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Rotational bands in odd-*A* Cm and Cf isotopes: Exploring the highest neutron orbitals

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Rotational bands have been identified up to high spins ($\approx 28\hbar$) in the odd-A nuclei ^{247,249}Cm and ^{249}Cf through inelastic excitation and transfer reactions around the $Z = 100$ region where stability results from shell effects. The [620]1/2 Nilsson configuration in ^{249}Cm is the highest-lying neutron orbital, from above the $N = 164$ spherical subshell gap, for which high-spin rotational behavior has been established. The data allow for an unambiguous experimental assignment of configurations to the observed bands, unusual for odd-A nuclei near $Z = 100$. The high-spin properties are described in terms of Woods-Saxon cranking calculations.

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Spectroscopy of the heaviest nuclei up to high spins in the region where stability is due mostly to shell effects ($Z \approx 100$) is challenging. Most current studies have focused on prompt collective structures in even-even nuclei (e.g., [1–3]), since these are relatively easier to investigate. Information on odd-A nuclei allows for more sensitive tests of theoretical predictions of single-particle energies, moments of inertia (MOI), and electromagnetic properties associated with specific nucleonic configurations. There are few predictions of high-spin collective properties of odd-A nuclei [4], which are largely untested owing to the paucity of data [5,6]. Self-consistent mean field (SCMF) techniques, using different effective interactions, have primarily focused on the collective properties of even-even transplutonium nuclei [7–9]. The objective of this work is to study high-spin collective properties of various isotopic and isotonic, odd-A nuclei with the highest possible Z. Extensive cranking calculations using the universal parametrization [10] of the Woods-Saxon potential have been performed for nuclei in this region and some relevant results are presented.

High-spin studies of odd-A nuclei near $Z = 100$ pose several challenges. Production cross sections are low (submicrobarn) in fusion-evaporation reactions. Though substantially higher cross sections ($\approx$millibarns) are obtained through inelastic excitation and transfer reactions on relatively long-lived isotopes with $Z \leqslant 98$, strong contamination from other reaction channels, such as fission and Coulomb excitation of Au (which is typically used as a backing for the actinide targets), tends to dominate. Target activities also limit the feasibility of such studies. The γ intensity in odd-A nuclei is often fragmented across multiple band structures. Low-energy transitions are highly converted and there is usually insufficient information about excited states to build decay schemes using γ-γ coincidence techniques. Consequently, to date, only a few odd-A transplutonium nuclei have been studied to high spins, viz., ^{241}Am ($Z = 95$), ^{251}Md ($Z = 101$), and ^{253}No ($Z = 102$) [5,6,11,12]. We present new results on high-spin ($\approx 25\hbar$) rotational bands based on the ν[734]9/2 orbital of $j_{15/2}$ parentage in the $N = 151$ isotones ^{247}Cm ($Z = 96$) and ^{249}Cf ($Z = 98$). In ^{249}Cm ($N = 153$), a band built on the ν[620]1/2 orbital of $2g_{7/2}$ parentage, from above the $N = 164$ spherical subshell gap, has been established up to $\approx 28\hbar$. This is the highest-lying neutron configuration investigated to high spins and represents a substantial advance toward studying states close to the next predicted neutron magic shell gap. Cf is the element with the highest Z studied through inelastic excitation with a heavy-ion beam. Unambiguous configuration assignments have been made using measured branching ratios and the variation with Z and N of high-spin properties has been explored. In tandem with our experimental studies [13], low-spin work on ^{249}Cm was also performed [14].

The data were obtained through a series of experiments using the Gammasphere array [15,16] that consist of ≈ 100 Compton-suppressed Ge detectors for these experiments, with beams from the ATLAS superconducting linear accelerator at Argonne National Laboratory. The Cm isotopes were studied with a 1450-MeV ^{209}Bi beam on a 200 μg/cm^2 ^{248}Cm target through neutron transfer, while excited states in ^{249}Cf were populated using inelastic excitation with a 1430-MeV ^{207}Pb beam on a 150 μg/cm^2 ^{249}Cf target. Both targets had an ≈ 50 mg/cm^2 Au backing and 200 μg/cm^2 Au in front. The total amount of ^{249}Cf material was 7 μg, with an activity of ≈ 30 μCi, leading to a ≈ 3 kHz count rate in each Ge detector. Low-spin states had been established in ^{247}Cm through the α decay of ^{251}Cf [17], and in ^{249}Cm through thermal neutron capture in ^{248}Cm [18]. Further, states at low excitation in ^{249}Cf had been studied through earlier (d, d') work [19]. Despite the available low-spin information for these nuclei, transitions from known levels in all nuclei were at or below the threshold for detection in our experiments (except for three γ rays in ^{249}Cf, two of which are quite weak in the present data). With

