Ground-State Band and Deformation of the $Z = 102$ Isotope ^{254}No

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The ground-state band of the $Z = 102$ isotope ^{254}No has been identified up to spin 14, indicating that the nucleus is deformed. The deduced quadrupole deformation, $\beta = 0.27$, is in agreement with theoretical predictions. These observations confirm that the shell-correction energy responsible for the stability of transfermium nuclei is partly derived from deformation. The survival of ^{254}No up to spin 14 means that its fission barrier persists at least up to that spin. [S0031-9007(98)08223-4]

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The classical fission barriers of the heaviest elements with $Z > 100$ approach zero because of the large Coulomb energy. However, a series of measurements [1] has established that elements with Z up to 112 are sufficiently bound against fission to preferentially decay by α emission. A large shell-correction energy leads to additional binding and, hence, creates sizable fission barriers of up to 8 MeV [2,3]. The relative stability of these very heavy elements is a striking manifestation of shell structure in nuclei, and arises from the same mechanism responsible for the proposed [4] stability of an "island" of superheavy elements around $Z = 114$, $N = 184$. Hence, nuclei with large Z ($>$100), which are stable only because of the shell-correction energy, may be characterized as belonging to the family of superheavy nuclei, since their structures and formation mechanism are governed by the same physics. We shall refer to these as transfermium nuclei (TFN).

The proposal of an island of superheavy elements was based on doubly closed neutron and proton shells, associated with a spherical shape [4]. Subsequent theoretical work (see, e.g., recent reviews [2,5]) has explained the observed stability of TFN with Z up to 112; however, in these cases, the shell-correction energy is derived from the ability of the nucleus to deform, with not only quadrupole but also higher multipole moments. Confidence in these calculations comes from their agreement with experimental α-decay energies, α-decay lifetimes, and long fission lifetimes [1,2,5,6]. A direct demonstration that these nuclei are deformed and a determination of the quadrupole deformation parameter constitute further important tests of these calculations.

The spin-dependent properties of TFN also provide another test of shell-correction energies, since rotational frequency and deformation play similar roles in determining the energies of orbitals (which represent the essence of the shell correction). For example, the moment of inertia and its variation with spin are sensitive to pairing and to the energies of quasiparticle orbitals, particularly those with high intrinsic angular momenta. The structure of nuclei at the limits of stability also provides a test of effective nuclear forces for Hartree-Fock-Bogoliubov or relativistic mean-field theories.

In addition, observation of high-spin ($I \geq 10$) states in TFN gives information on the fission barrier at high angular momentum. This information is important for understanding the mechanism for producing the heaviest elements since the fission barrier governs their survival probability. The barrier at zero spin has been calculated, but there are no predictions at finite spin, which would require calculations of the spin dependence of the shell-correction energy. In fact, it is *a priori* not obvious that high-spin states of shell-stabilized nuclei will even survive against fission.

The standard method for identifying high-spin states is in-beam γ spectroscopy with (heavy ion, xn) reactions, but it is rarely used for studying very heavy nuclei because of an overwhelming fission background. This problem can be overcome by *combining* efficient γ-ray detection power with the ability of a residue separator to identify unambiguously very weakly produced evaporation residues. The heaviest element that had been studied using this method is uranium, in ^{226}U [7], with $Z = 92$. In this Letter, we report on the ground-state band in the $Z = 102$ isotope ^{254}No, the heaviest element for which high-spin data now exist.

The ^{208}Pb(^{48}Ca, $2n$) reaction was used to produce ^{254}No. A beam energy of 215 MeV was chosen since excitation function measurements [8] showed a maximum in the production cross section ($\sim 3\ \mu$b) at this energy. The combination of ^{208}Pb and ^{48}Ca, each a doubly closed shell nucleus, results in a large negative Q value for compound-nucleus formation. The consequent low excitation energy (19.3 MeV) results in ^{254}No being essentially the only evaporation-residue channel, which survives the competition against fission.

