# *K* Isomers in $^{254}$No: Probing Single-Particle Energies and Pairing Strengths in the Heaviest Nuclei

S. K. Tandel,[1] T. L. Khoo,[2] D. Seweryniak,[2] G. Mukherjee,[1,2,*] I. Ahmad,[2] B. Back,[2] R. Blinstrup,[2] M. P. Carpenter,[2] J. Chapman,[2] P. Chowdhury,[1] C. N. Davids,[2] A. A. Hecht,[2,4] A. Heinz,[5] P. Ikin,[3] R. V. F. Janssens,[2] F. G. Kondev,[2] T. Lauritsen,[2] C. J. Lister,[2] E. F. Moore,[2] D. Peterson,[2] P. Reiter,[6] U. S. Tandel,[1] X. Wang,[2,7] and S. Zhu[2]

[1]*Department of Physics, University of Massachusetts Lowell, Lowell, Massachusetts 01854, USA*
[2]*Argonne National Laboratory, Argonne, Illinois 60439, USA*
[3]*Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[4]*University of Maryland, College Park, Maryland 20742, USA*
[5]*Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06511, USA*
[6]*Universität zu Köln, Zülpicherstrasse 77, D-50937 Köln, Germany*
[7]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*

(Received 13 April 2006; published 22 August 2006)

We have identified two isomers in $^{254}$No, built on two- and four-quasiparticle excitations, with quantum numbers $K^\pi = 8^-$ and $(14^+)$, as well as a low-energy 2-quasiparticle $K^\pi = 3^+$ state. The occurrence of isomers establishes that $K$ is a good quantum number and therefore that the nucleus has an axial prolate shape. The 2-quasiparticle states probe the energies of the proton levels that govern the stability of superheavy nuclei, test 2-quasiparticle energies from theory, and thereby check their predictions of magic gaps.

DOI: 10.1103/PhysRevLett.97.082502 PACS numbers: 23.20.Lv, 21.10.Pc, 21.10.Tg, 27.90.+b

The strong Coulomb repulsion in heavy nuclei leads to spontaneous fission. Yet reports [1] of the existence of nuclei with large atomic number $Z$ (112–116) indicate that the nuclear attraction is still able to overcome the large Coulomb repulsion. This delicate balance is sensitive to the nuclear interaction, which gives rise to characteristic shell energies. The gaps in the single-particle spectrum yield a stabilizing shell-correction energy, which creates a fission barrier where none would otherwise exist. Hence, a reliable theoretical description of the stability and structure of the heaviest elements depends critically on accurate single-particle energies. It is important to study nuclei with the largest feasible atomic number to maximize the Coulomb repulsion, which also moves the Fermi level towards the levels relevant for superheavy elements and closer to postulated proton magic gaps. While orbit energies in actinide nuclei are normally obtained from quasiparticle (qp) energies in odd-A nuclei, 2-qp energies in even-even nuclei also provide valuable information, with additional insight into the pair gap. Furthermore, the structure of excited states probes how shell-stabilized nuclei, barely held together inside small fission barriers, respond to the combined actions of excitation energy, angular momentum, and reduced pairing.

Systematic studies [2] have shown that the Woods-Saxon (WS) potential successfully reproduces (within ~300 keV) proton and neutron 1-qp energies in odd-A actinide nuclei with $Z = 91$–$99$. In contrast, although self-consistent mean-field theories can reproduce many qp energies within ~0.5 MeV, the discrepancy can exceed 1 MeV for levels originating from a number of spherical shells [3–5]. The differences in single-particle energies are responsible for the divergent predictions about magic gaps for superheavy nuclei [3,4].

The observation of rotational bands with in-beam $\gamma$ spectroscopy has demonstrated that nobelium nuclei are deformed [5–9]. Macroscopic-microscopic and self-consistent mean-field theories predict a prolate, axially symmetric shape for $^{254}$No. Axial symmetry gives rise to a good quantum number $K$, the projection of the total angular momentum on the symmetry axis. Therefore, a straightforward indicator of axial symmetry is the occurrence of $K$ isomers, where electromagnetic decay is hindered by a $K$ selection rule. An isomer with a 0.28 s half-life was found [10] in $^{254}$No, but its quantum numbers were not identified. Recent work has confirmed the isomer [11–13], and the isomeric electron spectrum was measured [12]. The copious yield of low-energy, in-beam electrons [14] was attributed to high-$K$ rotational bands in $^{254}$No.