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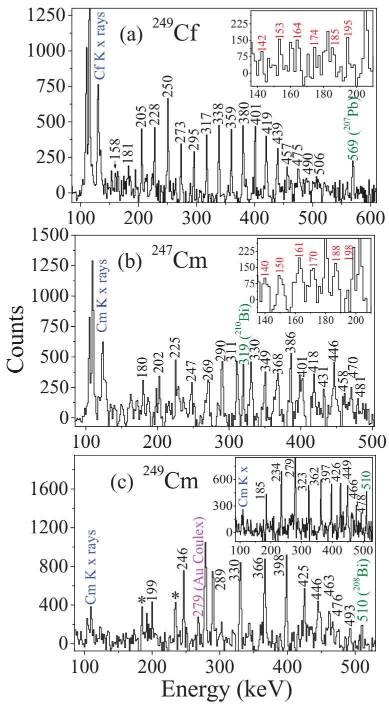

FIG. 1. (Color online) (a) Transitions in the $\nu[734]9/2$ band in ^{249}Cf, with the $\Delta I = 1$ transitions shown in the inset. (b) Same as (a), for ^{247}Cm. (c) The $\nu[620]1/2$ band in ^{249}Cm, with γ rays in the favored signature shown in the larger panel, with the inset depicting those in the unfavored sequence. The transitions marked with asterisks (^{249}Cm) are observed through coincidences with the signature partner. In all the cases, the γ rays from the binary reaction partner, observed in coincidence, are indicated as well.

the large background in the Cf data, sufficient selectivity could not be obtained by requiring coincidence with a single γ ray. Therefore, γ-γ coincidences with known transitions could not be used to assign new γ rays to the respective nuclei. In order to enhance selectivity and enable unambiguous identification, a variety of techniques, such as x-γ coincidences for Z identification and cross-coincidences with binary reaction partners coupled with band search techniques, were adopted.

Rotational bands have been established up to $\approx 25\hbar$ in both ^{247}Cm and ^{249}Cf. Coincidences with Cf and Cm K x rays and cross-coincidences with the 569- and 319-keV transitions from the lowest excited states in ^{207}Pb and ^{210}Bi [Figs. 1(a) and 1(b)], respectively, allow for an unambiguous assignment of the observed bands to ^{249}Cf and ^{247}Cm (Fig. 2). The similarity of MOI of the two bands below 0.15 MeV [Fig. 3(c)] suggests identical configurations, and rotational parameters extracted from the newly established levels are consistent with those obtained from the established [17,19] low-spin states based on the [734]9/2 bandhead [$A \approx 5.7$ keV, with energies $E = E_0 + AI(I+1)$]. Strong coincidences between signature partners are also observed (Figs. 1 and 2). The observation of $\Delta I = 1$ transitions between signature partners [insets of Figs. 1(a) and 1(b)], in addition to the in-band $E2$ transitions, yields $M1/E2$ branching ratios. The $(g_K - g_R)/Q_0$ values (where g_K is the nucleon g factor, g_R is the rotational g factor, and Q_0 is the intrinsic quadrupole moment) extracted from the branching ratios can be compared to those expected for different Nilsson orbitals to aid configuration assignments. Values of $g_R = 0.31$ and $Q_0 = 12$ eb, typical for this region, were used [3,20]. The configuration assignments are, however, robust under variation of both g_R and Q_0. For the bands in ^{249}Cf and ^{247}Cm, a $\nu[734]9/2$ configuration of $j_{15/2}$ parentage is indicated, and other low-lying orbitals are ruled out, with the agreement better in ^{249}Cf than in ^{247}Cm [Figs. 3(a) and 3(b)]. Thus far, the excitations built on the $\nu j_{15/2}$, [734]9/2 orbital were the highest-lying ones studied up to high spins in ^{253}No [5,6]. The same orbital has now been explored in ^{247}Cm and ^{249}Cf, which are $N = 151$ isotones of ^{253}No.