Beams of up to 9 pnA of ^{48}Ca were provided by ATLAS, the Argonne superconducting linear accelerator. To enable the ^{208}Pb targets to survive such beams, they were mounted on a rotating wheel, which controlled pulsing of the beam, so that only the targets were irradiated. In addition, the beam was dispersed vertically by ± 2.5 mm through wobbling (at 5 Hz) with a magnetic steerer.

Gamma rays were detected using Gammasphere [9], a multidetector array consisting of 101 Ge detectors, surrounded by bismuth germanate Compton suppressors. In order to identify γ rays from ^{254}No in a background of $>10^4$ times more intense fission γ rays, it was essential to require coincidences with evaporation residues. These were separated from the beam by a fragment mass analyzer (FMA) [10]. At the focal plane of the FMA, particles were detected in a position-sensitive detector, either a multichannel-plate detector in one experiment or a parallel-plate avalanche counter in a second experiment. After transmission through the focal-plane detector, the residues were implanted in a double-sided Si strip detector (DSSD), which had 1600 (1×1)-mm pixels. To isolate the rare nobelium residues from a more copious background of scattered beam and some fission fragments, coincidence gates were set on a two-dimensional histogram (Fig. 1a) of the flight time from the focal-plane detector to the DSSD vs the DSSD implant energy. Further coincidence gates were placed on (i) the time of flight of the evaporation residues from the target to the focal plane (Fig. 1b), and (ii) the focal-plane detector positions corresponding to two charge states ($q = 20$ and 21) of ions with a mass of 254 (Fig. 1c). The resulting γ spectrum from ^{254}No is shown in Fig. 2a.

The production of ^{254}No was unambiguously demonstrated by the observed α decay chain (Fig. 1d). After implantation of a ^{254}No evaporation residue in a specific DSSD pixel, subsequent α decay in that pixel was used to identify ^{254}No, with additional requirements on energy (8.09 MeV) and decay time (1–200 s, commensurate with its 55 s half-life). Correlations of γ rays with focal-plane signals corresponding to uniquely identified No residues constitute the recoil decay tagging (RDT) technique, whereby unambiguous identification of the γ-ray parentage is achieved in the spectrum shown in Fig. 2b. This spectrum confirms that the spectrum in Fig. 2a, which

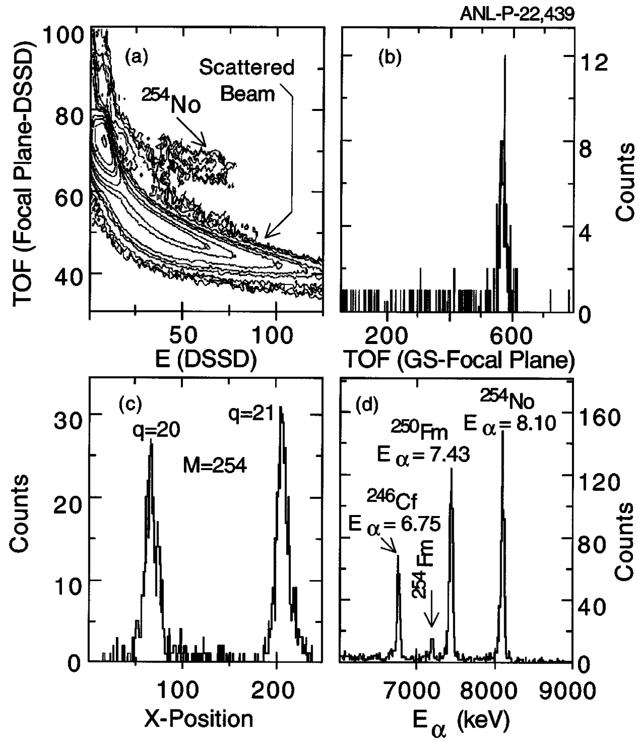

FIG. 1. (a) Two-dimensional spectrum of the flight time from the focal-plane detector to the DSSD vs the evaporation-residue implant energy in the DSSD. (b) Time-of-flight spectrum from Gammasphere to the focal-plane detector. (c) Mass/charge spectrum at the focal-plane detector. (d) Alpha spectrum from the DSSD detector, showing the peaks from three generations of α decay, starting with ^{254}No. (The ^{254}Fm α peak follows two successive electron-capture decays from ^{254}No.)

