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Identification of high spin states in neutron-rich ^{113,115,117}Pd nuclei

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New band structures in the neutron-rich ^{113,115,117}Pd nuclei have been constructed by measuring the γ-γ-γ coincidences emitted from the spontaneous fission of ^{252}Cf with GAMMASPHERE. The triple γ-ray coincidence data revealed new negative-parity bands built on $11/2^-$ isomeric states in ^{113,115,117}Pd. These bands built on the $\nu h_{11/2}$ orbital suggest a band crossing at a frequency of $\hbar\omega \approx 0.45$ MeV. The rotational behavior and energy level spacings of these bands suggest a prolate shape. Two previously unreported bands are also observed in ^{113,115}Pd and tentatively assigned positive parity. These have band crossings at 0.25 and 0.32 MeV.

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Nuclei in the $A \approx 100$ mass region exhibit a wide variety of nuclear shapes ranging from spherical to highly deformed. As in many of the heavier transitional nuclei, the characteristic gradual shape change and shape coexistence are interpreted as an increased softness of the nuclear potential toward triaxial deformations known as γ softness. Mean-field calculations [1] show a minimum in the potential energy surface in support of the γ-soft interpretation. In particular, Pd nuclei in this mass region are expected to undergo a shape change from prolate to oblate at ^{111}Pd [2]. Evidence for shape change has been reported in the even-even Pd nuclei [3]. Based on cranked shell model calculations [4], the band crossings in the yrast bands of the lighter, even-even $^{104-108}$Pd isotopes have been interpreted as arising from the alignment of the $\nu(h_{11/2})^2$ prolate driving configuration. The yrast bands in the heavier even-even ^{112,114,116}Pd isotopes, however, have been described as an oblate driving quasiparticle alignment of the $\pi(g_{9/2})^2$ orbital, based solely on comparison with cranked shell model calculations [3]. The yrast bands of odd-*A* Pd nuclei indicate a prolate shape from the $\nu h_{11/2}$ configuration in ^{105,107}Pd [5] and ^{109,111}Pd [6]. We find that the rotational behaviors of the yrast bands in the heavier odd-*A* isotopes ^{113,115,117}Pd still indicate a prolate shape built on the $\nu h_{11/2}$ configuration. Moreover, the shift of the crossing frequency to a higher value compared to the frequencies in $^{112-116}$Pd indicates that a $\nu(h_{11/2})$ pair is continuing to be responsible for the backbends. In the present study, we report on the identification of several high-spin bands in the heavier odd-*A* ^{113,115,117}Pd isotopes. The new bands were constructed by analyzing the prompt γ-γ-γ coincidence data from the spontaneous fission of ^{252}Cf taken with GAMMASPHERE.

The experiment was carried out with a ^{252}Cf source of strength about 28 μCi sandwiched between Ni foils of thickness 11.3 mg/cm^2 and then sandwiched between 13.7 mg/cm^2 thick Al foils and placed at the center of GAMMASPHERE with 72 Compton suppressed Ge detectors. The coincidence data were analyzed by building a γ-γ-γ cube using RADWARE software [7]. Further experimental details can be found in Ref. [8]. Prior to our study, only the low-lying levels, mainly positive-parity states of ^{113,115,117}Pd, were known from β-decay studies of the corresponding Rh isotopes [9–11]. High-spin states in the very neutron-rich Pd isotopes are nearly impossible to populate with fusion evaporation reactions. Induced and spontaneous fission, however, provide excellent means of populating high spin states in these nuclei.

In ^{113}Pd, the two levels at 189.8 and 454.5 keV were observed in the earlier β-decay studies of ^{113}Rh [9] and confirmed in this work. Two new positive-parity bands built on these levels in ^{113}Pd are identified. The spin and parity assignments of these levels are tentative, based on lighter Pd systematics.

