Structure of the Odd-A, Shell-Stabilized Nucleus $^{253}_{102}$No

P. Reiter,[1] T. L. Khoo,[2] I. Ahmad,[2] A. V. Afanasjev,[3] A. Heinz,[2,*] T. Lauritsen,[2] C. J. Lister,[2] D. Seweryniak,[2]
P. Bhattacharyya,[4,†] P. A. Butler,[5] M. P. Carpenter,[2] A. J. Chewter,[5] J. A. Cizewski,[6] C. N. Davids,[2] J. P. Greene,[2]
P. T. Greenlees,[7] K. Helariutta,[7] R.-D. Herzberg,[5] R. V. F. Janssens,[2] G. D. Jones,[5] R. Julin,[7] H. Kankaanpää,[7] H. Kettunen,[7]
F. G. Kondev,[2] P. Kuusiniemi,[7] M. Leino,[7] S. Siem,[2,8] A. A. Sonzogni,[2,‡] J. Uusitalo,[7] and I. Wiedenhöver[2,§]
[1]*Institut für Kernphysik, Universität zu Köln, Zülpicher Str 77, 50937 Köln, Germany*
[2]*Argonne National Laboratory, Argonne, Illinois 60439, USA*
[3]*University of Notre Dame, Notre Dame, Indiana 46556, USA and University of Latvia, LV 2169 Salapils, Miera str. 31, Latvia*
[4]*Purdue University, West Lafayette, Indiana 47097, USA*
[5]*University of Liverpool, Liverpool L69 7ZE, England, United Kingdom*
[6]*Rutgers University, New Brunswick, New Jersey 08903, USA*
[7]*University of Jyväskylä, Jyväskylä, Finland*
[8]*University of Oslo, Oslo, Norway*
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In-beam γ-ray spectroscopic measurements have been made on $^{253}_{102}$No. A single rotational band was identified up to a probable spin of $39/2\hbar$, which is assigned to the $7/2^+[624]$ Nilsson configuration. The bandhead energy and the moment of inertia provide discriminating tests of contemporary models of the heaviest nuclei. Novel methods were required to interprete the sparse data set associated with cross sections of around 50 nb. These methods included comparisons of experimental and simulated spectra, as well as testing for evidence of a rotational band in the $\gamma\gamma$ matrix.

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There has been great progress in superheavy element research, with reports of the identification of elements $Z = 110$–116 [1,2]. The heaviest nuclei are stabilized by a shell-correction energy, which lowers the ground state, thereby creating a barrier against fission. The shell-correction energy originates from the clustering of single-particle orbitals and the occurrence of regions of low level density. The most direct data on the single-particle energies come from odd-A nuclei, providing our motivation to investigate the odd-N nucleus ^{253}No. Comparison of experimental and theoretical single-particle energies also provides a direct test of nuclear models [3–5] that predict the properties of superheavy nuclei. This gives a basis for judging their reliability for predicting, e.g., the next spherical shell closures beyond ^{208}Pb. The variation of moments of inertia as functions of mass and rotational frequency also tests theory [4–8] and provides information on the energies of single-particle orbitals, particularly of those with large j (particle angular momentum).

Great strides have also been made in experiments on the structure and formation mechanism of the shell-stabilized nuclei $^{254,\,252}$No by in-beam spectroscopy [9–13]. A heavy odd-A nucleus poses greater challenges than an even-even nucleus for in-beam γ spectroscopy, since M1 admixtures in transitions between the signature partners (with $\Delta I = 1$) usually lead to overwhelming competition from conversion electrons. Furthermore, the γ-ray flux is fragmented among several close-lying quasiparticle bands (rather than concentrated in the ground band), and is further divided between the two signatures of each band. The consequence is meager data, a situation that will be encountered with increasing frequency in the spectroscopy of loosely bound nuclei, which have diminutive cross sections. Therefore, innovative methods must be developed to deduce level schemes from such data. We use an approach, which (a) compares the measured γ spectra with simulated spectra expected from the low-lying bands, and (b) tests a sparse $\gamma\gamma$ matrix for evidence of a rotational band.