was generated without the α-decay requirements, contains only ^{254}No γ rays. Hence, the latter spectrum, which has approximately twice as many counts, was used for further analysis. This spectrum shows the No K_α and K_β x rays, a sequence of transitions with spacings that are characteristic of transitions from a rotational band, and γ rays above ~ 500 keV, which are presumably from excited bands. (These transitions have been observed also in a more recent experiment performed at Jyväskylä [11].) The transitions that exhibit rotational characteristics are assigned to the ground-state band of ^{254}No.

Spectra from coincidence gates on individual transitions of this rotational band are given in Figs. 2c–2f. The high efficiency of Gammasphere enables coincidence relationships to be established even with the low statistics associated with a small production cross section. Although the ground-band peaks contain only 1–2 counts, the background is <0.01/channel. The coincidence spectra contain No x rays, which further confirm the nobelium parentage. Although not all pairwise coincidences are detected (as expected from the low statistics), a sufficient number are observed to support the assignment of a cascade within the ground-state band. The 367-keV transition, with an estimated cross section of the order of 100 nb, is too weak to yield coincidences, and is assigned to the

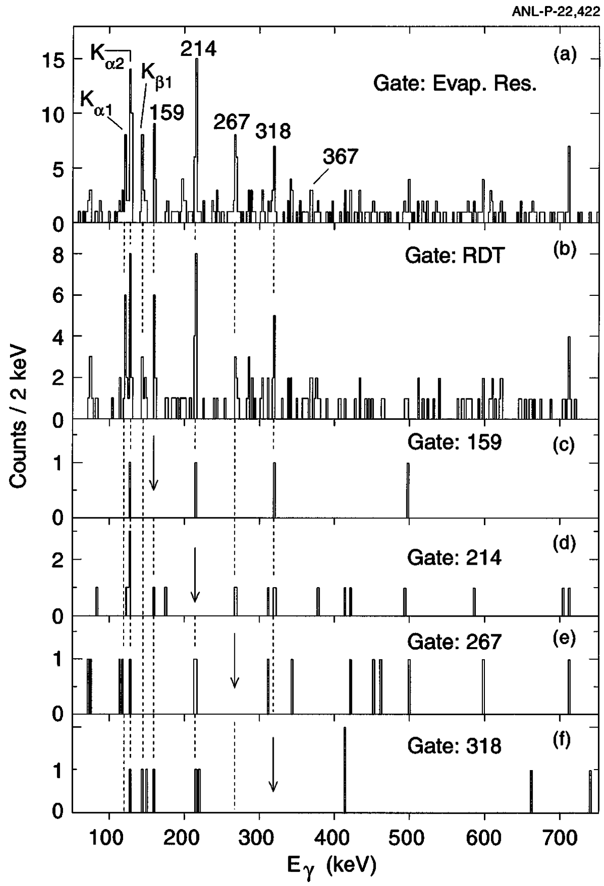

FIG. 2. (a) Gamma spectrum obtained using coincidence gates on the "peaks" in Figs. 1(a)–1(c). The background level is 0.4 counts/channel. Peaks labeled by energy are assigned as transitions within the ground-state band of ^{254}No. The peak at 73 keV from Pb x rays appears from incomplete subtraction of random coincidences. (b) Spectrum with an additional requirement on the ^{254}No α peak shown in Fig. 1(d). (c)–(f) Coincidence spectra from gates set on the transitions indicated by arrows. Vertical dashed lines help visual alignment of peaks in the different panels.

band only on the basis of its energy. At present it is not possible to tell if other low-energy transitions, e.g., one at 341 keV, represent a further continuation of the band; if they do, a backbend would be indicated.

