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High-K structure in ^{250}Fm and the deformed shell gaps at $N = 152$ and $Z = 100$

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The structure of high-spin and nonyrast states of the transfermium nucleus ^{250}Fm has been studied in detail. The isomeric nature of a two-quasiparticle excitation has been exploited in order to obtain spectroscopic data of exceptional quality. The data allow the configuration of an isomer first discovered over 30 years ago to be deduced, and provide an unambiguous determination of the location of neutron single-particle states in a very heavy nucleus. A comparison to the known two-quasiparticle structure of ^{254,252}No confirms the existence of the deformed shell gaps at $N = 152$ and $Z = 100$.

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The existence of atomic nuclei with a proton number of more than 100 or so is dependent on the underlying single-particle shell structure, the effects of which act to overcome the strong Coulomb repulsion between the protons. These shell effects result in the prediction of an "island" of spherically symmetric and rather stable superheavy nuclei. A theoretical description of the properties of these nuclei requires extrapolation to a region far removed from that used to fit the interactions used in current self-consistent mean-field models. The heaviest elements are experimentally difficult to study in detail, as in the most extreme cases it is only possible to produce a few atoms per month [1,2]. Nuclei in the vicinity of ^{254}No are axially deformed, due to stabilizing gaps in the single-particle energy spectra away from sphericity. Recent Hartree-Fock-Bogoliubov calculations using the Skyrme interaction SLy4 for this mass region predict the largest deformed shell gaps at proton number $Z = 98$ and 104, and at neutron number $N = 150$ (see, e.g., Ref. [3]), whereas macroscopic-microscopic approaches tend to predict $Z = 100$ or 102 and $N = 152$ [4]. Nuclei in this region can be produced with rates of tens per hour, rendering them accessible to modern in-beam spectroscopic techniques, meaning that detailed and unambiguous nuclear structure data can be obtained. These nuclei also exhibit both collective and intrinsic (few particle) excitations at low energy. The axial symmetry leads to the quantum number, K, which is the projection of the total angular momentum onto the symmetry axis. Electromagnetic decay is hindered by K selection rules, giving rise to K isomers. The energies of these isomeric states reveal the underlying single-particle structure, providing a stringent test for current nuclear structure theories, essential to improve the predictive power of such models for the superheavy elements. An experiment has been performed to determine the structure of high-spin and nonyrast states in ^{250}Fm, in which the ground-state rotational band (g.s.b.) was previously observed up to a spin of $18\hbar$ [5]. One of the main aims of the experiment was to determine the structure of an isomeric state in ^{250}Fm first observed over 30 years ago by Ghiorso *et al.* [6] which has not been possible until now. The experiment employed the ^{204}HgS(^{48}Ca,$2n$)^{250}Fm reaction at a center-of-target bombarding energy of 209 MeV. The beam was accelerated by the University of Jyväskylä K130 cyclotron with an average intensity of approximately 8 pnA. The 510 μg/cm^2 ^{204}HgS targets (enrichment 90.5%) were covered with thin layers of carbon (<30 μg/cm^2). Fusion-evaporation residues of ^{250}Fm were separated from the primary beam and fission products by the gas-filled recoil separator RITU [7], and implanted in the double-sided silicon strip detectors (DSSD's) of the GREAT spectrometer at the focal plane (see Ref. [8] for details). Prompt γ rays produced at the target were detected by the JUROGAM array of 43 EUROGAM PhaseI-type germanium detectors [9]. The photopeak efficiency of JUROGAM is 4.2% at 1332 keV. Delayed γ rays emitted in the decay of implanted nuclei were detected in a segmented planar germanium detector located directly behind the DSSD's and in an array of three large-volume segmented clover germanium detectors surrounding the focal plane detector chamber. The photopeak efficiency of the array of clovers is estimated to be 4.6% at 1332 keV, while that of the planar detector is approximately 9% at 150 keV [10]. The energies of events occurring in all detectors were recorded by the triggerless total data readout (TDR) data acquisition system and time stamped using a 100 MHz clock [11]. Subsequent temporal- and spatial-correlations between the various detector groups were performed using the GRAIN data analysis package [12]. After 170 h of irradiation, approximately 13000 full-energy 7.43 MeV α particles from the decay of ^{250}Fm were detected. In order to confirm the presence and determine the structure of the isomeric state, a novel variation on the well-known recoil-decay tagging (RDT) technique has been used, first suggested by Jones [13–15]. A calorimetric "sum energy"