This Letter reports the properties of the known 2-qp isomer and the discovery of a 4-qp isomer in $^{254}$No. The energies of two 2-qp states are well described (within 140 keV) in terms of WS orbit energies.

The aim of our experiments was to identify the $\gamma$ rays and conversion electrons emitted in the decay of isomers in $^{254}$No. The $^{208}$Pb($^{48}$Ca, $2n$) reaction was employed, with a $^{48}$Ca beam of 217 MeV (at midtarget), having intensities up to 120 pnA from ATLAS, the Argonne superconducting linear accelerator. Evaporation residues of $^{254}$No were transported and identified by their mass/charge ratio with the Fragment Mass Analyzer (FMA), then (after a 1.7 $\mu$s flight time) implanted into a 140 $\mu$m thick double-sided Si strip detector with $40 \times 40$ pixels, each with 1 mm$^2$ area. (See Ref. [7] for details.)

An isomeric decay in $^{254}$No was identified by time and spatial correlations, namely, an electron signal within ~1 s of an evaporation residue in the *same pixel* as the implanted nucleus. Typically, the decay of an isomer would populate a rotational band, with highly converted transitions, and the pixel would serve as a calorimeter [15] for the electron sum energy and $L$ x rays. Each of several electrons could be fully captured in a pixel or escape. The maximum electron sum energy is vital for constructing the decay scheme. Gamma rays were detected, in prompt coincidence with isomeric electron signals, in three large clover Ge detectors (each consisting of four Ge crystals) with a total efficiency of ~4% at 900 keV.

The electron time distribution exhibits two distinct half-lives, namely, 266(10) ms, from the known isomer, and 171(9) $\mu$s from a new isomer—see insets in Fig. 1. The FMA confirms $M = 254$ parentage for both. The electron sum-energy spectra from the isomers are shown in Figs. 1(a) and 1(b). The decay of the 266 ms isomer yields prominent $\gamma$ rays at 944, 842, and 53 keV [see Fig. 1(c)] with the 53- and 944-keV $\gamma$ rays coincident. The two high-energy $\gamma$ rays are also observed in beam [7,9], so they must have nanosecond decay times. Therefore, in the proposed decay scheme in Fig. 2, the 53-keV $\gamma$ ray directly depopulates the isomer, feeding a rotational band. The latter decays from the presumed bandhead to the $2^+$ and $4^+$ members of the ground-state band via high-energy transitions, which must have $M1$ multipolarity to account for the observed $K$ x-ray intensity. That suggests $I, K^\pi = 3, 3^+$ for the bandhead. The low-energy intraband ($M1$ or $E2$) transitions are highly converted and not detected as $\gamma$ rays in our experiment, except for the 82- and 151-keV transitions. We have used a model (as described in Ref. [5]) to assist in constructing the rotational band, with the level energies given by $E_I = E_0 + AI(I + 1)$, with $A = 5.81$ keV. With respect to the ground-state band rotational parameter, $A$ is reduced by 20%, which is typical for 2-qp bands. This rotational parameter accounts for the experimentally determined energy separations given in Fig. 2. Detection of the 53-keV $\gamma$ ray is possible only if it has $E1$ multipolarity (with the smallest conversion coefficient), which implies a parity change. The isomer is assigned $I^\pi = 8^-$ since a lower spin would have caused feeding into levels with $I \leq 6$. For the $K^\pi = 3^+$ band, the observed crossover-to-cascade $\gamma$-intensity ratio [$R = I(151)/I(82) = 1.1(4)$] unambiguously indicates a proton configuration ($R = 1.1$) rather than a neutron configuration ($R = 4.6$). That also implies a proton configuration for the $K = 8$ state, since the electromagnetic operator cannot connect 2-qp neutron and proton states.