The new negative-parity bands in ^{113,115,117}Pd are built upon the low-lying isomeric $11/2^-$ state in each Pd isotope. The $11/2^-$ isomeric states have been reported previously at 89.3 and 203.2 keV, respectively, in ^{115,117}Pd [10,11]. A corresponding $11/2^-$ state has not been reported in ^{113}Pd. Because the lifetime of this state is most probably longer than our prompt coincidence timing window, we do not observe any γ ray that connects this state to the remainder of the level scheme. Therefore, we do not assign an energy to this state. Figure 1 shows the level schemes for ^{113,115,117}Pd, including the previously assigned level energies for the $11/2^-$

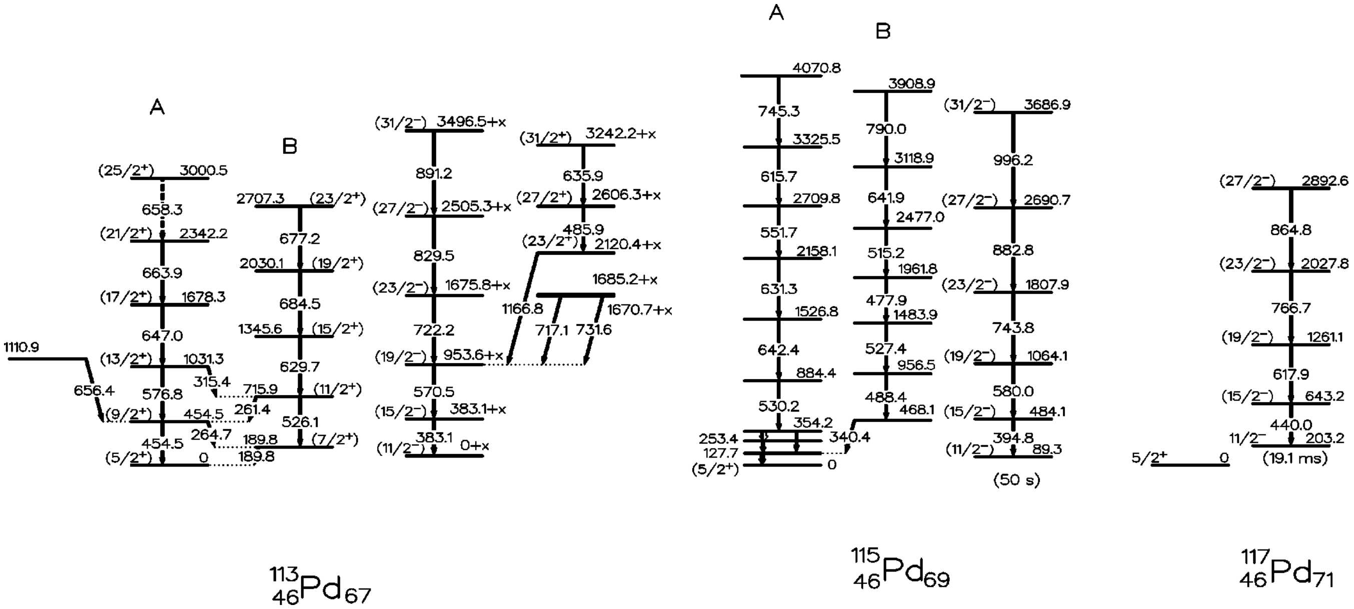

FIG. 1. Level schemes for ^{113,115,117}Pd.

isomeric states. The new bands built on these isomeric states, as well as these positive-parity bands observed in ^{113,115}Pd, are shown in Fig. 1. The spin assignments for the new levels are tentative, based on lighter Pd systematics and the expectation that $\Delta I = 2$ transitions lead to lower-lying states.

In our identification of new bands built on the $11/2^-$ isomeric states, we do not rely upon previous reporting of the $11/2^-$ states. Instead, we have taken a rigorous approach in assigning these bands to a particular Pd isotope, despite not having observed connecting transitions from the bands to their ground states. The requirement for assigning a band to Pd is that the band transitions are coincident with a number of Te partners, namely ^{132,134,136}Te. We have determined from our earlier spontaneous fission work [12] that in ^{252}Cf the three or four neutron emission channels are the most probable. Gating on the fission partner Te restricts the assignment of the bands to Pd. The primary experimental evidence for assigning a band to a particular Pd isotope comes from setting one gate on a strong fission partner transition in a particular isotope and setting a second gate on a transition in the bands of Pd isotopes. Additionally, we require that the relative intensities of transitions in the Te isotopes, as seen in a double gate on transitions in a particular band in Pd, meet the expected intensities for those three, four, and five neutron emission channels. Figure 2 illustrates this requirement. With a double gate on the 383.1 keV and 570.5 keV transitions in ^{113}Pd, we see that the ^{136}Te fission partner, corresponding to a three neutron channel, appears most intense, with small amounts of ^{134,132}Te appearing from $5n$ and $7n$ channels, respectively. Double gating on the 394.8 and 580.0 keV transitions in ^{115}Pd, the yield for ^{134}Te ($3n$ channel) is the largest, while the yields for ^{132}Te ($5n$ channel) and ^{136}Te are significantly smaller. Likewise, double gating on transitions in ^{117}Pd reveals predominately the $3n$ channel, ^{132}Te, with a much smaller yield for the $1n$ channel, ^{134}Te. Kutsarova *et al.* employed a similar ‘‘mass tracking’’ technique to identify the $11/2^-$ bands in ^{109,111}Pd [6].