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signal from internal conversion electrons is used to indicate when the decay of the isomeric state has occurred (see Refs. [16–19]). In the present experiment, the technique has been extended to allow γ-ray transitions between states *above* the isomeric band-head to be clearly identified. This represents a clear advance in γ-ray spectroscopic techniques as delayed coincidences across isomeric states with half-lives of several *seconds* (rather than microseconds) become possible. The technique could be applied to almost any nucleus in which an isomeric state decays via a highly converted transition, within the usual constraints of implant rate and lifetime resulting from the use of correlations. In general, the electron "tag" is also more efficient than conventional isomer tagging using γ rays. This is due to the fact that the electron is emitted within the detector and the solid angle covered is large.

The spectrum of decay events observed at the same position in the DSSD and up to 10 seconds after the implantation of a fusion-evaporation residue is shown in Fig. 1(a), along with the decay curve extracted from the time difference between recoil and decay events. The half-life deduced ($T_{1/2} =$ 1.92(5) s) is in excellent agreement with the value of 1.8(1) s given by Ghiorso *et al.* [6]. More than 30 years later, the existence of the isomer can thus be confirmed.

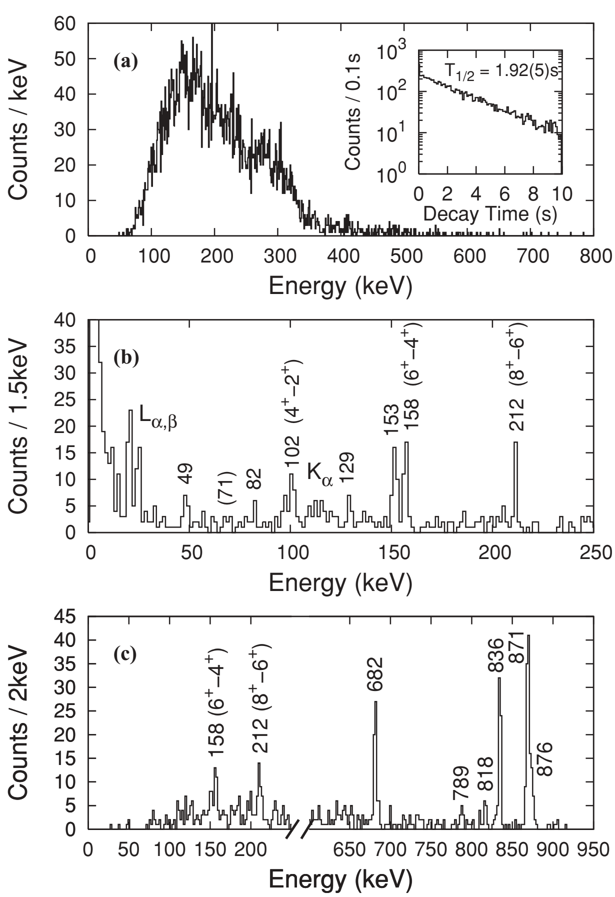

FIG. 1. (a) Spectrum of "sum energy" electrons observed within 10 s of a fusion-evaporation residue at the same position in the DSSD. (b) Gamma rays detected in prompt coincidence with the electrons of part (a) in the planar germanium detector. (c) As in (b), but in the array of clover detectors.

Figure 1(b) (planar detector) and (c) (clover detectors) shows γ-ray spectra of events in prompt coincidence with the electrons shown in Fig. 1(a). Gamma rays of energy 158 and 212 keV can be seen in both spectra, which correspond to the 6^+ to 4^+ and 8^+ to 6^+ transitions of the g.s.b. [5], suggesting a branch from the decay of the isomer to the g.s.b. Also seen in the clover spectrum are a number of higher energy γ rays, with energies as marked in the figure. A limited number of γ-γ coincidences were observed between events in the planar and clover detectors, which allow the 682 and 871 keV transitions to be placed feeding the 8^+ and 6^+ states of the g.s.b., respectively. A relatively strong γ ray of energy 836 keV is visible in the clover spectrum [Fig. 1(c)], which is also seen in the recoil-gated γ-ray singles spectrum shown in Fig. 2(a).