The identification of a rotational band in ^{254}No immediately establishes that the nucleus is deformed and constitutes an important confirmation of the predictions of theories that calculate the shell-correction energies of TFN. Figure 3 shows the moments of inertia, $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$, for the ground-state band of ^{254}No. ($\mathcal{J}^{(1)} = \hbar^2(2I - 1)/E_\gamma(I)$; $\mathcal{J}^{(2)} = 4\hbar^2/[E_\gamma(I) - E_\gamma(I - 2)]$; $\hbar\omega = E_\gamma/2$.) The Harris parametrization,

$$\mathcal{J}^{(2)} = \mathcal{J}_0 + 3\mathcal{J}_1\omega^2, \qquad (1)$$

$$\mathcal{J}^{(1)} = \mathcal{J}_0 + \mathcal{J}_1\omega^2, \qquad (2)$$

provides excellent fits of $\mathcal{J}^{(2)}(\omega)$ and $\mathcal{J}^{(1)}(\omega)$. From the parameters $\mathcal{J}_0$ and $\mathcal{J}_1$, we deduced the spins of the emitting states, using a procedure described in Ref. [12] and the

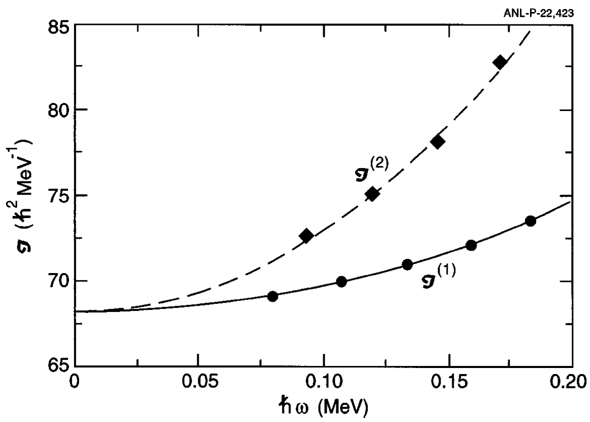

FIG. 3. Moments of inertia, $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$, for the ground-state band of ^{254}No. The lines are fits to the data with Eqs. (1) and (2), using $\mathcal{J}_0 = 68.2\hbar^2$ MeV^{-1}, $\mathcal{J}_1 = 164.9\hbar^2$ MeV^{-3}.

expression

$$I = \mathcal{J}_0\omega + \mathcal{J}_1\omega^3 + 1/2. \qquad (3)$$

The spins have even integer values between 6 and 14 (within 0.01),providing support for assigning the transitions to the ground-state band. (This method gives correct spins for known ground-state bands.)

The proposed level scheme of ^{254}No is shown in Fig. 4. We estimate the energies of transitions from the 2^+ and 4^+ states as 44(1) and 102(1) keV, respectively, using Eq. (3). These γ rays were not detected because the states decay almost entirely by internal electron conversion. The deduced transition energies also conform to those extrapolated from neighboring lighter nuclei, providing additional support for the assigned spins.

Lifetimes have not been measured. However, the $B(E2)$ values of rotors are related to the 2^+ level energies by empirical formulas [13–15]. By using Eq. 4 of Ref. [14] and equations from Ref. [15] relating the $B(E2)$, quadrupole moment, and deformation, we deduce a quadrupole deformation parameter of $\beta = 0.27(2)$ for ^{254}No. [The uncertainty is given by the systematic deviations between measured $B(E2)$ values in heavy nuclei and those deduced from the empirical relationship of Ref. [14].] This value is in agreement with a value of 0.25 given by different macroscopic-microscopic model calculations [6,16,17], and with respective values of 0.27 and 0.26 from a Hartree-Fock-Bogoliubov (HFB) calculation with the SLy4 force [18] and from a relativistic Hartree-Bogoliubov calculation with the NL3 Lagrangian parametrization [19]. Other HFB and relativistic mean-field calculations with other force parametrizations [20] predict values as large as $\beta = 0.3$. Hence, the properties of TFN can, in principle, test the predictive power of the different interactions used in HFB and relativistic mean-field calculations for nuclei far from stability.

