In-beam γ-ray and α-decay spectroscopy of ^{170}Ir

B. Hadinia,[1,*] B. Cederwall,[1] D. T. Joss,[2,†] R. Wyss,[1] R. D. Page,[3] C. Scholey,[4] A. Johnson,[1] K. Lagergren,[1,‡] E. Ganioğlu,[1,5] K. Andgren,[1] T. Bäck,[1] D. E. Appelbe,[2] C. J. Barton,[2,§] S. Eeckhaudt,[4] T. Grahn,[4,†] P. Greenlees,[4] P. Jones,[4] R. Julin,[4] S. Juutinen,[4] H. Kettunen,[4] M. Leino,[4] A.-P. Leppänen,[4] R. J. Liotta,[1] P. Nieminen,[4,‖] J. Pakarinen,[4,†] J. Perkowski,[4,¶] P. Rahkila,[4] M. Sandzelius,[1] J. Simpson,[3] J. Uusitalo,[4] K. Van de Vel,[4,**] D. D. Warner,[2] and D. R. Wiseman[3]

[1]*Department of Physics, Royal Institute of Technology, SE-10691 Stockholm, Sweden*
[2]*CCLRC, Daresbury Laboratory, Daresbury, Warrington, WA4 4AD, United Kingdom*
[3]*Oliver Lodge Laboratory, Department of Physics, University of Liverpool, Liverpool, L69 7ZE, United Kingdom*
[4]*Department of Physics, University of Jyväskylä, Post Office Box 35, University of Jyväskylä, FIN-40014 Jyväskylä, Finland*
[5]*Science Faculty, Physics Department, Istanbul University, TR-34459 Istanbul, Turkey*

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Excited states in the highly neutron deficient odd-odd nucleus ^{170}Ir have been investigated. The experiment was performed using the ^{112}Sn(^{60}Ni, pn)^{170}Ir reaction and employing the recoil-decay tagging technique. Gamma rays were detected using the JUROGAM γ-ray spectrometer and those belonging to ^{170}Ir were selected based on recoil identification provided by the RITU gas-filled recoil separator and the GREAT spectrometer at the RITU focal plane. A partial level scheme of ^{170}Ir is presented for the first time. New α-decay branches are assigned to ^{170}Ir and a tentative level structure for ^{166}Re is deduced from a study of the α-decay fine structure and the associated α-γ correlations.

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I. INTRODUCTION

Odd-odd nuclei exhibit rich and complex structures, reflecting the many possibilities of coupling between the odd proton and the odd neutron. They therefore offer significant experimental challenges and have been less studied compared to even-even and odd-A nuclei. Despite their complexity, studies of the structural properties of doubly odd nuclei are important for our understanding of nuclear properties in general and may for instance yield detailed information of the residual proton-neutron interaction. In the particular case of the iridium isotopes, ^{176}Ir is the lightest odd-odd isotope for which extensive information on excited states is available [1]. This work reports on an in-beam study of the structure of the $^{170}_{77}$Ir$_{93}$ nucleus, yielding information on the α-decay properties of the high-spin isomeric state and on excited states built on it. Previous information on the structure of ^{170}Ir comes from studies of the fine structure in the α decay of the mother nucleus, ^{174}Au, for which three levels have been proposed to be populated at 65, 153, and 190 keV relative to the excitation energy of the α-decaying isomeric state [2,3] in ^{170}Ir.

II. THE EXPERIMENT

Excited states in ^{170}Ir were populated by using the ^{112}Sn(^{60}Ni, pn)^{170}Ir* fusion-evaporation reaction. The experiment was performed at the JYFL accelerator facility at the University of Jyväskylä, Finland. The ^{60}Ni ions, with an average beam intensity of 4.7 pnA, were accelerated by the K130 cyclotron to an energy of 266 MeV. The target consisted of a stack of two self-supporting foils of enriched (93%) ^{112}Sn, with areal densities of 800 and 400 μg/cm^2. Prompt γ rays were detected at the target position by the JUROGAM γ-ray spectrometer, which consisted of 43 EUROGAM [4] type escape-suppressed high-purity germanium detectors, with a total photo-peak efficiency of 4.2% at 1.3 MeV. The germanium detectors were distributed over six angles relative to the beam direction with five detectors at 158°, ten at 134°, ten at 108°, five at 94°, five at 86°, and eight at 72°.

The fusion-evaporation products were selected by using the gas-filled recoil separator RITU [5,6] and the GREAT [7] spectrometer. The GREAT spectrometer is a composite detector system consisting of two double-sided silicon strip detectors (DSSDs), a multiwire proportional avalanche counter (MWPC), and an array of 28 Si PIN-diode detectors. In addition, one germanium detector placed close to the RITU focal plane was used for detecting isomeric γ decays with γ-ray transitions following the decay of the fusion-evaporation reactions. Each DSSD had a total active area of 60 × 40 mm^2 and a strip pitch of 1 mm in both directions, yielding in total 4800 independent pixels. To separate the produced fusion-evaporation products from the scattered beam particles, time

*hadinia@nuclear.kth.se
†Present address: Oliver Lodge Laboratory, Department of Physics, University of Liverpool, Liverpool, L69 7ZE, United Kingdom.
‡Present address: Joint Institute for Heavy Ion Research, Holifield Radioactive Ion Beam Facility, Oak Ridge, Tennessee 37831,USA.
§Present address: Department of Physics, University of York, York, Heslington, YO1 5DD, United Kingdom.
‖Present address: Australian National University, Canberra, ACT 0200, Australia.
¶Present address: Department of Nuclear Physics, Radiation Safety, University of Lodz, Pomorska, 149/153, PL-90-236, Lodz, Poland.
**Present address: Instituut voor Kern-en Stralingsfysica, Department of Physics, University of Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium.

of flight and energy loss in the MWPC were used to identify the recoiling nuclei.