The spectrum shown in Fig. 2(a) consists of those γ rays detected at the target position by the JUROGAM array when a fusion-evaporation residue is registered at the focal plane of RITU. This indicates that the 836 keV γ ray must be due to a transition which is fast (order of ns or below), otherwise the γ ray would be emitted outside the focus of

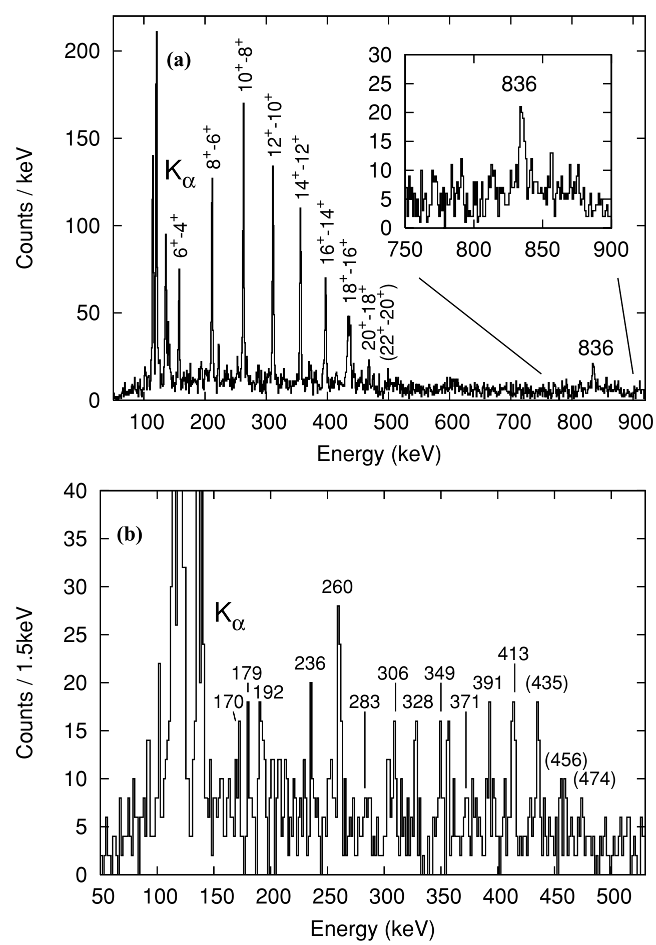

FIG. 2. (a) Spectrum of γ rays detected in the JUROGAM array when a fusion-evaporation residue is observed at the focal plane of RITU. (b) As in (a), with the additional requirement that an electron sum event is observed within 10 s of the recoil at the same position in the DSSD.

the germanium detectors. The fact that transitions (at least corresponding to the 836 keV γ ray) which are observed at the focal plane are observed in the prompt spectrum of Fig. 2(a) indicates that there is feeding which bypasses the isomeric state. Consideration of the Alaga rules [20], the observed decay pattern and comparison to the known decay properties of $K^\pi = 2^-$ bands in ^{250}Cf and ^{246}Cm [21,22], leads to the conclusion that the 836 keV γ ray corresponds to a transition from a high-lying 2^- state to the g.s.b. 2^+ state. Energy sum arguments along with the limited γ-γ coincidence data can then be used to construct the level scheme from the decay of the isomeric state shown in the lower part of Fig. 3. The other high-energy transitions (789, 818, 871, and 876 keV) are assigned as interband $E1$ transitions from the $K^\pi = 2^-$ band to the g.s.b., while the 682 keV γ ray is assigned to be