As the first step of our investigation, the cross section of the ^{207}Pb(^{48}Ca, 2n)^{253}No reaction was determined to be $\sigma \approx 500$ nb at a beam energy of 219 MeV with the RITU recoil separator at Jyväskylä. This cross section indicated that in-beam γ spectroscopy was feasible, leading to a subsequent experiment at Argonne, where Gammasphere [14], a multidetector array with 101 Compton-suppressed Ge detectors, and the fragment mass analyzer (FMA) [15] were combined to detect γ rays in coincidence with ^{253}No evaporation residues. The experimental setup and analysis methods are described in Refs. [9,11]. Beams with intensities of up to 13 pnA were provided by ATLAS, the Argonne superconducting linear accelerator. The compound nucleus (midtarget) excitation energy was $\approx$22.7 MeV.

The γ spectrum [Fig. 1(a)] obtained in coincidence with ^{253}No residues has many weak lines, but is dominated by nobelium K_α and K_β x rays. The γ-ray intensity per nobelium residue for the strongest lines in the ^{253}No spectrum of Fig. 1(a) is $\sim$3 times smaller than those of the strongest transitions of the ground-state band of ^{254}No [11]. These observations are expected for an odd-A nucleus, for the reasons explained above.

Nonetheless, it is possible to discern in Fig. 1(a) a regular sequence of transitions from 207 to 455 keV, with approximately equal energy spacings, a characteristic of a

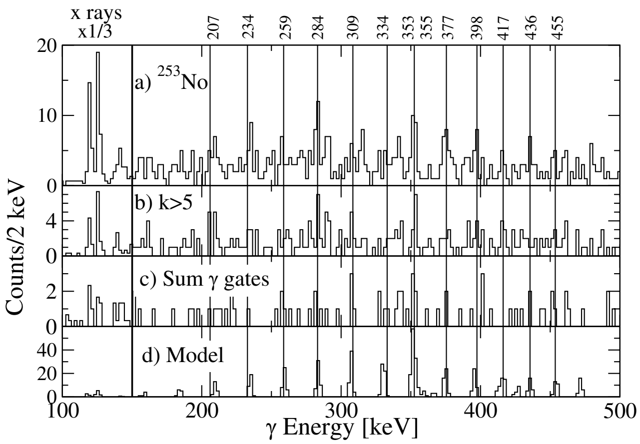

FIG. 1. (a)–(c) Experimental spectra, all requiring coincidences with ^{253}No residues in the FMA; (a) only ^{253}No required; (b) coincidence fold ≥ 6; and (c) sum of gates on peaks. Vertical lines mark the candidate lines of the $7/2^+[624]$ band. The x-ray region is divided by 3. (d) Calculated spectrum [for comparison with (a)] for a $7/2^+[624]$ rotational band, based on 4 times the number of detected ^{253}No nuclei and assuming a 20% population of the band.

rotational band. However, the meager counts represent γ spectroscopy at the limits of feasibility, and require new methods to identify rotational bands. As a tool for interpreting the data, we use the rotational model to calculate the γ spectra, which would be expected for the lowest quasiparticle bands in ^{253}No.

Calculations with a Woods-Saxon potential [3] suggest that the lowest bands are built, in order of increasing energy, on the ($\Omega^\pi[Nn_z\Lambda]$) $9/2^-[734]$, $7/2^+[624]$, $5/2^+[622]$, and $1/2^+[620]$ orbitals. These suggestions are consistent with the level scheme of the isotone ^{249}Cf [16]. The γ-ray spectrum, including x rays from converted transitions, is calculated with the rotational model. The spin dependence of the level population in ^{253}No is assumed to be the same as that for ^{254}No given in Ref. [11]. E2 and M1 strengths depend on the quadrupole moment Q_0 and $K(g_K - g_R)$, respectively, where g_K and g_R are the intrinsic and rotational g factors. We adopted $Q_0 = 13.1$ eb, taken from the neighboring nucleus ^{254}No. The g_K values, characteristic of the single-particle configuration, are -0.12, $+0.25$, -0.38, and -1.57, respectively, for the above orbitals (given by the model of Ref. [3]). Most orbitals have negative g_K values, which lead to large magnitudes of $K(g_K - g_R)$, thus giving strong M1 intraband transitions, with large electron conversion coefficients. Indeed, intense conversion electrons have been detected in ^{253}No [17]. *Only* the $7/2^+[624]$ configuration has a positive g_K value (due to antialignment of the intrinsic spin and orbital angular momentum), which allows detectable $\Delta I = 2$, E2 γ transitions. These expectations are indeed borne out by our simulated spectra. Hence, the γ rays that are marked in Fig. 1 are assigned to the $7/2^+[624]$ configuration. The model level energies are given by $E(I) = E_0 + AI(I+1) + B[I(I+1)]^2$, with $A = 6.55$ keV (within 2% of the value of 6.44 keV for the isotone ^{249}Cf [16]) and $B = -0.35$ eV. The parameters A and B are adjusted to obtain nearly matching peak energies in the simulated and experimental spectra in Figs. 1(a) and 1(d). The simulated spectrum also includes the interband E1 transitions to the ground band, with presumed configuration $9/2^-[734]$ and level energies given by $A = 5.55$ keV, again within 2% of the value for ^{249}Cf. With the $7/2^+$ bandhead at 355 keV, a multiplet of interband transitions at 353 and 355 keV is obtained in the simulated spectrum. In addition, there is also a 355 keV intraband γ ray. We postulate that this degeneracy of γ-ray energies also gives rise to the broad multiplet in the experimental spectrum. Coincidences with the 353–355 multiplet support this interpretation. Our bandhead energy concurs with the 379 keV assigned [18] from α spectroscopy, within the experimental uncertainties. The proposed level scheme for the $7/2^+[624]$ band is shown in Fig. 2.

