PHYSICAL REVIEW C VOLUME 58, NUMBER 5 NOVEMBER 1998

Extruder proton-hole band in the near-drip-line nucleus ^{127}Pr

S. M. Mullins,[1] A. Galindo-Uribarri,[2,*] C. E. Svensson,[3] R. A. E. Austin,[3,†] G. C. Ball,[2,‡] M. Cromaz,[4,§] V. P. Janzen,[2] D. C. Radford,[2,*] I. Ragnarsson,[5] J. C. Waddington,[3] and D. Ward[2,§]

[1]*Department of Nuclear Physics, RSPhysSE, The Australian National University, Canberra, ACT 0200, Australia*

[2]*AECL, Chalk River Laboratories, Chalk River, Ontario, Canada KJ0 1J0*

[3]*Department of Physics and Astronomy, McMaster University, Hamilton, Ontario, Canada L8S 4M1*

[4]*Department of Physics, University of Toronto, Toronto, Ontario, Canada M5S 1A7*

[5]*Department of Mathematical Physics, Lund Institute, P.O. Box 118, S-221 00 Lund, Sweden*

(Received 16 June 1998)

The near-drip-line nucleus ^{127}Pr was populated with the reaction ^{92}Mo(^{40}Ca,αp) at a beam energy of 175 MeV. Particle-γ-γ coincidences were collected, and the total energy plane gating technique was used to enhance events associated with the αp exit channel. This enabled two new rotational bands to be assigned to ^{127}Pr, including a strongly coupled structure. Its similarity with analogous bands in heavier Pr isotopes suggests this structure is most likely based on a hole in the extruder $[404]9/2^+$ proton orbital. The occupancy of this orbital is associated with enhanced quadrupole deformation in this mass region. [S0556-2813(98)50311-1]

PACS number(s): 27.60.+j, 23.20.Lv, 21.10.Re

The existence of rotational bands in the $A \sim 130$ mass region based on a ''superdeformed'' second minimum in the nuclear potential energy surface is well documented. These bands are generally populated at, and observed to, high spin, with subpicosecond inband lifetimes from which enhanced deformations of $\beta_2 \geqslant 0.30$–0.35 are inferred. It has been a matter of some debate as to the underlying mechanism that gives rise to these highly elongated shapes, particularly with regard to shell gaps in the single-particle spectrum and ''deformation-driving'' intruder neutron particlelike orbitals, both of which appear at the relevant particle numbers.

Recently the importance of ''deformation-driving'' extruder proton *hole*-like orbitals has gained attention [1]. This has been mainly due to the observation of highly deformed bands in light odd-Z nuclei [2–5] in which the neutron Fermi surface is too far from the intruder particlelike orbitals for them to play a significant role at low excitation energies. Indeed, reexamination of the deformation systematics as a function of both Z and N strongly suggests that the extruder proton orbitals are as important as either the neutron intruder orbitals, or the shell gaps. It is therefore of interest to track the extruder orbitals in odd-Z nuclei down to, and perhaps just beyond, the proton dripline. This motivated the present study of light $A \sim 130$ nuclei, of which ^{127}Pr was one product. Indeed, the proton dripline probably falls at ^{126}Pr [6,7], although the ground-state proton decay of ^{121}Pr has been measured [8]. It should be noted that ground-state deformations are expected to increase as one moves away from $N = 82$, so that orbitals that are usually associated with the second minimum may form the ground or low-lying excited states as the neutron number decreases.

The measurement was performed at the TASCC facility of AECL's Chalk River Laboratories. A 175-MeV beam of ^{40}Ca ions supplied by the upgraded MP tandem accelerator was directed onto a self-supporting metallic-foil target of ^{92}Mo which had a nominal thickness of $\sim 500\ \mu$g/cm^2. The target was placed at the center of the ALF-miniball charged-particle array [9] that was located inside the 8π γ-ray spectrometer. Data were written onto magnetic cassettes, where the event master trigger required two of the twenty Compton-suppressed hyperpure germanium (HPGe) detectors to fire in prompt coincidence, along with a minimum of eight of the seventy bismuth germanate detectors of the inner calorimeter. Charged-particle information was recorded in conjunction with the γ-ray coincidences. Calibration of the HPGe detectors was undertaken with a standard ^{152}Eu source.

