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$K^\pi = 8^-$ isomers and $K^\pi = 2^-$ octupole vibrations in $N = 150$ shell-stabilized isotones

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Isomers have been populated in ^{246}Cm and ^{252}No with quantum numbers $K^\pi = 8^-$, which decay through $K^\pi = 2^-$ rotational bands built on octupole vibrational states. For $N = 150$ isotones with (even) atomic number $Z = 94$–102, the $K^\pi = 8^-$ and 2^- states have remarkably stable energies, indicating neutron excitations. An exception is a singular minimum in the 2^- energy at $Z = 98$, due to the additional role of proton configurations. The nearly constant energies, in isotones spanning an 18% increase in Coulomb energy near the Coulomb limit, provide a test for theory. The two-quasiparticle $K^\pi = 8^-$ energies are described with single-particle energies given by the Woods-Saxon potential and the $K^\pi = 2^-$ vibrational energies by quasiparticle random-phase approximation calculations. Ramifications for self-consistent mean-field theory are discussed.

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I. INTRODUCTION

Superheavy nuclei (SHN) represent a frontier of nuclear science. In these nuclei, the average attraction between nucleons is offset by the Coulomb repulsion between protons. This balance is especially sensitive to the properties of nucleon-nucleon interactions, which lead to gaps in the energies of the quantum states. The result is a shell-correction energy, which lowers the ground state and creates a barrier against fission, enabling the existence of the SHN. Locating the states near the Fermi surfaces is critical for an accurate theoretical understanding of SHN and for predicting where nuclear systems ultimately come to an end. Nuclear models predict different magic shell gaps for SHN at atomic number $Z = 114$, 120, or 126 due to differences in the energies of these states (e.g., see Ref. [1]). The heaviest element whose existence has been confirmed has $Z = 112$ [2], but there have been exciting reports [3,4] of the synthesis of elements with $Z = 113$–116, 118. Traditionally, SHN have been investigated by synthesizing nuclei with ever-increasing mass. Recently, a new approach has emerged, which elucidates the structural properties of heavy systems around $Z = 100$ and, thereby, infers answers to key questions. As with their heavier cousins, nuclei with $Z \sim 100$ survive only because of shell stabilization. However, with their larger production cross sections, spectroscopy of excited states is possible. Deformation drives down single-particle energies, so that orbitals from above a predicted $Z = 114$ gap can be probed.

In ^{254}No, 2- and 4-quasiparticle (qp) high-K isomers have been identified [5,6]. The energies of 2-qp states, determined via their decay, provide discriminating tests [5] of the predictions of nuclear models and, specifically, reveal that single-particle energies given by the universal Woods-Saxon potential [7] are accurate, up to at least $Z = 102$. In contrast, those given by self-consistent mean-field theories exhibit deficiencies and signal the need for improved interactions [5], with implications for predictions of magic gaps for superheavy nuclei. The low energy (0.99 MeV) of a 2-qp $K^\pi = 3^+$ state in ^{254}No, as well as 1-qp states in ^{251}Es, ^{247}Bk [8], ^{255}Lr, and ^{251}Md [9], provides firm data on the energy of the proton 1/2[521] orbital from the $f_{5/2}$ shell above the $Z = 114$ gap. Since various models give energy gaps at different proton or neutron numbers, a comprehensive test requires a collection of data with varying neutron and/or proton numbers.

As a basis for comparison, Woods-Saxon energies, given in Fig. 1, suggest the following features. The well-known $N = 152$ gap, visible in α or neutron separation energies, would lead to higher neutron 2-qp excitation energies in $^{254}_{102}\mathrm{No}_{152}$ and, thereby, favor low-energy proton 2-qp states. This was indeed observed [5,6]. Decreasing N by 2 moves the neutron Fermi level between two orbitals with large Ω and should yield a low-lying neutron 8^- {9/2[734], 7/2[624]} isomer. Furthermore, a neutron 2^-{9/2[734], 5/2[622]} state should also have low energy, which would then constitute a major component of the wave function of a $K^\pi = 2^-$ octupole vibrational state. As the proton Fermi level is varied for $N = 150$ isotones, any change in the 8^- or 2^- energies would signal contributions from proton configurations, thereby providing data on the proton energies. For example, from Fig. 1, one can predict a low-lying proton 2^- {7/2[633], 3/2[521]}