In ^{249}Cm, a band with a large signature splitting and a decoupling parameter $a = 0.35$ is observed [Figs. 1(c) and 2]. This value is in agreement with $a = 0.33$ from the known levels at low spin. Coincidences with Cm K x rays and cross-coincidences with the 510-keV γ ray from the second excited state in ^{208}Bi [Fig. 1(c)] allow for the band to be associated with ^{249}Cm. There are weak coincidences between the signature partners, though no $\Delta I = 1$ transitions are observed. The weaker $\Delta I = 1$ transitions are also responsible for the smaller intensity of the K x rays observed in coincidence in ^{249}Cm [Fig. 1(c)] as compared to ^{249}Cf and ^{247}Cm [Figs. 1(a) and 1(b)]. However, $M1/E2$ branching ratios could be inferred for two states in the band from observed coincidences between the signature partners. The $(g_K - g_R)/Q_0$ values extracted from the data are consistent only with the $\nu[620]1/2$ configuration of $2g_{7/2}$ parentage [Fig. 3(c)], which originates from above the $N = 164$ spherical subshell gap. The low-spin part of the $\nu[620]1/2$ band is in good agreement with that reported in [14].

The investigation of isotonic (^{247}Cm, ^{249}Cf) and isotopic (^{247,249}Cm) nuclei allows an exploration of the variation of high-spin properties with Z and N, in a regime where the shell-correction energy is crucial for stability against fission. These properties are described below in terms of Woods-Saxon (WS) cranking calculations. The calculations have been performed using the universal parametrization of the WS potential [10]. For each case, the deformation was fixed at the value calculated for the ground state ($\beta_2 \approx 0.24$, $\beta_4 \approx 0.02$–0.03, and $\gamma = 0^\circ$). Empirical values of pair-gap energies were used, which were chosen to be 80% of five-point odd-even mass differences [21]. The reduction of the pair-gap energy by this amount was found to explain observed properties in the actinides better, and the extent of quenching was chosen to reproduce existing data.

For the $\nu[734]9/2$ bands in ^{247}Cm and ^{249}Cf, the $j_{15/2}$ neutron crossing is blocked. An upbend in the experimental alignment just beyond $\hbar\omega = 0.2$ MeV is observed in ^{247}Cm, and a very small increase around 0.25 MeV is seen in ^{249}Cf [Fig. 4(a)], which may possibly be the precursor of an alignment. For the $K = 1/2$ band in ^{249}Cm, both $\nu j_{15/2}$ and $\pi i_{13/2}$ crossings are possible, unlike ^{247}Cm. The experimentally observed alignment gain is larger (by about $3\hbar$) in ^{249}Cm, compared to ^{247}Cm, over the observed range of frequencies [Fig. 4(a)].

The WS cranking calculations predict that the $\pi i_{13/2}$ crossing in ^{247}Cm, with the [642]5/2 orbital being involved, should occur at 0.22 MeV [Fig. 5(a)]. In comparison, the calculated crossing frequency is higher for ^{249}Cf (0.25 MeV)