The data were sorted offline into E_γ-E_γ correlation matrices. The total energy plane gating technique [10] was used to generate an αp-gated matrix that contained coincidences solely from the decay of states in ^{127}Pr (αp) and ^{126}Ce ($\alpha 2p$). A small fraction of an $\alpha 2p$-gated matrix was subtracted, to leave an almost pure αp matrix. This sorting procedure was crucial, since it allowed transitions from the comparitively weak αp channel to be enhanced relative to those from other nuclei. Even so, the inherent lack of statistics prevented the extraction of reliable angular-correlation ratios for these transitions. The total-projection spectrum of the ''pure'' αp matrix is shown in Fig. 1(a), in which the yrast band of ^{127}Pr, based on a low-Ω $h_{11/2}$ orbital, dominates. A summed coincidence spectrum for this band is shown in Fig. 1(b). The first two transitions were originally identified with the Daresbury recoil separator [11], and the band has recently been extended to its $47/2^-$ state [12] with data taken from the PEX array [13]. It has been observed to the $55/2^-$ state in the present data, as is shown in the level scheme for ^{127}Pr presented in Fig. 2. The discrepancy between the transition energies measured here, and those presented in Ref. [12], arose from a calibration problem introduced in the

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*Present address: Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831.

†Present address: Department of Physics and Astronomy, University of British Columbia, Vancouver, BC, V6T 1Z1 Canada.

‡Present address: TRIUMF, Vancouver, BC, Canada.

§Present address: Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720.