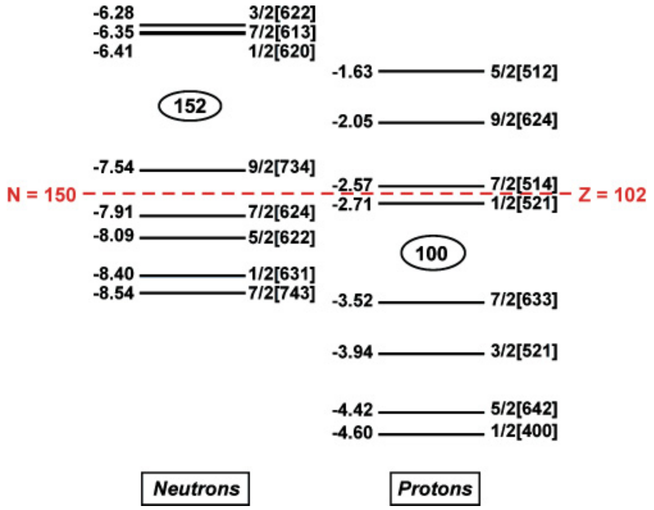

FIG. 1. (Color online) Single-particle levels for ^{252}No ($\beta_2 = 0.24$) from the Woods-Saxon potential with the so-called universal [7] parameter set, which describes near closed-shell nuclei with mass 40–208. The dashed lines indicate the approximate locations of the respective Fermi levels.

configuration at $Z = 98$. In addition, if a significant span of Z could be covered, one would test whether nuclear properties, such as the octupole vibration, might change with increasing Coulomb energy.

In this work, we report on $K^\pi = 8^-$ isomers and $K^\pi = 2^-$ octupole vibrational bands in the $N = 150$ isotopes, ^{246}Cm and ^{252}No. For the first time, we also present the complete set of 8^- and 2^- energies for $N = 150$ isotones with Z ranging from 94 to 102. The results confirm the above expectations and support single-particle energies given by the Woods-Saxon potential. The trend of $K^\pi = 2^-$ energies is reproduced in quasiparticle random-phase approximation (QRPA) calculations, including a pronounced minimum in ^{248}Cf [10], which reflects two close-lying proton single-particle levels at $Z = 98$.

II. EXPERIMENTS

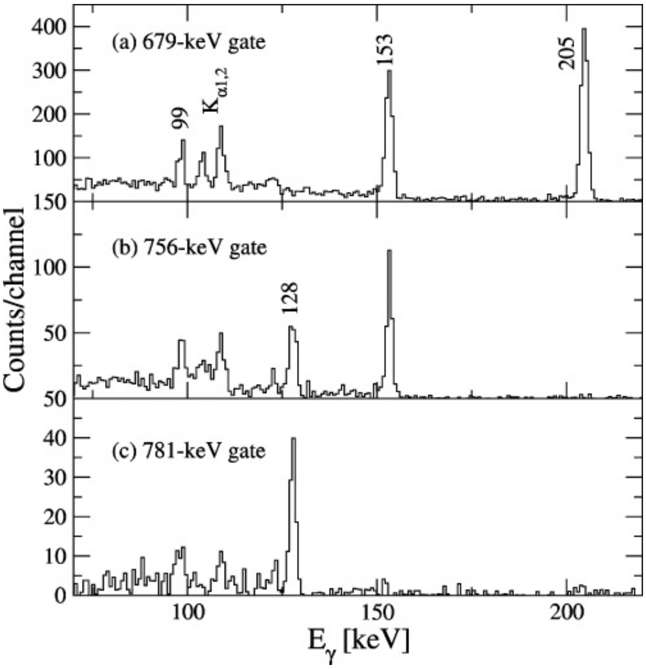

FIG. 2. Coincidence γ spectra obtained with gates on the (a) 679-, (b) 756-, and (c) 781-keV γ rays in ^{246}Cm. The labels give the energies of the peaks in keV.