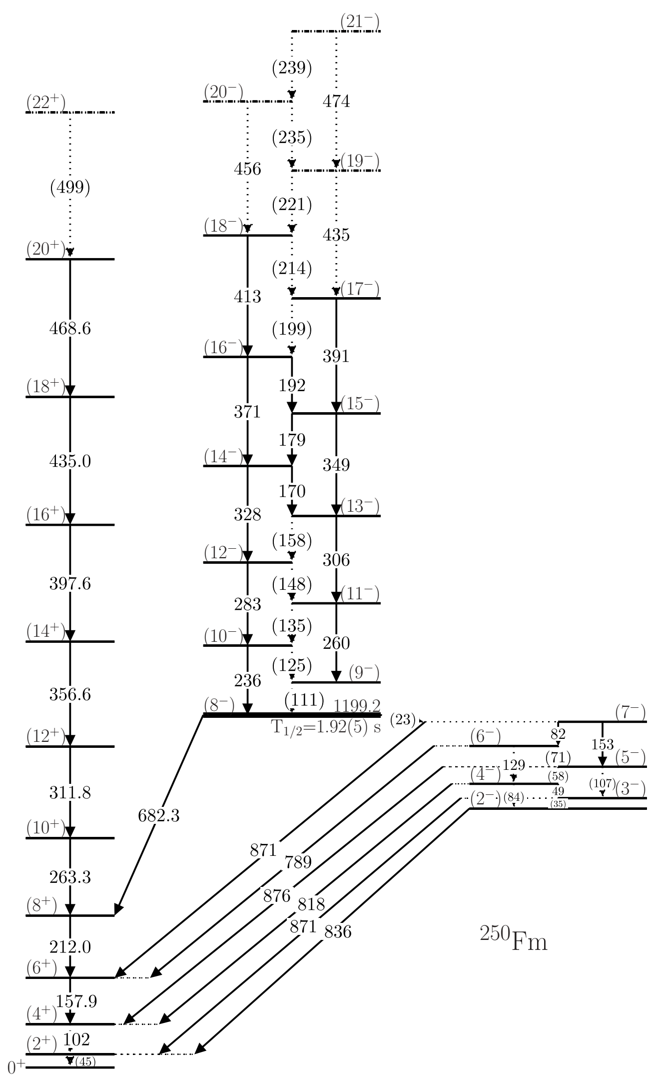

FIG. 3. Partial level scheme of ^{250}Fm deduced in the present work. The ground state rotational band had previously been observed up to a spin of $18\hbar$ [5]. The $M1$ transition energies in the $K^\pi = 8^-$ band are marked for clarity though a large number of them were not observed. The error on the transition energies shown is ± 0.5 keV for those marked to one decimal place and ± 1 keV for those marked with integer numbers.

due to an $E1$ transition from an isomeric $K^\pi = 8^-$ state at an excitation energy of 1199.5 keV. Energy sum arguments lead to the conclusion that the 7^- member of the $K^\pi = 2^-$ band must be fed by an unobserved 23 keV $M1$ transition. Gamma rays with energies of 82 and 153 keV are also observed in the planar germanium spectrum of Fig. 1(b), corresponding to the 7^- to 6^- and 7^- to 5^- transitions, respectively. Gamma-ray intensity ratios show that the branching ratios for the 682 keV $E1$ and 23 keV $M1$ transitions are approximately 18% and 82%, respectively. The ratio of the experimental partial half-life to the Weisskopf estimate in the form $f_\nu = [t_{1/2}^{\exp}/t_{1/2}^{WU}]^{1/\nu}$, where $\nu = \Delta K - \lambda$ (λ is the transition multipolarity) gives a quantitative measure of the degree of forbiddenness of the transitions from the $K^\pi = 8^-$ state [23]. The values obtained are $f_\nu(682, E1) = 213$ and $f_\nu(23.5, M1) = 192$, for the $\Delta K = 8$ and $\Delta K = 6$ transitions, respectively. These values are somewhat larger than those determined by Hall *et al.* for the decay of the $K^\pi = 7^-$ state in ^{256}Fm (30–40), but are consistent with the as yet unpublished values for other $N = 150$ isotones [24–26]. As pointed out by Hall *et al.*, admixtures of lower K values can result in faster transitions. A much higher f_ν value of 804 is observed for the $\Delta K = 5 E1$ transition from the $K^\pi = 8^-$ isomer in ^{254}No [16,17], but this is also not exceptional as high f_ν values for $E1$ transitions have been previously observed, for example in ^{234}U [27]. The values obtained in the present case are rather "normal" and will not be discussed further here.