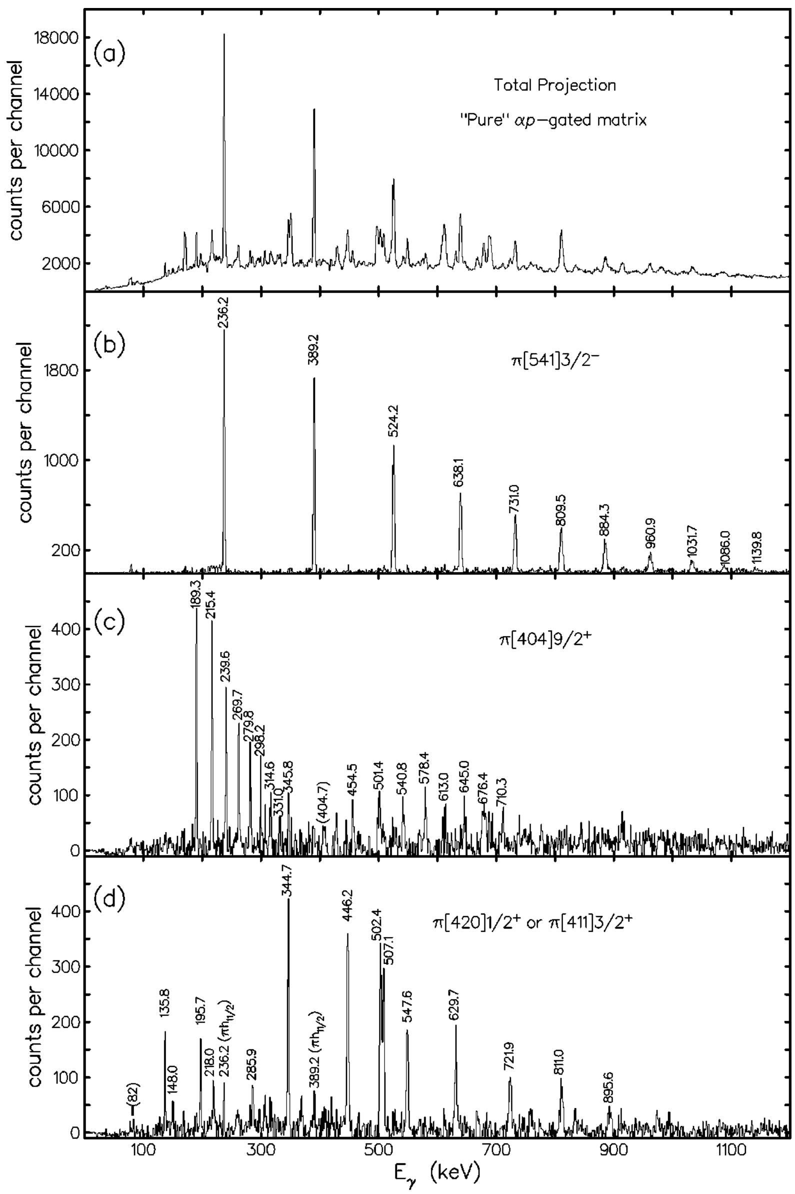

FIG. 1. (a) Total projection of the ''pure'' αp γ-γ coincidence matrix. (b) Sum-of-gates spectrum which shows the $\pi h_{11/2}$ yrast band in ^{127}Pr. (c) Sum-of-gates spectrum of the strongly coupled band in ^{127}Pr assigned to the $\pi[404]9/2^+$ extruder orbital. (d) Sum-of-gates spectrum for the band in ^{127}Pr tentatively assigned to either the $\pi[420]1/2^+$ or the $\pi[411]3/2^+$ orbital. There is evidence for coincidences with the two lowest members of the $\pi h_{11/2}$ band, as indicated. The evidence for the 82 keV transition is not compelling, as discussed in the text.

analysis of the latter. The derived $\mathcal{J}^{(2)}$ values are very similar, however, so that the interpretation presented in Ref. [12] remains unaffected.

A number of regularly spaced transitions in the energy range ~190–300 keV were present in the total projection spectrum. The enhancement of these transitions in the αp-gated matrix allows their unambiguous assignment to ^{127}Pr. When coincidence spectra are projected on these transitions, it is clear that they are the $\Delta J=1$ cascade members of a strongly coupled band. A sum-of-gates spectrum is shown in Fig. 1(c), and the band structure is shown in Fig. 2. The same band structure has been recently observed with the GAMMASPHERE/microball detector combination [14]. The similarity of the band to those assigned to the $[404]9/2^+$ extruder orbital in ^{129}Pr [2,3,15], ^{131}Pr [4], and ^{133}Pm [5], suggests that it too should be identified with this Nilsson state. This orbital appears near the proton Fermi surface for $Z=59$ at quadrupole deformations of $\beta_2 \geqslant 0.35$, which are considerably larger than those associated with the occupancy of the low-Ω $h_{11/2}$ Nilsson states in the heavier Pr isotopes.

A third band, also new, was found, and can be clearly seen in the total projection, which suggests that it should be assigned to ^{127}Pr. It is probably based on a normal-deformed (ND) positive-parity orbital of mixed $d_{5/2}/g_{7/2}$ spherical parentage. This orbital may form the ground state of ^{127}Pr, and probably has $J^\pi=3/2^+$ or $1/2^+$, corresponding to the $[411]3/2^+$ or the $[420]1/2^+$ Nilsson orbitals, respectively. There is weak evidence for coincidences between the higher members of this band and the two lowest members of the $h_{11/2}$ band, as is indicated in Fig. 1(d). If the two tentative linking transitions (775, 890 keV) shown in Fig. 2 are correct, then the $J^\pi=1/2^+$ assignment is favored, but this