We have investigated the level scheme of ^{246}Cm in the β^- decay of ^{246}Am ($T_{1/2} = 39$ m, $I, K^\pi = 7, 7^-$), which was produced by the ^{244}Pu(α, pn) reaction at a beam energy of 42 MeV. The americium was chemically isolated, using the procedures described in Ref. [11], and sources were prepared after mass separation in an electromagnetic isotope separator [12]. Conversion electron spectra and γ-γ coincidences were measured. Several coincidence γ spectra are displayed in Fig. 2. The coincidences and intensities observed here, together with all other coincidence relationships, unambiguously establish the decay scheme in Fig. 3(a), which was first inferred [13] based only on energy sums. The intensities of the 128-keV peak in Figs. 2(b) and 2(c) confirm its assignment as $E2$ transitions connecting both the interband $8^- \rightarrow 6^-$ and intraband $6^- \rightarrow 4^-$ transitions. In addition, the measured L conversion coefficients [$\alpha_{L1,2} = 3.4(5)$, $\alpha_{L3} = 1.6(2)$] and the $\alpha_{L1,2}/\alpha_{L3}$ ratio [2.1(4)] unambiguously establish $E2$ multipolarity for both transitions at 128 keV. The 8^- state decays through a rotational band built on the $K^\pi = 2^-$ octupole vibrational state [13,14] and to the 8^+ member of the ground state band. Based on the low K x-ray intensity (<1.6% of $K^\pi = 8^-$ intensity, after subtracting the contributions of low-energy transitions), the high-energy interband transitions must have $E1$ multipolarity, with $M1$ ruled out [I_{KX} (theory) =0.6 and 9.4% for $E1$ and $M1$, respectively]. Based on

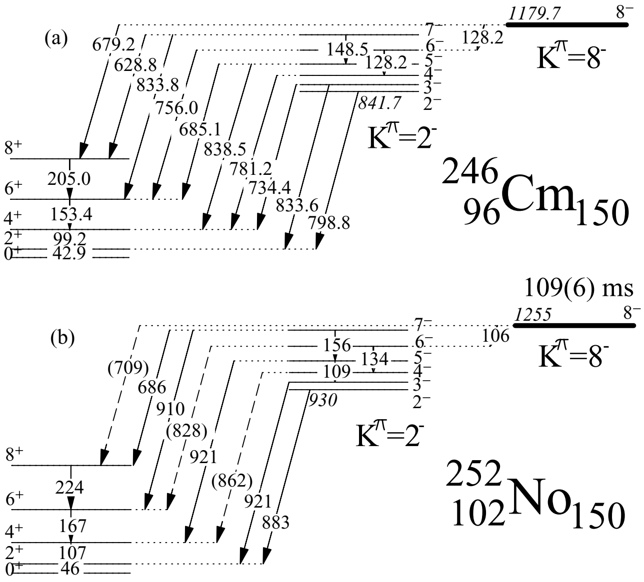

FIG. 3. Decay scheme of $K^\pi = 8^-$ isomers in (a) ^{246}Cm and (b) ^{252}No. In each case, the low-energy $8^- \rightarrow 7^-$ transition, although not directly detected (and not shown), can be confidently deduced.

all the above, an *unequivocal* assignment of $I, K^\pi = 8, 8^-$ is made for the 1180-keV state. A recent measurement has demonstrated that this state is an isomer [15]. The ground state and $K^\pi = 2^-$ rotational bands demonstrate that nuclei in this mass region are excellent deformed rotors. The levels of the latter are accurately described (within 0.2 keV) by a rotational model, with $E_I = E_0 + AI(I+1) - B[I(I+1)]^2$, where $A = 5.827$ keV and $B = 1.19$ and 0 eV for odd and even spin levels, respectively.