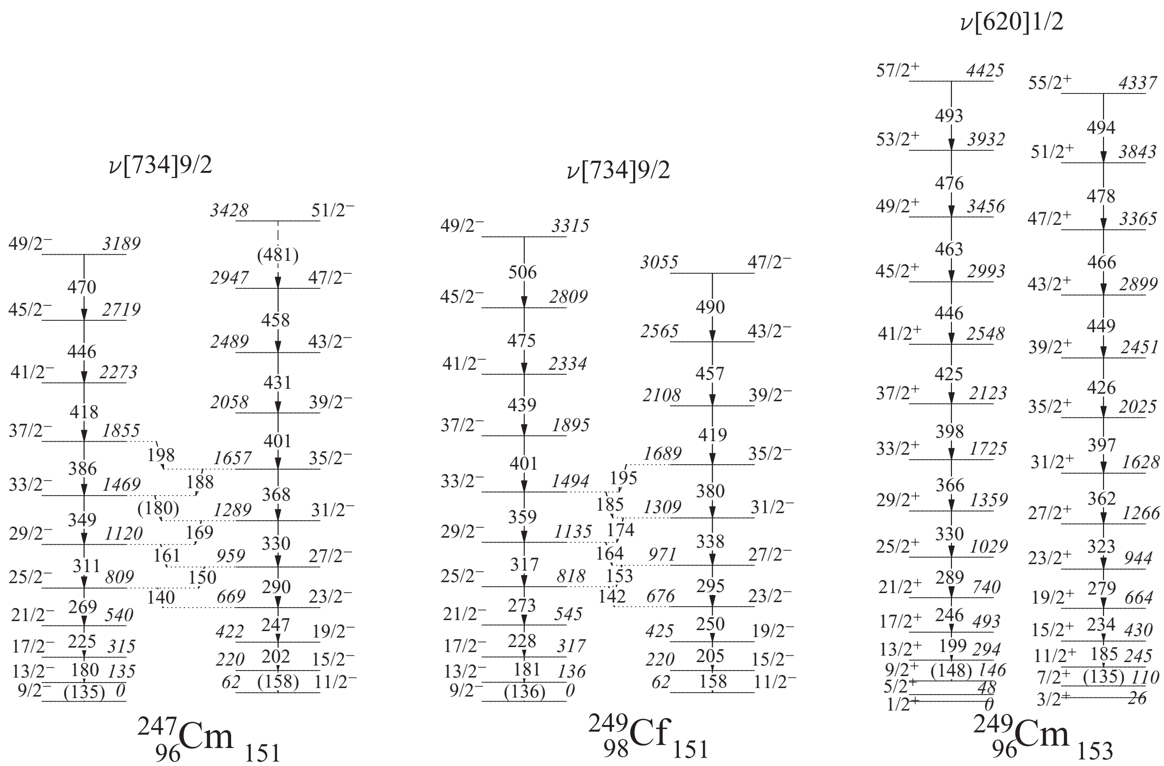

FIG. 2. The observed level structure for the $\nu[734]9/2$ bands in ^{247}Cm and ^{249}Cf, and the $\nu[620]1/2$ band in ^{249}Cm. Almost all of the transitions have been newly observed in this work.

due to the presence of the higher-Ω, [633]7/2 orbital near the Fermi surface [Fig. 5(b)]. The interaction strength at the crossing in ^{249}Cf is predicted to be significantly larger ($\approx$0.2 MeV) than that in ^{247}Cm ($\approx$0.07 MeV). However, it is difficult to determine whether this is the case experimentally as only the very first stage of an alignment is observed in ^{249}Cf. The predicted values for the $\nu j_{15/2}$ and $\pi i_{13/2}$ crossing frequencies in ^{249}Cm [Fig. 5(c)] are very similar (0.21 and 0.22 MeV, respectively). Therefore, it is reasonable to suggest that the additional alignment observed in ^{249}Cm is attributable to $j_{15/2}$ neutrons. Figure 5(d) depicts a comparison of the experimental and predicted Routhians for the $j_{15/2}$ neutron band in ^{249}Cf. While the predictions are consistent with observation, they may not necessarily offer a unique explanation. No evidence for a $j_{15/2}$ alignment has been found at $N = 144$ and 146 [11,20,22,23], even though CSM calculations predict that this should occur at $\hbar\omega \approx 0.20$ MeV [11], while tentative evidence for it has recently been presented for the $N = 142$ ^{235}Np nucleus [24]. In the latter case, an alternative explanation is also possible [24]. Hence, an understanding of this possible strong neutron number dependence of the $j_{15/2}$ crossing frequency is currently not understood. The observation of a rotational band built on a $j_{15/2}$ neutron configuration in ^{249}Cm could possibly help establish with more certainty whether or not the expected $j_{15/2}$ alignment is observed at $N = 153$, provided this collective sequence can be established to sufficiently high spin.

Experimental alignments for $N = 150$ isotones from Pu ($Z = 94$) to No ($Z = 102$) [2,3,22] are given in Fig. 4(b). There is an apparent increase in the crossing frequency with increasing Z. The $\nu j_{15/2}$ crossing frequency is expected to be constant since these are isotones, and as discussed above, little or no $\nu j_{15/2}$ alignment has been observed in most actinides. Therefore, the change in the alignment behavior of these isotones can be attributed to the $\pi i_{13/2}$ quasiparticle alignment, although the β_6 deformation may play a role as well. The variation with Z of the $\pi i_{13/2}$ alignment process is also apparent through a scrutiny of the experimental kinematic moment of inertia ($J^{(1)} = I/\omega$, where I is the spin and ω is the rotational frequency) for the $\nu[734]9/2$ bands in the $N = 151$ isotones, ^{247}Cm, ^{249}Cf, and ^{253}No [Fig. 4(c)]. At low rotational frequencies, the MOI are quite similar as a result of identical underlying configurations. The increase in MOI at higher frequencies cannot be attributed to $\nu j_{15/2}$ alignment since it is blocked. This increase is evident around $\hbar\omega \approx 0.2$ MeV for ^{247}Cm, around 0.25 MeV for ^{249}Cf, while there is no appreciable change in the case of ^{253}No for the observed range of frequencies.