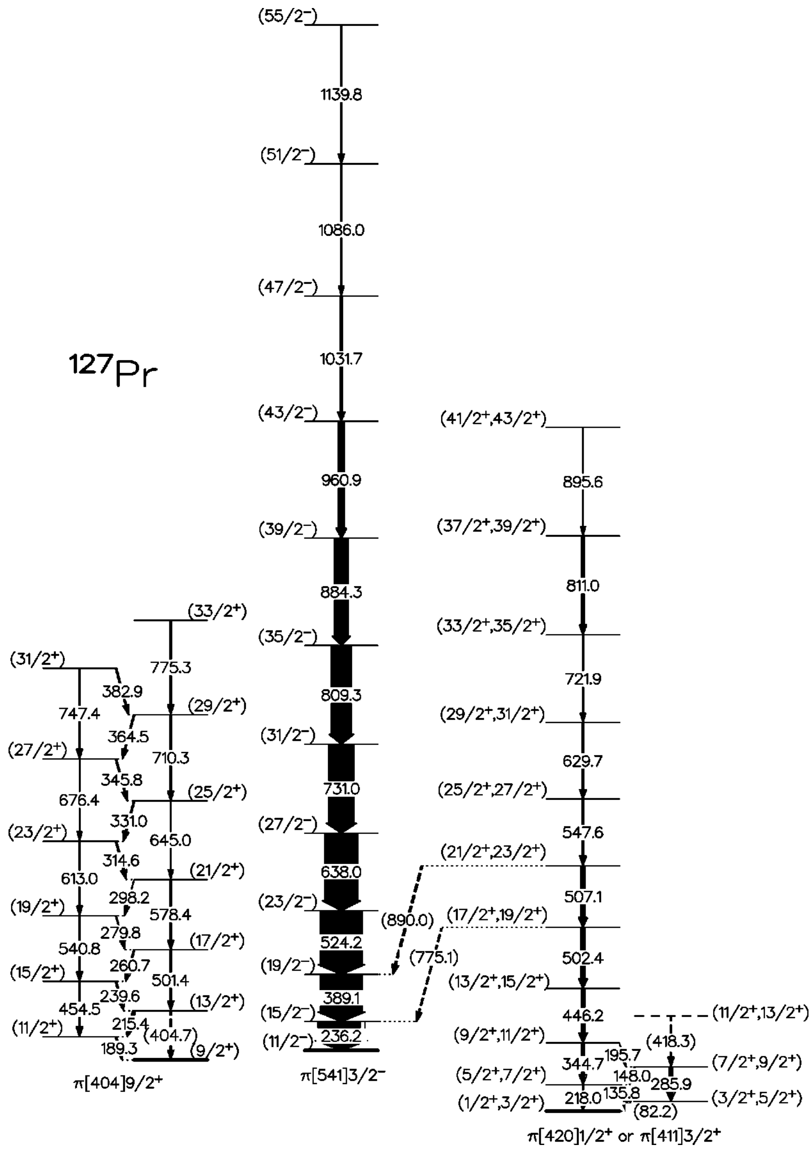

FIG. 2. Level scheme for ^{127}Pr derived from the present data. The relative excitation energies of the three bands are uncertain. All spins and parities are tentative.

would conflict with the systematics of the heavier Pr isotopes, where the ground state has $J^{\pi}=3/2^{+}$. It is possible that these two linking transitions are incorrect, so the J^{π} assignments corresponding to both possibilities are shown in Fig. 2. Moreover, the existence of the 82 keV transition (which would have $\alpha_e = 2.4$ for pure M1 multipolarity) at the bottom of the band is crucial to the assignment, since its omission would raise the possibility that the 218 keV transition is an interband decay, perhaps to the $9/2^{+}$ bandhead, if this were the ground state instead. The evidence for the 82 keV transition in Fig. 1(d) is not compelling, but this could largely be due to the degradation of the γ-detection efficiency at low energy arising from absorption by the ALF miniball.

Bands based on the $3/2^{+}$ ground state have been observed in the heavier Pr isotopes, but in these cases both signatures receive equally strong population, and the energy splitting between them is essentially zero. A second common feature is that a large fraction of the γ-ray flux usually decays to the yrast band by strong $E1$ transitions at the $h_{11/2}$ **AB** quasiproton alignment, so that the one-quasiparticle bands below the crossing are only weakly populated. The band in ^{127}Pr has two unusual characteristics. Firstly, although the $(3/2^{+},5/2^{+})$ and $(7/2^{+},9/2^{+})$ states appear to be favored at low spin, only the opposite signature is observed at high spin, where the band undergoes a crossing due to the **AB** $\pi h_{11/2}$ alignment (see below). Secondly, the bulk of the intensity remains inband through the crossing, which made it difficult to fix the relative energy of this band to the yrast sequence. If the two tentative linking transitions (775, 890 keV) are indeed correct, the $11/2^{-}$ state resides 500 keV above the (presumed) ground state.

The relative excitation energies of the ground-state, $\pi h_{11/2}$ and $\pi g_{9/2}^{-1}$ bands in ^{129}Pr have been determined from the β decay of ^{129}Nd [16]. Unfortunately, this is not yet the case for ^{127}Pr, due largely to the fact that ^{127}Nd is a strong β-delayed proton emitter. Levels in ^{127}Ce are known from the β^{+} decay of ^{127}Pr [17], which are consistent with the presence of $11/2^{-}$ and $9/2^{+}$ parent levels, but there is no information concerning their relative excitation energy.