An additional confirmation of the mass assignments to the negative-parity bands is provided by the new positive parity bands. As seen in the level schemes of Fig. 1, unlike the bands built on the $11/2^-$ isomeric state, transitions connecting the new bands in ^{113,115}Pd to their ground states are strongly observed in prompt coincidence. Here, too, the corresponding Te partner transitions are observed. Figure 3 clearly shows the same mass distributions of the Te partners in the gates set on the transitions in the positive-parity bands. These mass distributions are similar to the ones obtained with the transitions in the negative-parity bands (Fig. 2). Double gating on the two strongest transitions at 189.9 and 264.7 keV in ^{113}Pd yields not only the other members of the tentatively assigned band, but also the Te partner transitions with the same relative intensities as a function of mass number A as are seen in the negative-parity gates. A similar result is obtained when gating on strong transitions in the tentatively assigned positive-parity bands A and B of ^{115}Pd (positive parities are tentatively assigned [10] to the four states below 355 keV in bands A and B). Unfortunately, this check cannot be performed for ^{117}Pd, as no additional sequence was observed.

Once the new bands are assigned to a particular Pd isotope, it is relatively straightforward to determine the order of the transitions within the bands. For the analysis, use of γ-γ-γ coincidence data with its reduced background greatly simplifies the transition ordering. Examples of coincident transitions for the $11/2^-$ bands in ^{113,115,117}Pd can be seen in Fig. 2. Besides the new $11/2^-$ bands, we have also added two new bands to each of the decay schemes of ^{113}Pd and ^{115}Pd. A positive-parity is assigned because they are built on known or tentatively assigned positive-parity states. Examples of the coincident transitions, as well as the connection of these bands to the ground state, can be seen in Fig. 3.

The transition energy systematics for the $11/2^-$ bands in ^{113,115,117}Pd closely match those of both the less neutron-rich