Another analysis tool is enhancement of high γ multiplicity events by requiring >5 detectors to fire. The ratio of $7/2^+[624]$ band γ rays to x rays is enhanced [Fig. 1(b)], since there is less internal conversion associated with this band.

Normally, $\gamma\gamma$ coincidences provide unequivocal evidence for a band, but in this case the low statistics give only 0–2 counts in each peak, completely consistent with our model simulations. Nevertheless, it is clear that the sum of all the gates on the candidate lines [Fig. 1(c)] enhance most of those same lines.

Despite the sparse data, one can quantitatively test whether the coincidences validate the proposed level scheme. We use a new method (inspired by J. Kuehner's

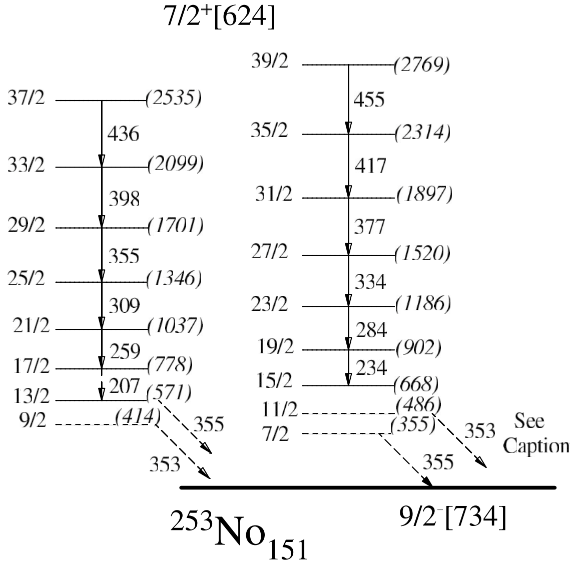

FIG. 2. Proposed level scheme of the $7/2^+[624]$ rotational band in ^{253}No. The levels with $I = 7/2$–$15/2$ are based on extrapolation with the model (see text). The text describes how the spins have been be deduced. Detected transitions are placed above the calculated 13/2 and 15/2 levels.

program BANDAID for finding superdeformed bands), which exploits the fact that the background is lower in two dimensions than in one, and that a rotational band gives a 2-dimensional grid of almost equidistant points in a $\gamma\gamma$ matrix. We test for this pattern, using a template, which consists of a set of two-dimensional gates, each 3×3 keV wide. The template is first centered on the allowed coincidences (of the proposed level scheme) in the $\gamma\gamma$ matrix. From this origin, the template is moved ± 25 keV, in 1 keV steps, in both x and y directions, across the $\gamma\gamma$ matrix, and counts are recorded. This process samples the whole relevant portion of the $\gamma\gamma$ matrix. The results are plotted in Fig. 3, as a function of the template position. If the coincidences indeed originate from a band, then: (a) a peak should be seen at the origin, when the set is centered on the allowed coincidences; (b) low counts should surround the peak; and (c) 8 additional, but smaller, peaks at x, $y \sim \pm 20$ keV, i.e., at the corners of a square and at the midpoint of each edge. If the data were random, no peaks should be observed. Figure 3 indeed shows the expected pattern. The peak at the origin (0,0) has 22 counts, compared with an average count of three in the background areas. Hence, Fig. 3 demonstrates that the distribution of counts in the $\gamma\gamma$ matrix provides evidence for the rotational band as an entity. However, it does not prove that every single transition in Fig. 2 has been correctly assigned; e.g., the energies of 1 or 2 transitions may be inaccurate by up to ~3 keV.