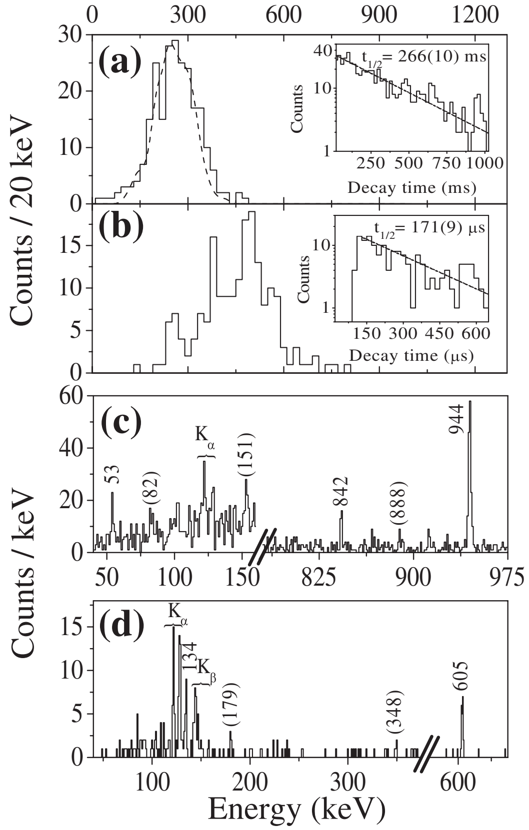

FIG. 1. (a) Electron sum-energy spectrum from the decay of the 266 ms isomer. The attenuation at low energy is due to electronic thresholds; the calculated spectrum (dashed line) includes this effect. (b) Same as (a) for the 171 $\mu$s isomer. Insets in (a),(b) show decay time distributions, with the results of least-squares fits given as dashed lines. Electronic dead time negates the first ~80 $\mu$s of data. (c),(d) Gamma-ray spectra from the long- and short-lived isomers, respectively. The isomers have estimated cross sections of ~600 and 80 nb.

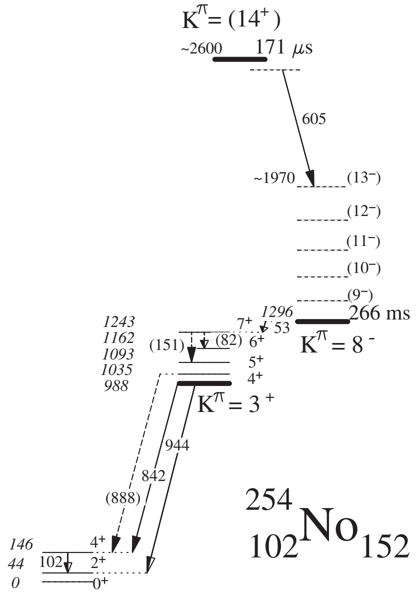

FIG. 2. Decay scheme proposed for the 2- and 4-qp isomers. Although transitions are not detected from every level of the $K^\pi = 3^+$ band, the levels are established via a model that accounts for all observed level spacings (see text). The pathway connecting the two isomers is speculative and may contain additional transitions. It is based on a model of the decay (see text) since $\gamma$ rays within the $K^\pi = 8^-$ band were not detected.

Our model calculations (described later) indicate that the lowest 2-qp states (see Fig. 3) have proton configurations $K^\pi = 3^+$ $\{[514]7/2, [521]1/2\}$ and $K^\pi = 8^-$ $\{[514]7/2, [624]9/2\}$. The $K$ quantum numbers, relative parity, and proton configurations are all in agreement with experiment, which allows configuration assignments to be made with some confidence. For the $K^\pi = 3^+$ band, the calculated transition rates give the electron sum-energy spectrum [dashed line in Fig. 1(a)], which agrees with the measured one.