The WS calculations predict an increase in the $i_{13/2}$ proton crossing frequency with Z [Fig. 4(d)], from a predicted value of 0.22 MeV for Cm ($Z = 96$) to 0.29 MeV for No ($Z = 102$). This is consistent with the apparent increase in alignment frequency with increasing Z observed for the $N = 150$ and $N = 151$ isotones. Unfortunately, a precise value of the experimental $i_{13/2}$ crossing frequency cannot be determined for $Z > 94$, since the alignments have not been completely mapped. In addition, the interaction strengths are also predicted to change with Z. Thus, the differences

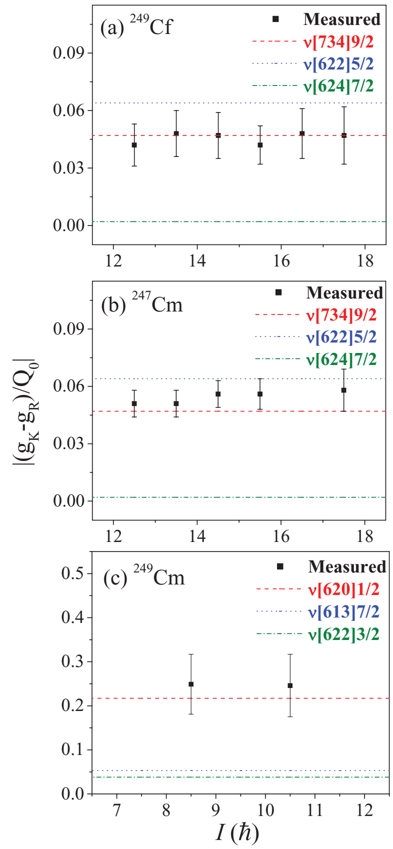

FIG. 3. (Color online) Experimental $(g_K - g_R)/Q_0$ values for the observed bands in (a) ^{249}Cf, (b) ^{247}Cm, and (c) ^{249}Cm. These are compared with those expected for low-lying neutron states in these nuclei (dotted lines). The experimental values favor the $\nu[734]9/2$ configuration in both ^{249}Cf and ^{247}Cm, and the $\nu[620]1/2$ orbital in ^{249}Cm.

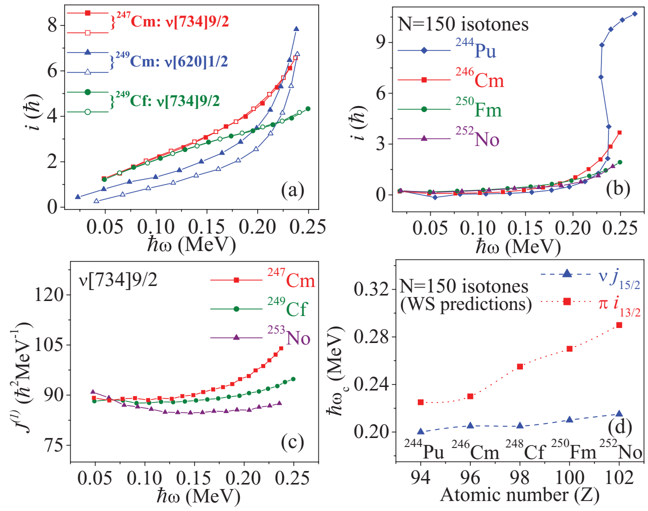

FIG. 4. (Color online) (a) Alignments as a function of rotational frequency for bands in ^{247,249}Cm and ^{249}Cf. Harris parameters [25] $J_0 = 65\hbar^2$ MeV^{-1} and $J_1 = 200\hbar^4$ MeV^{-3} have been used. (b) Experimental alignments for the yrast bands in the even-even $N = 150$ isotones from ^{244}Pu ($Z = 94$) to ^{252}No ($Z = 102$). The yrast band of ^{248}Cf ($Z = 98$) is not known to high spin and therefore not indicated. (c) Observed kinematic moments of inertia for $\nu[734]9/2$ bands in $N = 151$ isotones. (d) Predicted crossing frequencies, from Woods-Saxon cranking calculations, for $j_{15/2}$ neutrons and $i_{13/2}$ protons in $N = 150$ isotones.

observed in Figs. 4(b) and 4(c) for $Z > 94$ can possibly result from varying interaction strengths. Consequently, it is difficult to determine how accurately the WS calculations are able to predict the crossing frequencies and interaction strengths for $Z > 94$ based on existing data.