The moment of inertia is an important quantity for theory to describe, since it is sensitive to the single-particle energies and pairing. The ground-state moments of inertia have recently been calculated for some TFN [21],

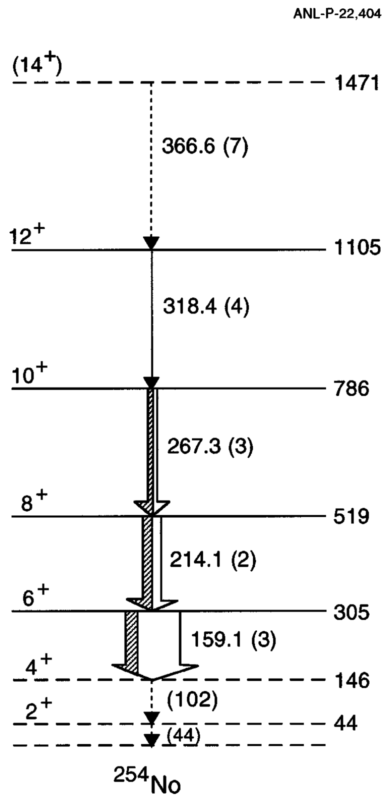

FIG. 4. Proposed level scheme for the ground-state band of ^{254}No. Spins are deduced using Eq. (3); the parity is assumed to be positive. The energies of the lowest two transitions, which were not detected decay because they decay by internal conversion electrons, were deduced by extrapolation. The $14^+ \rightarrow 12^+$ assignment is tentative. The widths of the filled and open arrows are proportional to the γ and electron intensities, respectively; the latter were computed by assuming that the transitions have $E2$ multipolarity. The transition intensities decrease as spin grows, as expected for a (heavy ion, xn) reaction.

and a preliminary value of 42.4 keV has been obtained for the 2^+ energy of ^{254}No, close to our deduced value of 44 keV. The measured moments of inertia of ^{254}No increase with spin, as seen in Fig. 3, probably due to the gradual alignment of quasiparticles, specifically those occupying the high-j proton $i_{13/2}$ and neutron $j_{15/2}$ orbitals. Hence, the increase of $\mathcal{J}^{(2)}$ and $\mathcal{J}^{(1)}$ with frequency can provide a stringent test of theory. However, no calculations of finite-spin properties have been published so far.

The observation of states with spin up to 14 implies that neutron evaporation can compete against fission up to at least that spin. Hence, a fission barrier must still exist up to that angular momentum in ^{254}No. In fact, preliminary analysis [22] of the multiplicity distribution from our experiment suggests that residues are formed with spin up to $\sim$18. Our data further imply that the shell-correction energy, which creates the barrier, is reasonably robust with spin. From a pragmatic point of view, they also demonstrate that high-spin states of TFN can be studied by means of (HI, xn) reactions. For future work, it will be interesting to investigate—by experiment and theory—the fission barrier and its dependence on angular momentum, not only in its own right, but also to provide insight into the production mechanism of the heaviest elements.

In summary, the ground-state band has been identified up to spin 12^+ (perhaps 14^+) in ^{254}No, an isotope of the heaviest element for which high-spin data now exist. This confirms predictions that the TFN gain stability against fission by exploiting the deformation degree of freedom. The deformation parameter deduced from the $2^+ \rightarrow 0^+$ energy is close to values predicted by several calculations. An increase with frequency in the moment of inertia is observed. The observation of states with spin up to 14 means that the fission barrier of ^{254}No must still exist at least up to that spin.

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