To investigate ^{252}No, an isotone of ^{246}Cm, a ^{48}Ca beam from the Argonne ATLAS accelerator facility bombarded a $\sim$0.5 mg cm^{-2} thick ^{206}Pb target, mounted on a rotating target wheel. The center-of-target energy was $\sim$217 MeV. The experiment was run for $\sim$6 days with an average beam current of $\sim$70 pnA. ^{252}No was produced via the $2n$-evaporation channel with an estimated cross section of 500 nb. The Argonne fragment mass analyzer (FMA) [16] was set to transmit $A = 252$ recoils, with charge states $q = 19^+$ and 20^+, through the focal plane detectors, into a double-sided Si strip detector (DSSD) with 40 × 40 strips, each 1 mm wide. Further information may be found in Refs. [17,18]. Approximately 3600 ^{252}No nuclei were detected. An isomeric decay was identified by an electron signal in the DSSD occurring within $\sim$0.7 s of an $A = 252$ recoil being implanted into the same pixel. The electron sum-energy spectrum [19] for isomeric decays is presented in Fig. 4(a). The electron time distribution corresponds to a half-life of 109(6) ms (see inset). The isomeric electron signal in a single pixel is followed by α's (including the 8.4-MeV peak) and fissions from the decay of the ground state of ^{252}No. γ rays were detected, in prompt coincidence with isomeric electrons, in two large clover Ge detectors (each consisting of four crystals) with a total efficiency of $\sim$7% at 900 keV. Figure 4(b) shows γ rays in prompt coincidence with the isomeric electrons. The γ spectrum is highly fragmented, with both high- and low-energy γ rays. Several of the latter are from the ground state band and have been previously identified [20]. The level scheme was constructed, guided by that of ^{246}Cm, which shows that the 8^- isomer decays via a 2^- band, with a direct branch to the 8^+ member of the ground state band. In addition, a rotational model for the $K^\pi = 2^-$ band provided an aid. When statistics are limited, the guidance from a model is indispensable [5,21], where one exploits the fact that nuclei in this mass region are excellent prolate rotors. In the case of the $K^\pi = 2^-$ band of ^{252}No, the rotational parameters in the model (see above), $A = 6.06$ keV, $B = 0.25$ and 0 eV for odd- and even-spin levels, give a very good description (within 1 keV) of the whole set of observed γ rays, with the bandhead energies given in Fig. 3(b). (The weakest γ rays are identified only as candidate transitions based on the model and could otherwise not be identified as peaks.) The large number of decay pathways permits a reasonably confident construction of the decay scheme due to consistent energy sums. The assignment of the 108-keV transition as a triplet of $E2$ transitions is consistent with the intensity $T = (1+\alpha)I_\gamma \sim 24I_\gamma = 250\%$ of the isomer decay strength, where α is the conversion coefficient. The decay scheme of the isomer (reported in preliminary form in Ref. [22]) is given in Fig. 3(b). It agrees with and confirms that of Ref. [23], from work which was conducted in parallel. The electron sum-energy spectrum has been calculated based on the level scheme and closely resembles the measured one; see Fig. 4(a). Limited observed coincidences support the decay scheme but are insufficient to prove it. The level schemes of ^{246}Cm and ^{252}No, and also that of ^{250}Fm [24], are strikingly similar.