The 171-$\mu$s isomer was observed by delayed coincidence to feed the 266-ms isomer. The $\gamma$ rays deexciting the former are shown in Fig. 1(d), with prominent ones at 134 and 605 keV. Strong nobelium $K$ x rays are also detected, from converted rotational-band transitions, with energy larger than the $K$ binding energy (149.2 keV). Coincidences between $K$ x rays are observed. The data are insufficient to define a unique decay scheme between the isomers, so one has been constructed with the aid of a model based on WS energies and by analogy with the decay of 4-qp isomers [16] in $^{176}$Hf. The model is required to account for all observables: $\gamma$-ray intensities, $K$ x-ray yield, and large electron sum energy. The model tentatively suggests an isomer energy of ~2.6 MeV and $K^\pi = 14^+$, guided by the estimated 4-qp energies of Fig. 3. (The energy is consistent with the value $E > 2.4$ MeV obtained using only data, i.e., a ~500-keV maximum electron sum-energy coincident with the 605-keV $\gamma$ ray.) One plausible decay pathway, through a band built on the $8^-$ isomer, is shown in Fig. 2. The isomer excitation energy is about twice that of the 2-qp states, which suggests a 4-qp configuration.

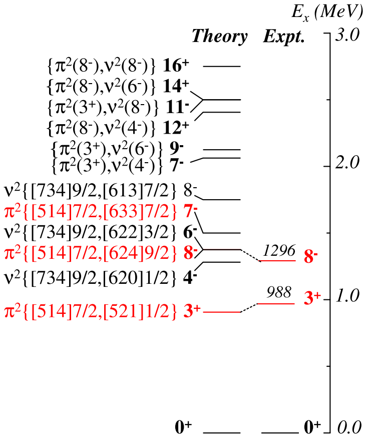

FIG. 3 (color online). Comparison of calculated and experimental 2-qp energies. The calculated 2-qp energies are based on WS single-particle energies and a Lipkin-Nogami treatment for pairing. Proton configurations are shown in red (or gray). Configurations below 1.5 MeV are spin-singlet states, for which a residual spin-spin interaction of $V = -100$ keV is assumed. For the triplet $\nu^2(8^-)$ state, $V = 100$ keV. Estimates (see text) of 4-qp energies ($E > 2$ MeV) are also shown.

The decay of both isomers has also been observed in a recent experiment at Jyväskylä [13], and their decay scheme of the $K^\pi = 8^-$ isomer agrees with ours.

The two isomers in $^{254}$No occur because violation of the $K$ selection rule retards the $\gamma$ radiation. A measure of the retardation due to $K$ forbiddenness is given by $f_\nu = [(t_{1/2})_{\mathrm{exp}}/(t_{1/2})_{WU}]^{1/\nu}$, where $(t_{1/2})_{\mathrm{exp}}$ and $(t_{1/2})_{WU}$ are the experimental and Weisskopf half-lives, $\nu = (\Delta K - \lambda)$, and $\lambda$ is the transition multipolarity. For the $K^\pi = 8^-$ isomer, the 53-keV $\gamma$ ray has $f_\nu = 804$ and the undetected direct decay to the $K^\pi = 0^+$ ground band gives $f_\nu(8^- \rightarrow 8^+) > 200$, a value typical for the most retarded transitions in the Hf region. The large $f_\nu$ values provide quantitative indication that $K$ is a good quantum number for both the initial and final states. This result confirms the predictions of self-consistent mean-field theories [3,17] that $^{254}$No has good axial symmetry in its ground-state band. The isomerism of the 4-qp state suggests that $K$ is conserved even at ~2.6 MeV (but only ~1.1 MeV above the yrast line), with broken pairs of protons and neutrons. No theoretical predictions have been reported of the $\gamma$ deformation of excited multi-qp high-$K$ states in shell-stabilized nuclei.

Our calculations of 2-qp energies in $^{254}$No have been performed with single-particle energies given by the "universal" parameters of the WS potential [18] and a Lipkin-Nogami formalism for pairing [19], which accounts for reduced pairing due to blocking. It is well known that the spin-singlet configurations of 2-qp excitations in even-even nuclei are lowered by the residual spin-spin interaction, which has values of 40–120 keV [20] in $^{234,236}$U and $^{248,250}$Cf. The calculated 2-qp energies for the spin-singlet states in $^{254}$No (Fig. 3) assume $-100$ keV for the residual interaction. For the 4-qp states, $E_{4\mathrm{qp}} = E_{2\mathrm{qp}}(\pi^2) + E_{2\mathrm{qp}}(\nu^2) - V$, where $V$, assumed to be 0.2 MeV, accounts for additional proton-neutron residual interactions [16]; experimental values of $E_{2\mathrm{qp}}(\pi^2)$ are used.