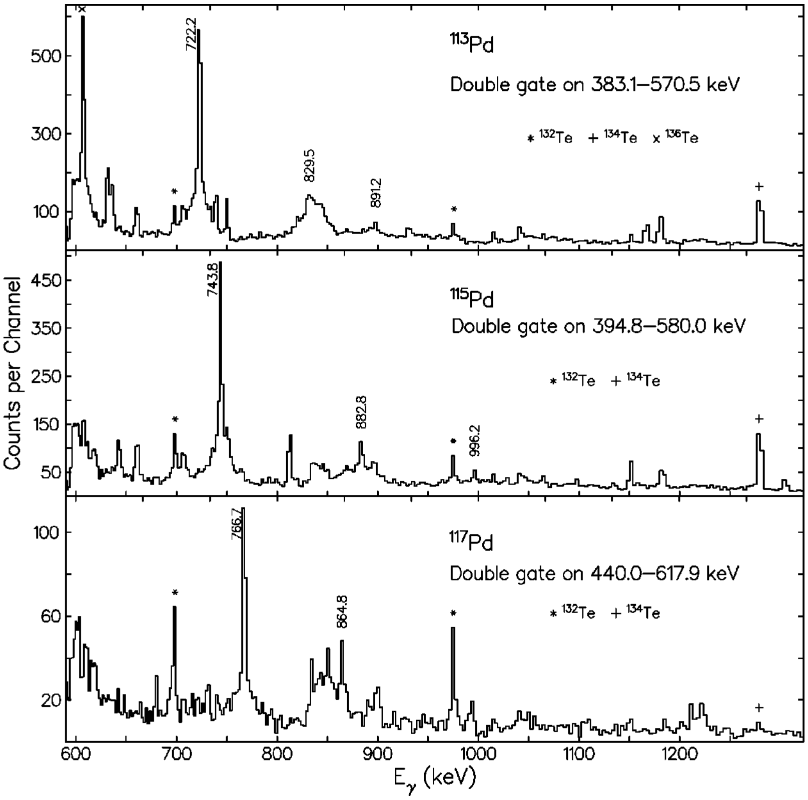

FIG. 2. (a) Coincidence spectrum obtained by double gating on the yrast 383 and 571 keV transitions in ^{113}Pd. (b) Coincidence spectrum obtained by double gating on the yrast 395 and 580 keV transitions in ^{115}Pd. (c) Coincidence spectrum obtained by double gating on the yrast 440 and 618 keV transitions in ^{117}Pd.

odd-A $^{107-111}$Pd isotopes and the even-even $^{106-116}$Pd isotopes. Shown in Fig. 4 is a plot of transition energies versus neutron number. The transition energies between yrast band members decrease smoothly as a function of mass until $N=68$. The transition energies then increase smoothly for both the even-even Pd isotopes and the odd-A Pd isotopes. This smooth trend further supports our level scheme assignments. The gradual energy shifts have been interpreted previously

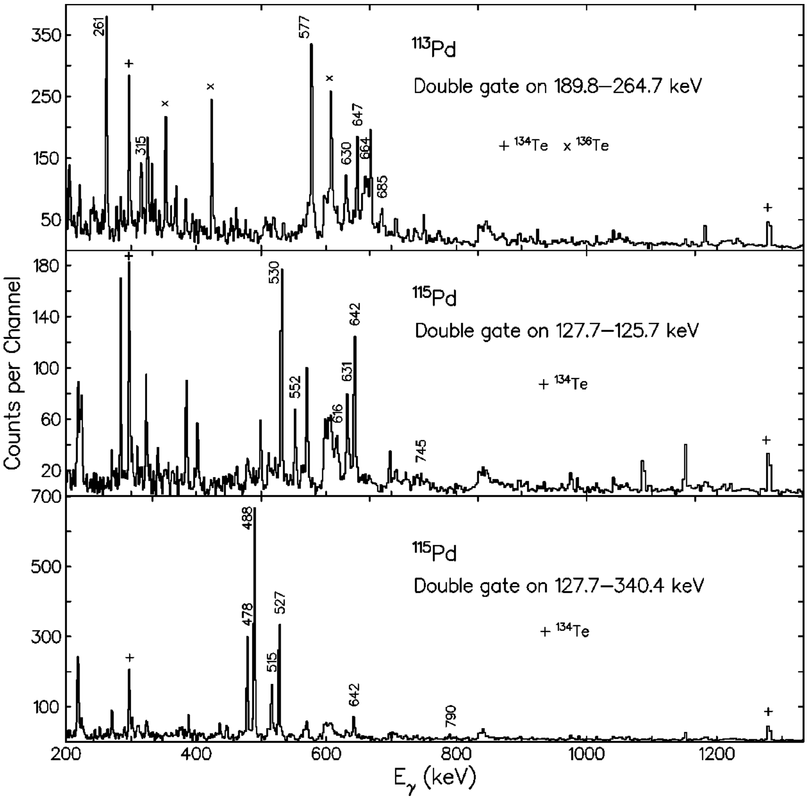

FIG. 3. (a) Coincidence spectrum obtained by double gating on the 190 and 265 keV transitions in ^{113}Pd. (b) Coincidence spectrum obtained by double gating on the 128 and 126 keV transitions in ^{115}Pd. (c) Coincidence spectrum obtained by double gating on the 128 and 340 keV transitions in ^{115}Pd.