The coincidence pattern corresponds, within statistics, to the calculated one. For example, (i) no transition is in coincidence with itself, (ii) no energetically forbidden coincidences are observed, (iii) coincidences occur between transitions of the same signature (with one exception), and (iv) nobelium x rays are seen. From the number of detected ^{253}No nuclei and γ rays, we deduce that ~20% of the γ cascades flow through the $7/2^+$ band. That implies level cross sections that range from 25 to 100 nb.

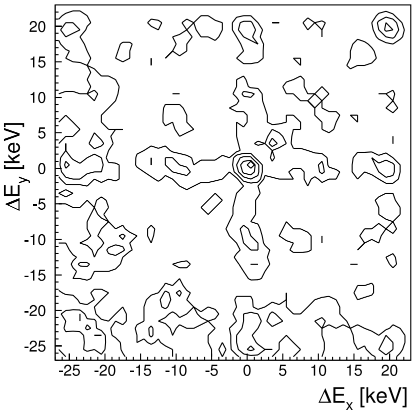

FIG. 3. Counts within a set of 3×3 keV coincidence gates as the set is moved across the $\gamma\gamma$ matrix in the x and y directions. At the origin (0,0), the set is centered on the points in the $\gamma\gamma$ matrix representing all *allowed* coincidences from the $7/2^+[624]$ band. Contour levels correspond to 5, 9, 13, 17, and 21 counts.

In the level scheme for the $7/2^+[624]$ band (Fig. 2), the transitions between the two signature partners have not been detected (in accord with the model). Hence, the relative energies between them are based on the model, which assumes no signature splitting. The lowest levels of the band are also inferred from the model since increasing internal conversion renders the E2 γ branch undetectable at low spin. As discussed above, the E1 interband decays to the yrast band, which is expected to be built on the $9/2^-[734]$ configuration [3,16], are suggested by the enhanced strength at 353 and 355 keV in the spectra of Figs. 1(a)–1(d), as well as by individual coincidences.

The moments of inertia $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$ (defined in, say, Ref. [9]) are shown in Fig. 4. The level spins in Fig. 2 have been be deduced by using Eq. (3) in Ref. [9] (i.e., from the spin dependence of $\mathcal{J}^{(2)}$), after rounding to the nearest half integer. This method gives the correct spin when the quasiparticle alignment is nearly zero, a condition seen to be fulfilled when $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$ level off and converge at low frequencies in Fig. 4(a). Furthermore, at low frequency, the experimental $\mathcal{J}^{(1)}$ values are equal, within 1%, to that of the $7/2^+[624]$ band in the isotone ^{249}Cf, thereby providing further support for the spin and configuration assignments of the ^{253}No band.

The $\mathcal{J}^{(2)}$ values of ^{253}No are compared with those of ^{252,254}No [11,12] in Fig. 4. At low frequencies, the $\mathcal{J}^{(2)}$ of ^{253}No is larger than those of the even-even neighbors—a