For the $K^\pi = 3^+$ and $8^-$ 2-qp states, the calculated and experimental energies agree within 140 keV. The energy of the $K^\pi = 3^+$ state is exceptionally low (988 keV) for a 2-qp state. This can occur only if the energies of the constituent particles lie close to and on either side of the Fermi level. This feature is strikingly reproduced by the WS potential. (The near degeneracy of the particle energies was first observed in Ref. [21].) Furthermore, this occurrence makes the energy especially sensitive to the pair gap. In our calculations, the strengths of the neutron and proton pairing force ($G_n = 17.2/A, G_p = 24/A$) are chosen to get agreement between the calculated ground-state pair gaps and $\Delta^{(5)}$ for nuclei near $^{254}$No. The 5-point ground-state mass difference $\Delta^{(5)}$ provides a good approximation of the pair gap [22]. The reproduction of the experimental energies of the $K^\pi = 3^+$ and $8^-$ states (see Fig. 3) supports the chosen pairing strength.

This agreement also implies that the WS proton energies are quite accurate for nuclei around $^{254}$No. Calculations with the Skyrme Hartree-Fock Bogolyubov (SHFB) model with the SLy4 force [4,23] yield proton 2-qp states in $^{254}$No with $K^\pi = 3^+$, $8^-$, and $7^-$ at 1.18, 2.2, and 1.38 MeV, respectively. The $3^+$ energy is close to the experimental value, but the $8^-$ is too high, probably due to an $i_{13/2}$ energy that is slightly too large [4]. No calculations of 2-qp states have been performed with the relativistic mean-field (RMF) model. However, an inspection of Fig. 5 of Ref. [3] would suggest significantly higher energies (>2 MeV) for the $K^\pi = 3^+$ and $8^-$ states than observed, particularly for the latter.

The location of a postulated proton shell gap beyond $Z = 82$ is important for superheavy elements. However, there is wide variation in the predictions, with $Z \sim 114$, 120, and 126 given by the WS, RMF, and SHFB models, respectively. A minimum requirement for a credible model is that the interaction reproduces known level energies in the heaviest nuclei. The [521]1/2 orbit, a constituent of the $K^\pi = 3^+$ state, is significant since it originates from the spherical $f_{5/2}$ shell, which is above a $Z = 114$ gap that appears with WS single-particle energies. The small experimental and calculated $K^\pi = 3^+$ energies, as well as the low [521]1/2 energy in $^{251}$Es [21], support the WS $f_{5/2}$ energy. Our results, together with extensive examinations by Ref. [2], favor WS energies for $Z$ up to ~102. This is perhaps not surprising since the universal parameters [18] of the WS potential are based on level energies in nuclei with A = 40–208. In contrast, the parameters of the interactions used in self-consistent mean-field SHFB and RMF models have been adjusted to fit bulk properties of closed-shell nuclei. Thus, the success of their single-particle energies [3,4] is impressive, but do require improvements to reproduce all measured 1- and 2-qp energies. To preserve the virtue of self-consistency when extrapolating to the heaviest nuclei, there is a need for a new interaction designed for this purpose [3]. Open issues for WS predictions are their reliability in extrapolating to even higher $Z$, the need for a radial dependence of the nuclear density (suggested by self-consistent theories [24]), and a shift of single-particle energies due to residual interactions [25].