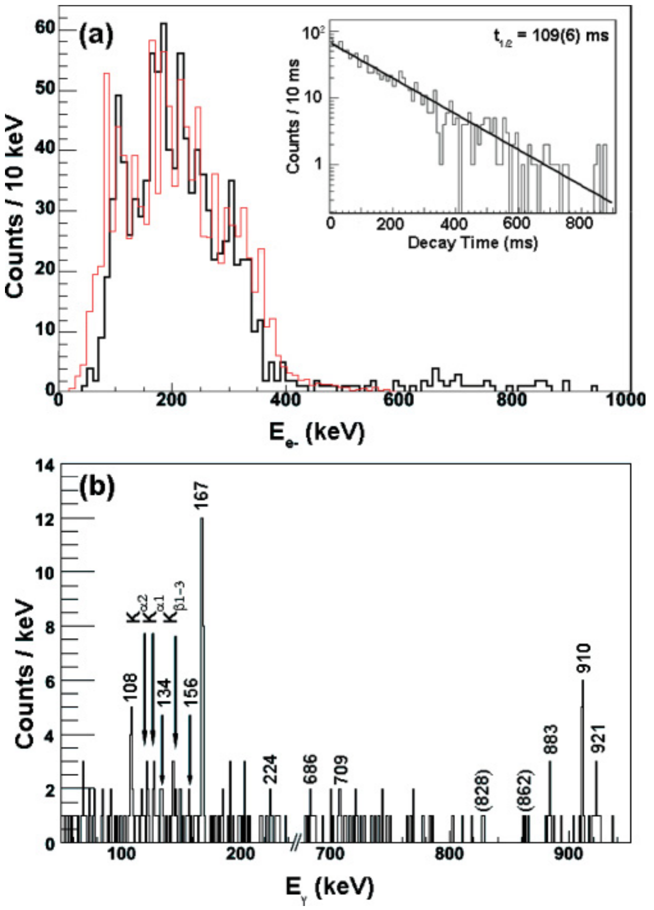

FIG. 4. (Color online) Electron sum-energy spectra from the decay of the isomer in ^{252}No (black histogram: experiment; red thin line: calculated). The inset gives the decay time distribution of the isomer. (b) γ spectrum from the isomer, from coincidences with the isomeric electrons in (a). Typical uncertainties in energy are 0.5 and 1 keV in the low- and high-energy portions of the spectrum, respectively.

With low 8^- energies of neutron and proton configurations observed in ^{252}No and ^{254}No, respectively, a long-lived 4-qp 16^+ isomer is expected. There was no evidence for this isomer within a search interval of $\sim$2 h.

III. DISCUSSION

It is illuminating to inspect the systematics of the $N = 150$ isotones. In ^{248}Cf, a $K^\pi = 2^-$ octupole band has been established [10], with the 2^- bandhead at 592 keV. Population of the band in the ^{249}Cf(d, t) reaction indicates that a major component of its wave function is the neutron 2^- {9/2[734], 5/2[622]} configuration [10]. From the 9/2[734] ground state of ^{249}Cf, this reaction should also populate

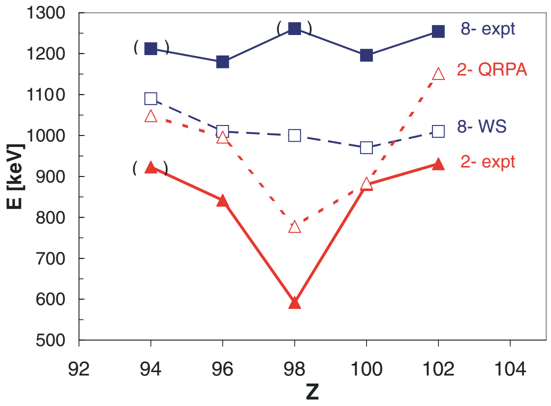

FIG. 5. (Color online) Energies of $K^\pi = 2^-$ and 8^- states for $N = 150$ isotones with even Z; filled and open symbols represent experimental and theoretical results, respectively. Theory: $K^\pi = 8^-$ energies are obtained as described in the text with Woods-Saxon (WS) single-particle energies; results (not shown) from the Gogny interaction [31] are within 50 keV. $K^\pi = 2^-$ octupole vibration energies are from QRPA calculations. References for experimental data are given in square parentheses: ^{246}Cm [this work], ^{252}No [this work and Ref. [23]], ^{244}Pu [26,28], ^{248}Cf [10,25], ^{250}Fm [24]. Bracketed symbols represent information deduced or reassigned in this work (see text).

the $K^\pi = 8^-$ {9/2[734], 7/2[624]} state in ^{248}Cf. We have assigned the levels at 1261 and 1351 keV [25] in Fig. 2 of Ref. [10], which were previously unassigned, as the 8^- and 9^- members of the $K^\pi = 8^-$ band, with relative cross sections consistent with transfer of a 7/2[624] neutron.

