picture the relative positions of the low-spin members of the $h_{11/2}$ band are very sensitive to the exact location of the Fermi level. On the other hand, the high-spin properties depend mainly on the core deformation.

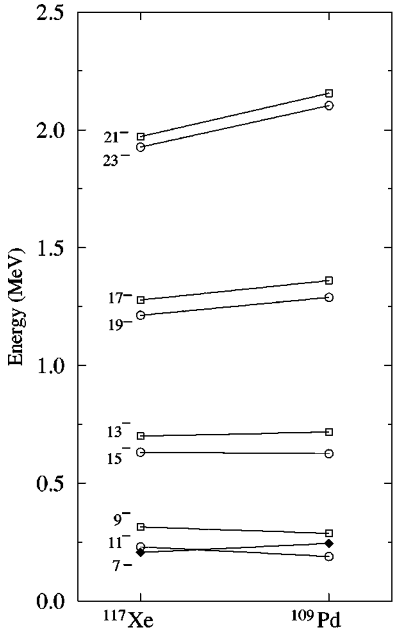

FIG. 4. Comparison of the negative parity levels in the $N = 63$ isotones ^{117}Xe and ^{109}Pd. A value of $2I$ is used for spins.

The rotational properties of the $h_{11/2}$ bands can be studied using the usual plots of aligned angular momenta as a function of the rotational frequency. Figure 5 shows the experimental alignments in the $h_{11/2}$ bands of ^{107,109,111}Pd together with those for the yrast bands of their even-even neighbors. The level spins are transformed into the rotational frame using the reference parameters of $\mathcal{J}_0 = 5\hbar^2/\mathrm{MeV}$ and $\mathcal{J}_1 = 16\hbar^4/\mathrm{MeV}^3$ which give almost constant alignment in the yrast band of ^{108}Pd above the crossing. The $\nu h_{11/2}$ bands of

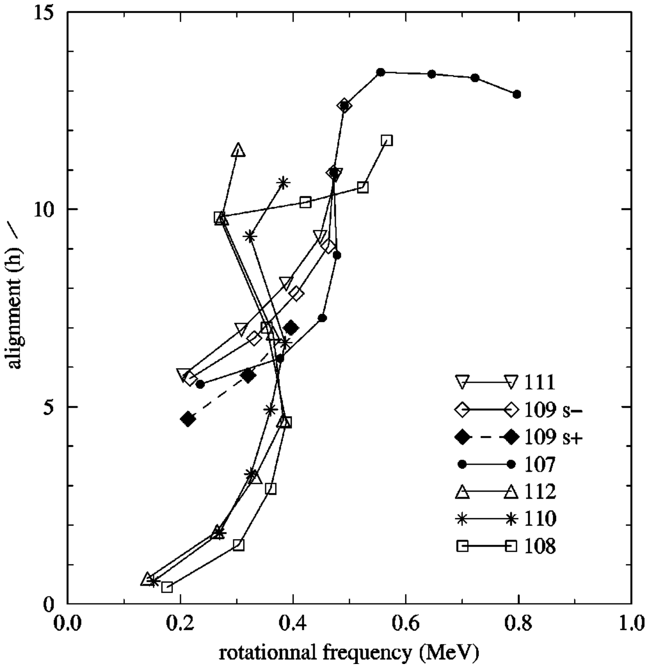

FIG. 5. Experimental alignments for the $h_{11/2}$ neutron bands in the odd isotopes and for the yrast bands in the even-even isotopes of palladium. In all cases the Harris parameters used are $\mathcal{J}_0 = 5\hbar^2/\mathrm{MeV}$ and $\mathcal{J}_1 = 16\hbar^4/\mathrm{MeV}^3$. The symbols correspond to: ^{108}Pd (squares, Refs. [20,5]), ^{110}Pd (stars, Ref. [20]), ^{112}Pd (triangles, Ref. [21]), ^{107}Pd (filled circles, this work and Ref. [6]), ^{109}Pd [open diamonds for the favored (s−) and filled diamonds for the unfavored (s+) signatures, respectively, this work], ^{111}Pd (inverted triangles, this work).

^{109,111}Pd display an alignment behavior which is similar to that of ^{107}Pd. As expected for $h_{11/2}$ neutrons in the lower part of the subshell, they have large initial alignments of $\sim 5.5\hbar$ and $\sim 4.5\hbar$ for the favored and unfavored signature, respectively. The alignment is almost complete for the favored signature sequence in ^{109}Pd. The fairly large gain of $\sim 8\hbar$ for ^{107}Pd is characteristic for the alignment of the first nonblocked pair of quasineutrons [6]. The band crossings occur at a frequency of $\hbar\omega \approx 0.47$ MeV for all favored bands. This crossing frequency is higher than the first band-crossing frequency observed in the ground state bands of the even-even nuclei ($\hbar\omega \approx 0.35$ MeV, see Fig. 5). The delayed alignment is due to the blocking of the lowest $h_{11/2}$ quasineutron. The yrast bands of ^{108,110,112}Pd gain around $10\hbar$ of aligned angular momentum at the crossing. This value is consistent with the observed initial alignments of the two signatures of the $h_{11/2}$ band in ^{109}Pd and supports, in addition to blocking argument, the interpretation of the first crossings in all these even-even Pd nuclei as being due to the alignment of a $\nu h_{11/2}$ pair. We may conclude, therefore, that the ground states of ^{110,112}Pd have prolate shapes, as already stated for ^{108}Pd [5].

The high efficiency of the γ-array EUROGAM combined to an original use of a fusion-fission reaction mechanism is a very useful mean to reach medium states of some neutron-rich nuclei and with quite high angular momentum. So new bands built on the $\nu h_{11/2}$ orbital have been identified in ^{109,111}Pd nuclei. The perturbed structure of the $h_{11/2}$ band observed in these odd-N Pd nuclei is typical for a band built on an orbital lying close to the middle of the $h_{11/2}$ subshell on the prolate side. The favored signature bands undergo delayed crossings due to blocking of $h_{11/2}$ orbital, thus supporting a quasineutron character of the backbendings in the even-even ^{110,112}Pd nuclei. Such crossings are expected for nuclei with prolate ground-state shapes.

The Eurogam project was funded jointly by IN2P3 (France) and the EPSRC (U.K.). We thank the crew of the Vivitron. We are very indebted to A. Meens for preparing the targets, and G. Duchêne and D. Prévost for their help during the experiment. This work was supported in part by the collaboration agreement Bulgarian Academy of Sciences-CNRS under contract No. 2937 and by the Bulgarian National Science Fund under contract No Ph565. Two of us (T. K. and A. M.) acknowledge the financial support and the warm hospitality during visits at CSNSM.

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