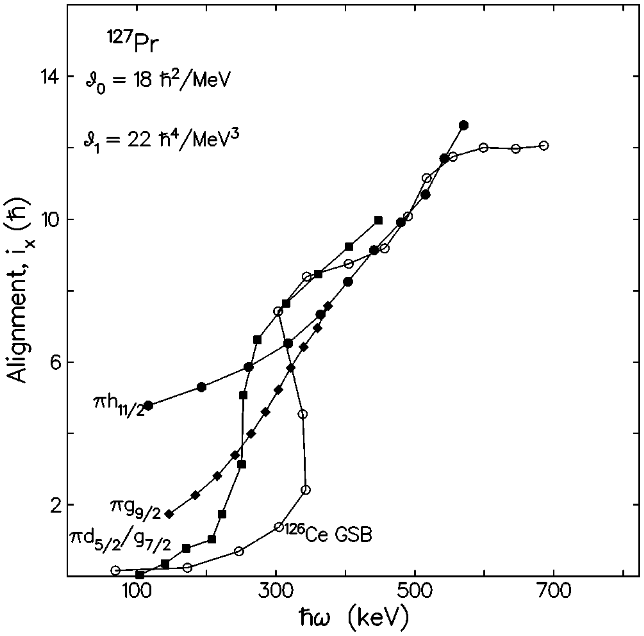

FIG. 3. Alignment plot for the bands in ^{127}Pr and the yrast band in ^{126}Ce.

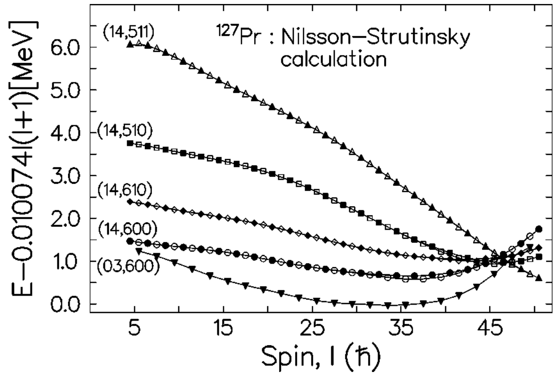

FIG. 4. Calculated excitation energy (relative to a liquid drop) versus spin for the lowest four configurations in ^{127}Pr that involve the $\pi g_{9/2}$ hole. The $\pi h_{11/2}$ yrast configuration is also shown for comparison. The calculations were of the configuration-constrained, cranked Nilsson-Strutinsky type.

In ^{129}Pr the enhanced-deformation [404]9/2$^+$ band decays to the ND positive-parity ground-state band via an isomeric 255 keV transition [18]. The half-life of ~60 ns hindered its observation with the 8π spectrometer [2,3] when an unbacked target was used, since a large fraction of the nuclei decayed after recoiling out of the focus of the HPGe detectors. Clear observation of this transition required the use of a backed target. If the 9/2$^+$ state in ^{127}Pr decays with a similar lifetime, then the present experimental conditions would strongly disfavor the observation of this transition, since an unbacked target was used. Moreover if the 9/2$^+$ state falls below the (5/2$^+$,7/2$^+$) state of the ground-state band, then the lifetime would increase dramatically, since it would have to decay via an $M3$ or $E4$ transition to the (3/2$^+$,5/2$^+$) state. The decay would not then be measurable under the nanosecond timing conditions employed here, even with a backed target. It is possible, however, that the 9/2$^+$ bandhead is itself the ground state, in which case the decay from the (1/2$^+$,3/2$^+$) state would be isomeric.

The alignments for the three bands in ^{127}Pr are shown in Fig. 3 relative to a common Harris reference. For comparison the ground-state band of the core nucleus ^{126}Ce is also shown. It had been previously established to its 14$^+$ state [19], but has been extended to the 32$^+$ state in the present data. Cranked shell model (CSM) calculations predict that the lowest frequency alignment arises from the decoupling of a pair of $h_{11/2}$ protons (the **AB** crossing in CSM parlance). The increase in alignment for ^{126}Ce at $\hbar\omega \simeq 0.35$ MeV has been attributed to this crossing [19]. This crossing is blocked in the $\pi h_{11/2}$ yrast band of ^{127}Pr, but occurs in the positive-parity $\pi d_{5/2}/g_{7/2}$ band, though the crossing frequency is much lower than in ^{126}Ce, and with a larger interaction strength. The shift in crossing frequency is presumably due to the reduction in proton pairing strength caused by the odd proton blocking a pair of orbitals near the Fermi surface. Similar differences in crossing frequencies between even- and odd-Z neighbors have been observed in many nuclei in the $A\sim130$ region. The alignment of the $\pi h_{11/2}$ band in ^{127}Pr shows a smooth increase with rotational frequency. Extended total Routhian surface (TRS) calculations [12] suggest that this behavior is due to the combined contributions of the first pair of $h_{11/2}$ neutrons (**ab**) and the second pair of $h_{11/2}$ protons (**BC**). It seems likely that the increase in alignment at $\hbar\omega \simeq 0.5$ MeV in ^{126}Ce is due to the **ab** neutron crossing.