The electron "sum energy" signal can also be used to select *only* prompt γ rays which feed the isomeric state. The prompt γ-ray spectrum observed when a correlated fusion-evaporation residue-electron pair is found is shown in Fig. 2(b). A number of γ rays with energies as marked in the figure are clearly observed. It should be noted that the sum of 170 and 179 keV is equal to 349 keV, and that of 179 and 192 keV equal to 371 keV. It is therefore concluded that the observed γ rays belong to a strongly-coupled rotational band structure based upon the $K^\pi = 8^-$ state. The deduced structure is shown in the partial level scheme of Fig. 3. The transitions with energies 435, 456, and 474 keV are marked as tentative as they show slight deviation ($\simeq$2 keV) from the smoothly-behaving rotational band sequence. Some γ rays (e.g., 355 keV) could not be placed in the level scheme. The γ-ray energies for the g.s.b. deduced in the present work are consistently around 0.5 keV higher than those of Bastin *et al.* [5]. Careful analysis of the γ-ray energies from standard sources shows no inconsistency, therefore it is concluded that there is a systematic error in the previously published values. The fact that both $M1$ and $E2$ transitions are observed allows an experimental value for the ratio of reduced transition probabilities $B(M1)/B(E2)$ to be deduced from the intensity ratios, and compared to theoretical values obtained using rotational model formulas [28] (see Table I). The lowest-lying $K^\pi = 8^-$ two-quasiparticle configurations are expected to be the neutron $\nu[734]9/2^- \otimes \nu[624]7/2^+ (g_K = -0.0225)$ and the proton $\pi[624]9/2^+ \otimes \pi[514]7/2^- (g_K = +1.001)$ [29]. Xu *et al.* also suggest a $K^\pi = 7^-$ proton $\pi[633]7/2^+ \otimes \pi[514]7/2^-$ configuration, which is discounted on the basis of the present level scheme [29].

TABLE I. Experimental and theoretical reduced transition probabilities $B(M1)/B(E2)$.

Initial spin ($\hbar$)	$B(M1)/B(E2)$ th.$(\mu_N/eb)^2$	$B(M1)/B(E2)$ th.$(\mu_N/eb)^2$	$B(M1)/B(E2)$ expt.$(\mu_N/eb)^2$
$K^\pi = 2^-$ band[a]			
7	–	0.03	0.02(1)
$K^\pi = 8^-$ band	proton[b]	neutron[c]	
14	0.77	0.38	0.2(1)
15	0.71	0.35	0.3(1)
16	0.67	0.32	0.3(1)

[a] $\nu[734]9/2^- \otimes \nu[622]5/2^+$ configuration only.
[b] $\pi[624]9/2^+ \otimes \pi[514]7/2^-$ configuration.
[c] $\nu[734]9/2^- \otimes \nu[624]7/2^+$ configuration.

A $K^\pi = 2^-$ state can be formed from the two-neutron configuration $\nu[734]9/2^- \otimes \nu[622]5/2^+ (g_K = -0.125)$, though it is expected that the wave function for this state is mixed, as has been shown for similar bands, e.g., in the isotone ^{248}Cf [30]. The theoretical values obtained using $g_R = 0.4$ and a value for Q_0 of 12.6 eb are shown in Table I. It can be seen that the experimental values are in excellent agreement with those expected for the neutron configurations, providing an assignment of the $\nu[734]9/2^- \otimes \nu[624]7/2^+$ configuration to the $K^\pi = 8^-$ isomer. The experimental value obtained for the $K^\pi = 2^-$ state is also remarkably close to that expected for the pure two-neutron configuration, which indicates the dominance of neutron excitations.

Proton two-quasiparticle $K^\pi = 8^-$ isomeric and $K^\pi = 3^+$ states have recently been identified in the $Z = 102$ and $N = 152$ nucleus ^{254}No [16,17]. Recently, a $K^\pi = 8^-$ isomeric state was found in ^{252}No and assigned the neutron two-quasiparticle configuration $\nu[734]9/2^- \otimes \nu[624]7/2^+$, though this could not be determined unambiguously from the data obtained [18].