In ^{244}Pu the 3^- member of the $K^\pi = 2^-$ band at 957 keV is strongly populated in the (d, d') reaction [26], giving a 2^- bandhead energy of 923(3) keV, assuming a rotational parameter of 5.67 keV. In ^{244}Pu, we suggest that the level at 1216 keV [27], which was previously assigned [28] $I^\pi = 7$ or 8^+, should instead have $I^\pi = 8^-$. With similar log ft values, we propose that the β^- decay of both ^{244}Np $\rightarrow$ ^{244}Pu and ^{246}Am $\rightarrow$ ^{246}Cm proceed via the transition $7^-\{5/2[642]\pi, 9/2[734]\nu\} \rightarrow 8^-\{7/2[624]\nu, 9/2[734]\nu\}$. Finally, in ^{250}Fm, $I, K^\pi = 2, 2^-$ and $8, 8^-$ states have been recently identified [24].

The energies of $I, K^\pi = 2, 2^-$ and $8, 8^-$ states in the $N = 150$ isotones are displayed in Fig. 5. They span an impressively wide range of $Z = 94$–102, especially for such heavy nuclei. The neutron pickup reaction to ^{248}Cf establishes a {9/2[734], 7/2[624]} neutron 2-qp configuration for the 8^- state, which is also evident from an inspection of the Woods-Saxon single-particle energies given in Fig. 1. The 8^- energies are rather constant (within 75 keV), a feature expected for isotones and reproduced by the calculated 8^- energies. The latter are 120–260 keV lower than the measured ones, but within the model uncertainty of ~300 keV. The 2-qp energies are calculated as described in Refs. [5,29], using Woods-Saxon single-particle energies and a Lipkin-Nogami [30] prescription for pairing, which incorporates a reduction of pairing due to blocking of occupied orbitals. The pairing strengths are $G_\nu = 17.8/A$ and $G_\pi = 24/A$. A residual interaction of -0.1 MeV is included for the 8^- spin singlet states. A comprehensive paper [31], based on the Hartree-Fock Bogoliubov (HFB) method with the Gogny D1S interaction, also reports 8^- energies for the $N = 150$ isotones, which are nearly constant around 1.05 MeV. With the inclusion of time-reversal symmetry breaking, the energies will decrease by ~0.05 MeV, giving energies within 50 keV of those from the Woods-Saxon potential.

Figure 5 indicates that the energies of the 2^- octupole bandhead are also constant within 90 keV, except in $^{248}_{98}\mathrm{Cf}_{150}$, where there is a sharp 34% drop. It is possible to recognize this singular minimum only when *all* energies in the isotonic chain are known. Figure 1 suggests that the 2^- {9/2[734], 5/2[622]} neutron configuration has a low energy and that it would constitute a major component in the wave function of a 2^- octupole state. The strong population in the ^{249}Cf(d, t) reaction [10] verifies this configuration. The localized minimum at $Z = 98$ suggests a near degeneracy in the proton 7/2[633] and 3/2[521] energies, even closer than the spacing given in Fig. 1. (The contribution of these proton orbitals is manifested in the population of the 2^- octupole band in the ^{249}Bk$(\alpha, t)^{250}$Cf reaction [32].) Indeed, the single-particle spectrum extracted in Ref. [33] reveals this degeneracy. Only in ^{248}Cf is there a confluence of low-lying proton and neutron 2^- states, increasing the octupole collectivity and, thereby, lowering the vibrational energy.