In summary, the occurrence of 2- and 4-qp isomers in $^{254}$No indicates that $K$ is a good quantum number in this nucleus and therefore that it has a prolate axially symmetric shape. The WS potential, which gives accurate 1-qp energies [2], also reproduces the $K^\pi = 3^+$ and $8^-$ 2-qp energies in $^{254}$No. This extends the validity of WS single-particle energies for nuclei with $Z$ up to at least 102. SHFB calculations with the SLy4 interaction describe the $K^\pi = 3^+$ energy, but not that of the $K^\pi = 8^-$ state. Improved interactions for theories with self-consistency, which is an obvious advantage, should provide more accurate single-particle energies. With the need for improvements in some single-particle energies, predictions of magic gaps at $Z = 120$ or 126 should be reexamined. Experimental 1- and 2-qp energies in nuclei with the largest possible $Z$ will help in the development of better interactions and provide discriminating tests of models of superheavy nuclei.

This research is supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contracts No. W-31-109-ENG-38, No. DE-FG02-94ER40848, and No. DE-FG02-91ER-40409. We thank P.-H. Heenen for communicating results before publication, and A. V. Afanasjev, P. A. Butler, T. Duguet, P. T Greenlees, R.-D. Herzberg, G. D. Jones, and M. Vernhart for valuable discussions.

---

*Present address: Variable Energy Cyclotron Center, Kolkata 700064, India.

[1] S. Hofmann and G. Münzenberg, Rev. Mod. Phys. **72**, 733 (2000); Yu. Ts. Oganessian *et al.*, Phys. Rev. C **70**, 064609 (2004); Kosuke Morita *et al.*, J. Phys. Soc. Jpn. **73**, 2593 (2004).
[2] R. Chasman *et al.*, Rev. Mod. Phys. **49**, 833 (1977); A. Parkhomenko and A. Sobiczewski, Acta Phys. Pol. B **35**, 2447 (2004); **36**, 3115 (2005).
[3] A. V. Afanasjev *et al.*, Phys. Rev. C **67**, 024309 (2003).
[4] M. Bender *et al.*, Nucl. Phys. **A723**, 354 (2003).
[5] P. Reiter *et al.*, Phys. Rev. Lett. **95**, 032501 (2005).
[6] R.-D. Herzberg *et al.*, Phys. Rev. C **65**, 014303 (2002).
[7] P. Reiter *et al.*, Phys. Rev. Lett. **82**, 509 (1999); **84**, 3542 (2000).
[8] M. Leino *et al.*, Eur. Phys. J. A **6**, 63 (1999).
[9] S. Eeckhaudt *et al.*, Eur. Phys. J. A **26**, 227 (2005).
[10] A. Ghiorso *et al.*, Phys. Rev. C **7**, 2032 (1973).
[11] P. A. Butler *et al.*, Acta Phys. Pol. B **34**, 2107 (2003).
[12] G. Mukherjee *et al.*, AIP Conf. Proc. **764**, 243 (2005).
[13] R.-D. Herzberg *et al.*, Nature (London) (to be published).
[14] P. A. Butler *et al.*, Phys. Rev. Lett. **89**, 202501 (2002).
[15] G. D. Jones, Nucl. Instrum. Methods Phys. Res., Sect. A **488**, 471 (2002).
[16] T. L. Khoo *et al.*, Phys. Rev. Lett. **35**, 1256 (1975).
[17] J. L. Egido and L. M. Robledo, Phys. Rev. Lett. **85**, 1198 (2000); T. Duguet, P. Bonche, and P.-H. Heenen, Nucl. Phys. **A679**, 427 (2001); H. Laftchiev *et al.*, Eur. Phys. J. A **12**, 155 (2001).
[18] S. Cwiok *et al.*, Comput. Phys. Commun. **46**, 379 (1987).
[19] Y. Nogami, Phys. Rev. **134**, B313 (1964).
[20] K. Katori, A. M. Friedman, and J. R. Erskine, Phys. Rev. C **8**, 2336 (1973); (unpublished).
[21] I. Ahmad *et al.*, Phys. Rev. Lett. **39**, 12 (1977); Phys. Rev. C **17**, 2163 (1978).
[22] T. Duguet *et al.*, Phys. Rev. C **65**, 014311 (2002).
[23] P.-H. Heenen (private communication).
[24] A. V. Afanasjev and S. Frauendorf, Phys. Rev. C **71**, 024308 (2005).
[25] T. Otsuka *et al.*, Phys. Rev. Lett. **95**, 232502 (2005).