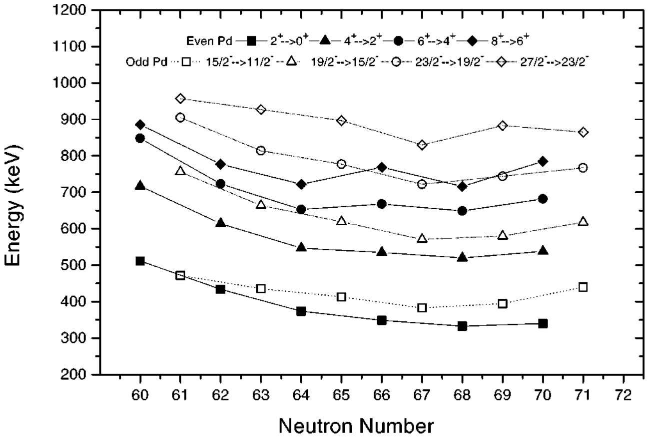

FIG. 4. Transition energy systematics for both the even-even and odd-*A* neutron-rich Pd isotopes. The yrast bands show smooth changes as a function of mass. The minimum energy at $N=68$ is due to a mid-shell closure of the $N=50$–82 shell.

as the onset of occupation of the $\nu h_{11/2}$ orbital, while the minimum at $N=68$ is viewed as a near mid-shell effect of the $N=50$–82 closed shells [3,6].

In ^{115}Pd, a positive parity has been tentatively assigned to the levels at 127.7, 253.4, and 354.2 keV, and the ground state following the β-decay studies of ^{115}Rh [10]. We could assign spins and parities assuming that the spin of the 127.7 keV level is $5/2^+$and band *B* built on this level in ^{115}Pd consists of a series of $E2$ transitions. These spins and parities are used to calculate the J_1 moments of inertia as shown in Fig. 5. Furthermore, assuming that the spin and parity of the 354.2 keV level is $7/2^+$ and that band *A* built on this level is connected via a series of $E2$ transitions, the J_1's are calculated for band *A* as shown in Fig. 5. Even though some of these spin assignments are somewhat arbitrary, changing the bandhead spins by one or two units up or down will not appreciably change the J_1's in Fig. 5, e.g., the backbend frequencies for bands *A* and *B* are essentially the same for this range of spins.

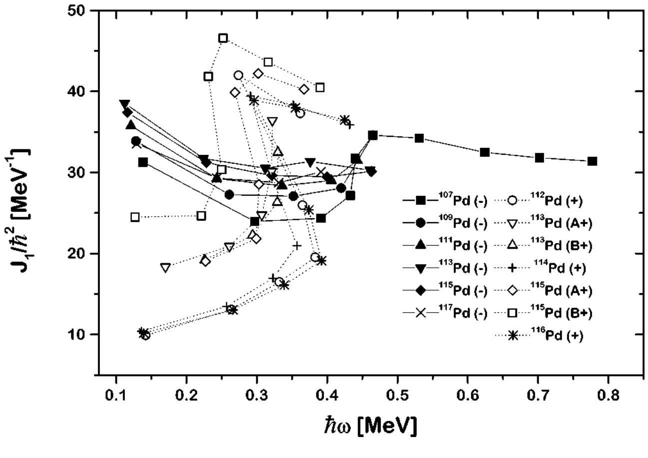

FIG. 5. Plot of the moments of inertia J_1 as a function of rotational frequency $\hbar\omega$ for odd-*A* $^{107-117}$Pd and even-even $^{112-116}$Pd isotopes. First band crossings for the negative-parity yrast bands occur at $\hbar\omega\approx0.45$ MeV. The positive-parity bands show a first crossing at $\hbar\omega\approx0.32$ MeV.

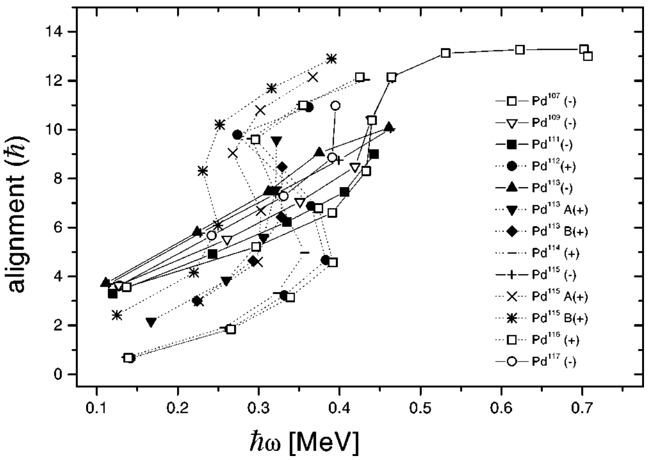

FIG. 6. Experimental alignments for the positive- and negative-parity bands in the odd Pd isotopes and for the yrast bands in the even-even ^{112,114,116}Pd isotopes. In all cases the Harris parameters used are $\vartheta_0=5\hbar^2/\text{MeV}$ and $\vartheta_1=16\hbar^4/\text{MeV}^3$.