The change in character of the $K^\pi = 8^-$ states can be understood with consideration of the data represented in Fig. 4. The plot shows the experimental level energies of the $K^\pi = 8^-$ states along with the experimentally observed $K^\pi = 3^+$ and 2^- states. Also shown are calculations of the $K^\pi = 8^-$ two-quasiparticle states based on a Woods-Saxon potential using the "Universal" parametrization with deformation parameters taken from Ref. [4]. For a discussion of the systematic behavior of the $K^\pi = 2^-$ bands in the $N = 150$ isotones, see Ref. [19]. The pair gap parameters Δ_p and Δ_n are taken from Ref. [31] and quenched by a factor of 0.6, to mimic the effect of blocking. This simple approach reproduces the energies of the proton and neutron $K^\pi = 8^-$ two-quasiparticle states in ^{254,252}No using the Lipkin-Nogami pairing formalism and including effects due to the spin-dependent residual interaction to within $\simeq$100 keV (see Refs. [17,19]). One sees that in ^{254}No, the states based on neutron configurations are at much higher excitation energy due to the existence of the deformed shell gap at $N = 152$, enclosed by the $\nu[620]1/2^+$ and $\nu[734]9/2^-$ single-particle states. In going to ^{252}No ($N = 150$), the energy of the neutron 8^- state is lowered dramatically as the Fermi surface moves below the $N = 152$ gap between the $\nu[734]9/2^-$ and $\nu[624]7/2^+$ states, while that of the proton state remains rather constant, as expected. Further, in going to ^{250}Fm, the states based on proton configurations move to much higher energies, as the Fermi surface now moves into the deformed shell gap at $Z = 100$ between the $\pi[521]1/2^-$ and $\pi[633]7/2^+$ states. The data obtained recently in neighboring nuclei and in the present work therefore lend support to the existence of deformed shell gaps at $Z = 100$ and $N = 152$. To date, few self-consistent calculations of the two-quasiparticle energies exist which could be used for comparison. Delaroche *et al.* reproduce a low-energy $K^\pi = 8^-$ neutron configuration in ^{250}Fm using the Gogny interaction, but fail to reproduce the proton $K^\pi = 8^-$ in ^{254}No [32]. As discussed earlier, calculations using the Skyrme interaction SLy4 predict the largest deformed shell gaps at proton number $Z = 98$ and 104, and at neutron number $N = 150$ [3]. Similar discrepancies exist for other parametrizations of the Skyrme interaction, for example SkI4 [33]. The new experimental data on two quasiparticle states in this region can provide a stringent test and impact on the development of self-consistent theories, and a systematic and critical analysis of the various interactions available is clearly called for. In order to make accurate predictions of the structure and stability of the heaviest elements, these discrepancies must be addressed.

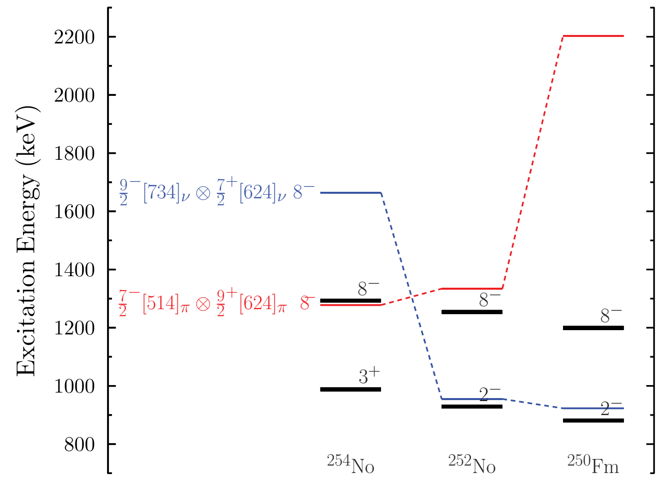

FIG. 4. (Color online) Comparison of experimentally observed and calculated energies of $K^\pi = 8^-$ two quasiparticle states in ^{254}No, ^{252}No, and ^{250}Fm. Experimental levels are marked with thicker lines. See text for details.

In summary, the structure of high-spin and nonyrast states in ^{250}Fm has been investigated in detail using novel spectroscopic techniques. The configuration of a $K^\pi = 8^-$ isomeric two-quasiparticle state could be determined, and comparison with similar states in ^{252,254}No supports the existence of the deformed shell gaps at $N = 152$ and $Z = 100$. As yet, modern self-consistent theories do not reproduce well the locations of these deformed shell gaps. The discrepancies between theory and experiment must be addressed in order to improve our understanding of the heaviest nuclei.

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