QRPA calculations [34] for octupole vibrations have been performed, based on quasiparticle excitations in a Nilsson potential. Instead of the standard Nilsson parameters, which yield some incorrect neutron single-particle energies for very heavy nuclei [35], a modified parametrization [35] was used, which gives single-particle energies approximating those from the Woods-Saxon potential. (Since the theoretical framework [34] of our program, including the self-consistent determination of matrix elements, has been developed—and tested—based on the Nilsson potential, calculations with the Woods-Saxon potential were not conducted.) The QRPA results give low-lying $K^\pi = 2^-$ octupole vibrational energies, which reproduce the trend with Z of the 2^- energies, including the minimum at $Z = 98$. All calculated energies are larger by <200 keV. This difference is not significant, since the calculated energies are very sensitive [36] to the magnitude of the octupole force, e.g., a 2% increase would give agreement with experiment. The wave functions from the QRPA calculations support the qualitative explanation given above. In particular, they show a peak in the proton 2^- 2-qp {7/2[633], 3/2[521]} amplitude at $Z = 98$ due to the drop in its energy.

With the exception of the sharp dip in the 2^- energy of ^{248}Cf, the energies of the 2^- and 8^- states are nearly constant over a wide span of $Z = 94$–102, up to the heaviest element known to have an octupole band and a high-K isomer. This interval encompasses an 18% increase in the Coulomb energy, yet the 8^- and 2^- energies remain very stable, probably the longest span with this feature for an isotonic series. This feature provides a test for self-consistent mean-field theory, which suggests that the large Coulomb energy could lead to shifts in the underlying single-particle energies [37]. However, the data do not reveal any discernible shift up to $Z = 102$. Can self-consistent HFB theories reproduce the 2^- and 8^- energies? The Gogny interaction gives a good description of the 8^- states [31], suggesting acceptable neutron single-particle energies. No results have been reported for collective 2^- energies. However, we note problems with proton single-particle spectra from the Gogny [31] and SLy4 [9] interactions, which yield gaps at $Z = 98$, 104 vs 100 with the Woods-Saxon potential. This is reflected in, for example, the discrepant proton 2^- 2-qp {7/2[633], 3/2[521]} energies for ^{248}Cf: 1.78 and 1.08 MeV, with the Gogny interaction [31] and the Woods-Saxon potential, respectively. (Problems are also seen in the relativistic mean-field theory with the commonly used Lagrangians [1].) The singular drop in the 2^- energy for ^{248}Cf reflects the small separation between the 7/2[633] and 3/2[521] proton levels at $Z = 98$ [33]. With a gap here instead, we predict that it would be a challenge for HFB theories to reproduce the sharp minimum.

IV. CONCLUSIONS

In summary, new conversion-electron and γ-γ coincidence measurements have firmly established the decay scheme and I, K^π assignments of the $K^\pi = 8^-$ state and 2^- band in ^{246}Cm. The decay scheme of an isomer in ^{252}No confirms that of Ref. [23] and defines the $K^\pi = 8^-$ and 2^- states. The results in ^{246}Cm, together with our new assignment for the $K^\pi = 8^-$ state in ^{248}Cf, anchor the assignments in the other $N = 150$ isotones. With the inclusion of previously published results, some reinterpreted, these isotones reveal remarkably constant 2^- and 8^- energies for a wide interval $Z = 94$–102. A singular minimum in the 2^- energy at $Z = 98$, which is described in QRPA calculations, provides an exquisitely specific indicator of the degeneracy of two particular proton orbitals around the Fermi level. The energies of 2-qp and vibrational states reveal details of the single-particle spectrum. The nearly constant 8^- energies imply rather pure neutron excitations and suggest that the deformed mean field is little altered by an 18% increase in the Coulomb energy. This set of systematic energies for $N = 150$ isotones encompassing a wide span in Z (94–102) demonstrates that one common framework, which incorporates deformation, describes the nuclei in this mass region. The data for the $N = 150$ isotones, as well as for ^{254}No [5,6], are reproduced with Woods-Saxon single-particle energies. The current best interactions (Gogny and SLy4) in self-consistent mean-field models give proton energy gaps and degeneracies at ostensibly the wrong locations. Since different theories predict different magic gaps for superheavy nuclei, these findings are important for a quantitative understanding of the heaviest nuclei.

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