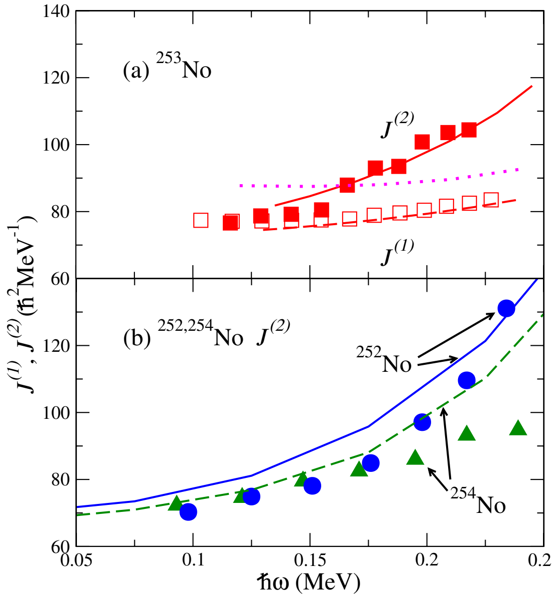

FIG. 4 (color online). Moments of inertia of $^{252-254}$No vs the rotational frequency $\hbar\omega$ from experiment (symbols) and CRHB theory (lines). (a) ^{253}No: $\mathcal{J}^{(1)}$ (open squares, dashed line) and $\mathcal{J}^{(2)}$ (filled squares, solid line) of the $7/2^+[624]$ band; CRHB $\mathcal{J}^{(1)}$ (dotted line) of the $9/2^-[734]$ band. (b) ^{252,254}No: $\mathcal{J}^{(2)}$ of the ground bands (circles, triangles [11,12], and full, dashed lines [4]).

characteristic, attributed to blocking, usually seen in odd-A nuclei. The relative moments of inertia of the three nuclides and the variations with frequency provide information on the relative positions of the Fermi level and the high-j $9/2^-[734]$ single-particle orbital, which is partially responsible for the rise in the experimental $\mathcal{J}^{(2)}$ moments of ^{252,253}No. Hence, they provide a test of theoretical single-particle energies and moments of inertia.

The self-consistent cranked relativistic Hartree-Bogoliubov (CRHB) theory [19] has been applied to calculate the $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$ moments of inertia of ^{253}No, in the manner described in Ref. [4]. The NL1 Lagrangian, which provides a fair description of the single-particle energies [4], has been employed. The theoretical $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$ values, shown in Fig. 4(a), reproduce the experimental ones. The $\mathcal{J}^{(2)}$ for ^{254}No is also well described for $\omega < 0.15$ MeV. In contrast, the calculated $\mathcal{J}^{(2)}$ for ^{252}No is too large, due to an incorrect location of the energy gap at $N = 150$ instead of at $N = 152$. Calculations with Skyrme Hartee-Fock- Bogoliubov (SHFB) theory [5,7] give similar moments of inertia, with those for ^{253}No again reproduced best.

The deduced bandhead energy for the $7/2^+[624]$ band is 355 keV. This value compares with theoretical energies of 240, 1200 and 400 keV, obtained, respectively, in calculations with the Woods-Saxon potential [3] and with self-consistent mean-field theories using the CRHB [4] and SHFB [5] methods. Of course, a systematic test of theory should encompass a set of quasiparticle states, and has recently been performed for self-consistent mean-field theories [4,5]. Generally, the CRHB theory reproduces quasiparticle energies within 500 keV, but the $7/2^+[624]$ configuration belongs to a small class of orbitals whose energies are systematically off by a larger amount [4]. The moments of inertia are nevertheless well reproduced since the $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$ values depend sensitively on, and hence are characteristic of, the occupied orbital, particularly of its alignment. For example, the $9/2^-[734]$ band (predicted to be the ground band), has higher particle alignment than the $7/2^+[624]$ band, so that its CRHB $\mathcal{J}^{(1)}$ is larger than that of the $7/2^+[624]$ band by $\sim 10\hbar^2$ MeV^{-1} [see Fig. 4(a)].

In summary, a rotational band has been identified in ^{253}No by using techniques that are generally valuable for sparse data. The likely configuration is the $7/2^+[624]$ orbital, since only this band has a sufficiently small M1 branch to permit detection of E2 γ rays. Its $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$ moments of inertia are well reproduced by the CRHB model [4]. Self-consistent mean-field theory can reproduce the known quasiparticle energies of the heaviest nuclei within 0.5 MeV, or 1 MeV for certain classes of orbitals [4,5]. This accuracy is not yet sufficient for confident predictions of the next proton and neutron shell closures beyond ^{208}Pb, where the theoretical gaps can be as small as 1.5 MeV [20]. Nonetheless, it is noteworthy that most theoretical approaches obtain large shell-correction energies for broad regions of superheavy nuclei.

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Note added in proof.—A recent experiment in Jyväskylä has also detected γ rays in ^{253}No [21].

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*Present address: Yale University, New Haven, CT 06520-8124
†Present address: Cleveland Clinic Foundation, Cleveland, OH 44105
‡Present address: Brookhaven National Laboratory, Upton, NY 11973
§Present address: FL State University, Tallahassee, FL 32306

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