Although the energy level systematics in the yrast bands of the odd-*A* Pd isotopes closely match those of the even-even Pd isotopes, these rotational behaviors do not. As shown in Fig. 5, one sees the band crossing frequencies for both the negative- and positive-parity bands in the odd-*A* Pd isotopes, as well as the yrast bands in the even-even ^{112,114,116}Pd isotopes. A first band crossing is found at $\hbar\omega\approx0.34$ MeV in the positive-parity yrast bands in ^{114,116}Pd isotopes, and has been attributed to the occupation of the $\pi(g_{9/2})$ orbital [3]. The alignment plot for the yrast bands in even-even ^{112,114,116}Pd and the positive- and negative-parity bands in odd-*A* $^{107-117}$Pd is shown in Fig. 6. This plot indicates that the magnitudes of the alignment for the $h_{11/2}$ bands in odd-*A* Pd isotopes are similar to those of the yrast bands in even-*A* Pd isotopes. From these considerations, it appears that the earlier interpretation, that the $g_{9/2}$ orbital is responsible for backbending at $\hbar\omega\approx0.34$ MeV in the yrast bands of even-*A* ^{114,116}Pd, is questionable. The odd-*A* ^{113,115,117}Pd isotopes have a first band crossing in the negative-parity bands built on the $h_{11/2}$- isomeric states at a substantially higher frequency, $\hbar\omega\approx0.45$ MeV. The band crossings in the negative-parity bands in ^{113,115,117}Pd very closely match those of the lighter ^{109,111}Pd isotopes, indicating the alignment of the $\nu h_{11/2}$ pair there too and a prolate shape. Kutsarova *et al.* [6] have suggested that the delayed alignment of a $\nu h_{11/2}$ pair in ^{109,111}Pd is because of blocking by the odd $h_{11/2}$ neutron orbital with prolate shape. This argument suggests that the alignment of a $\nu h_{11/2}$ pair is responsible for the backbend observed in the even-even ^{110,112}Pd isotopes [6] and in the heavier ^{114,116}Pd isotopes. The degrees of alignment from the new high spin states in $^{112-116}$Pd now suggest this too [13]. A similar study of the neutron-rich Ag isotopes would also be helpful in determining the systematic behavior of nuclei in this mass region. Figure 5 shows clearly the first band crossing frequency of $\hbar\omega\approx0.32$ MeV for the new positive-parity bands in ^{113}Pd and band *A* in ^{115}Pd, and $\hbar\omega\approx0.25$ MeV for the band *B* in ^{115}Pd. A study of those positive-parity states in ^{109,111}Pd would be helpful in understanding this. In addition to the rotational behavior, we believe that a prolate shape, which would form strongly coupled bands in ^{113,115,117}Pd, is indicated by the absence of $\Delta I = 1$ transitions. Even with careful searches, these transitions are not seen in the present data set.

In conclusion, we have observed new bands in ^{113,115,117}Pd up to moderately high spin. The newly identified negative-parity yrast band energy level systematics built on the $11/2^-$ isomeric states fit smoothly with the known systematics for other Pd isotopes, and show a minimum excitation energy at $N = 68$ related to a mid-shell closure. These new negative-parity yrast bands indicate a first band crossing at $\hbar\omega \approx 0.45$ MeV, nearly identical to those seen in ^{109,111}Pd [6], but significantly higher than those in the positive yrast parity bands in ^{113,115}Pd and in the even-even Pd isotopes. We have interpreted the new negative-parity yrast bands as having band crossings from the alignment of a $\nu h_{11/2}$ pair, and this suggests that ^{113,115,117}Pd maintain a prolate shape. Additionally, we have observed two new bands in ^{113,115}Pd which are tentatively assigned positive parity with band crossings at 0.25 and 0.32 MeV. These lower frequencies are consistent with a $\nu h_{11/2}$ pair alignment.

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