The alignment for the $\pi g_{9/2}$ band shows a smooth, but steep increase with rotational frequency, which may in part be due to an unsuitable choice of reference for this configuration. This smooth increase persists, however, for any reasonable choice of reference, as is also the case for the analogous bands in ^{129}Pr and ^{131}Pr. It is possible that this increase is due to the **AB** $h_{11/2}$ alignment, but with a larger interaction strength compared to either the ^{126}Ce core or the $\pi d_{5/2}/g_{7/2}$ band. Standard cranked shell model calculations offer no explanation for the increased interaction strength. This clearly cannot be due to any residual neutron-proton interaction, but may reflect the inadequate treatment of like-particle pairing in such calculations.

We have performed unpaired cranked Nilsson-Strutinsky calculations with constrained orbital occupancy in order to examine various configurations in ^{127}Pr which involve a $\pi g_{9/2}$ hole. The excitation energy of these configurations is shown versus spin in Fig. 4, where a rotating liquid drop energy has been subtracted. Each configuration is labeled with (*ab*,*cde*), where *a*,*b*,*c*,*d*, and *e* denote the number of $\pi g_{9/2}$ (holes), $\pi h_{11/2}$, $\nu h_{11/2}$, $\nu h_{9/2}/f_{7/2}$, and $\nu i_{13/2}$ orbitals, respectively, that are occupied. The lowest configuration of interest is labeled (14,600), that is, one $g_{9/2}$ proton hole, four $h_{11/2}$ protons and six $h_{11/2}$ neutrons. It seems reasonable to assign the observed band to it, since the other $\pi g_{9/2}^{-1}$ configurations, that involve excitations into the $\nu h_{9/2}/f_{7/2}$ and $\nu i_{13/2}$ orbitals, lie progressively higher in excitation energy over the spin range that is observed here. The calculated deformation for the (14,600) configuration remains constant with spin, with value of $\varepsilon_2 = 0.31$, while that of the (03,600) yrast $\pi h_{11/2}$ configuration has deformation of $\varepsilon_2 = 0.28$. The latter value agrees with that found from lifetime measurements of the first excited state in the core nucleus ^{126}Ce [19], where a quadrupole deformation of $\varepsilon_2 = 0.28 \pm 0.01$ was inferred. Hence, the calculation for ^{127}Pr suggests that a particle in the $\pi h_{11/2}$ orbital probably does not polarize the core strongly, whereas a hole in the $\pi g_{9/2}$ orbital may enhance the deformation by about 10%. It would be of interest to undertake lifetime measurements with the present reaction to confirm this relative difference between these states in ^{127}Pr *and* relative to the ^{126}Ce core. Moreover, this would also allow an extensive comparison to the equivalent states in ^{129}Pr $(3p)$ and to its ^{128}Ce $(4p)$ core, given sufficiently powerful instrumentation.

In conclusion, transitions have been assigned to the neutron-deficient nucleus ^{127}Pr by employing the total energy plane analysis to charged-particle-γ-γ data. The transitions have been assigned to three band structures, one of which is probably based on the $[404]9/2^+$ extruder orbital, which becomes favored at enhanced quadrupole deformation. The yrast band based on an $h_{11/2}$ proton was observed to spin 55/2. The third band is probably based on a positive-parity orbital, and may form the ground state. Alternatively, the enhanced-deformation $9/2^+$ state may in fact be the ground state.

ACKNOWLEDGMENTS

The support of the accelerator and general staff at the TASCC facility during difficult circumstances is acknowledged. This work was funded by the National Sciences and Engineering Research Council of Canada and AECL Research, with further support from the Swedish Natural Research Council.

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