It is noteworthy that WS calculations for rare-earth nuclei provide a good description of experimental data with pairing gaps at 100% of the five-point mass difference [26], unlike 80% of this value for the actinides. The required quenching of the pair gap for the actinides deserves further investigation.

While the description of most collective properties, both for odd-A and even-even nuclei, provided by WS calculations is reasonably satisfactory, several gaps remain. Additional data on odd-A and odd-odd nuclei near $Z = 100$ will provide more stringent tests of these calculations. It remains to be seen whether the WS calculations remain valid for the superheavy region; such tests will have to await much more sensitive future experiments.

SCMF theories offer a better approach, in principle, due to self-consistency. However, existing interactions need to be refined further or better ones found, which can more accurately describe the single-particle spectra [27]. As yet, most such SCMF calculations have focused on even-even nuclei (e.g., extensive calculations using the Gogny D1S interaction [9]). There are very few published SCMF calculations for odd-A nuclei, and it is important to address this shortcoming. One such example is the $\nu[734]9/2$ band in ^{253}No. The MOI of this band has been described in the framework of the relativistic

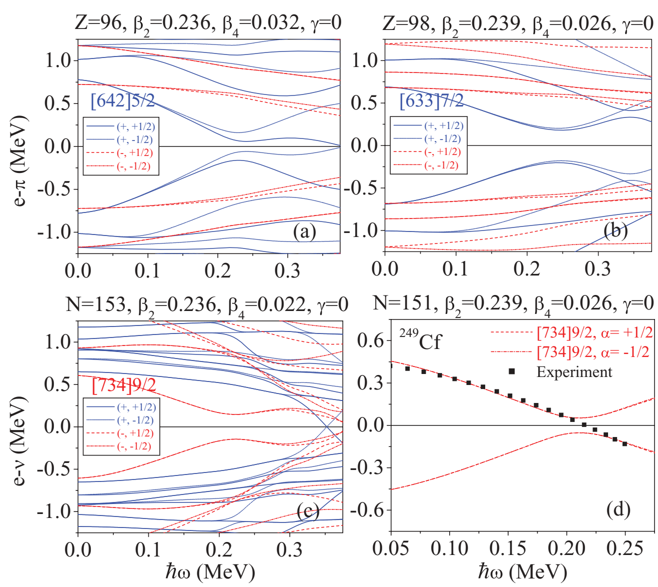

FIG. 5. (Color online) Quasiparticle levels from Woods-Saxon cranking calculations: (a) Protons in ^{247}Cm. (b) Protons in ^{249}Cf. (c) Neutrons in ^{249}Cm. (d) Calculated and experimental Routhians for the [734]9/2 neutron orbital in ^{249}Cf. The experimental energy has been offset by an arbitrary amount.

mean-field theory [6,8], and Skyrme Hartree-Fock calculations using the SLy4 interaction [7]. The latter calculations are in better agreement with experiment. More such calculations are required for odd-A transplutonium nuclei since they can provide sensitive and discriminating tests of the validity of various SCMF approaches and interactions.

In summary, rotational bands in the odd-A nuclei ^{247,249}Cm and ^{249}Cf have been identified up to high spins. This work provides the first detailed information on high-spin collective structures in several odd-A nuclei near the region where shell effects are responsible for stability. The $\nu[734]9/2$ and $\nu[620]1/2$ orbitals are the highest-lying neutron configurations investigated thus far up to high spin, with the [620]1/2 state being from above the $N = 164$ subshell gap. The underlying nucleonic configurations have been inferred from measured branching ratios. The variation of collective properties with both proton and neutron number has been investigated. Cranking calculations using the universal parametrization of the Woods-Saxon potential and a quenched, empirical pair-gap energy describe most of the observed properties, but there is no consistent explanation for the absence of alignment of $j_{15/2}$ neutrons in several nuclei. Calculations using self-consistent mean-field approaches for the heaviest odd-A nuclei accessible to spectroscopy are required for discriminating between and possibly improving available approaches and interactions. More sensitive experiments to investigate odd-A transfermium nuclei are on the horizon, and will add to existing sparse data and contribute to the refinement of theoretical descriptions of the heaviest nuclei.

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