The signals from all detectors were recorded independently and provided with an absolute "time stamp" with an accuracy of 10 ns using the Total Data Readout [8] acquisition system. Spatial and temporal correlations of recoil implants and their subsequent α decays were performed on- and off-line using the GRAIN software package [9] and γ rays associated with the depopulation of excited states of ^{170}Ir were identified using the recoil-decay tagging technique [10,11].

III. DATA ANALYSIS AND RESULTS

The decay of the nucleus ^{170}Ir has in a study by Page *et al.* been found to have 36(10)% probability of occurring through the emission of an α particle with an energy of either 6003(10) or 6083(11) keV [12]. The 6083-keV α decay has been assigned a half-life of 0.83(30) s and the 6003-keV α decay has been reported to have a half-life of 1.070(120) s [13,14]. Rowe *et al.* [15] assigned these two α decays to depopulate an isomeric state in ^{170}Ir and proposed an additional α decay with an energy of 5815(10) keV as the ground-state decay. As a result of the present experiment the α-decay energies corresponding to the decay of the isomeric state have been modified to 6007(10) and 6053(10) keV, respectively. In addition, new decay branches from this state are proposed as discussed in the following. Owing to contamination from other reaction channels we cannot confirm the proposed α decay from the ground state. Figure 1 shows the total recoil-correlated α-energy spectrum obtained with correlation times of up to 10 s and illustrates the population of all major reaction channels. Peaks in the spectrum have been labeled corresponding to the strongest fusion-evaporation channels.

Recoil-decay tagged prompt γ-ray energy spectra for ^{170}Ir are shown in Fig. 2. These spectra were produced by taking JUROGAM events correlated with recoil-α events at the RITU focal plane with a correlation time of 2 s (corresponding to approximately three half-lives of ^{170}Ir). The upper and lower spectra are obtained by requiring a fusion-evaporation residue to be detected in the same DSSD pixel and in delayed coincidence with the 6007(10)- or 6053(10)-keV α decay, respectively. Comparing these two spectra, we find that the same γ rays from the decay of excited states in ^{170}Ir are observed, providing evidence that both α decays occur from the same state.

Because the partial overlap of the α-decay peaks assigned to ^{169}Ir [16] with those of ^{170}Ir, the assignment of prompt γ rays to ^{169}Ir and ^{170}Ir cannot be performed with certainty by using only selections based on the α-decay energy. Furthermore, since the ^{165}Re and ^{166}Re daughters of ^{169}Ir and ^{170}Ir, respectively, also have similar α-decay energies, the use of mother-daughter correlations could not directly enable us to distinguish the γ rays of ^{170}Ir from those of ^{169}Ir. The half-lives are also similar (0.31 s for ^{169}Ir and 0.83 s for ^{170}Ir) and do not provide means for clean separation. However, the α-decay branching ratio for ^{169}Ir is almost twice as large as that of ^{170}Ir [12]. In addition, the α branching ratios for the daughters differ by a factor of $\approx$6.5 in the same direction. Hence, the intensities of mother-daughter correlated γ rays belonging to ^{169}Ir were enhanced by more than one order of magnitude relative to those belonging to ^{170}Ir in the mother-daughter correlated spectra compared to those in the single-α-tagged spectra. This enabled us to identify and separate the ^{169}Ir γ rays from those belonging to ^{170}Ir. The existence of ^{116}Sn contamination in the target allowed population of ^{174}Pt via the 2n-particle evaporation channel. ^{174}Pt decays via α emission from the ground state with previously reported energy of 6038(4) keV [12,17]. This α energy is in the region of the energies of the ^{170}Ir α decays and is another source of contamination in the ^{170}Ir data that has to be considered. However, since the level scheme of ^{174}Pt is well known [18] it was possible to distinguish these γ rays from those belonging to ^{170}Ir. In Table I we have listed the energies and the relative intensities of the γ rays assigned

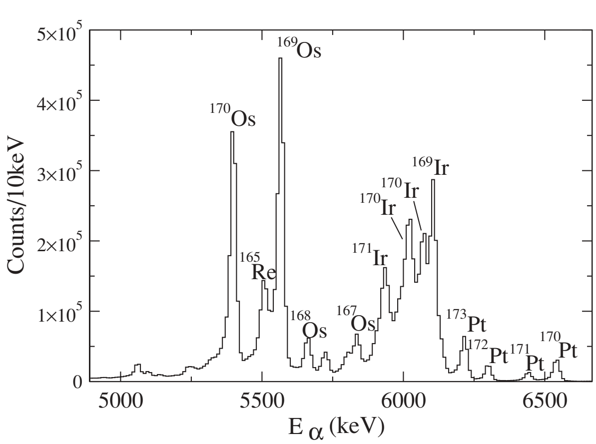

FIG. 1. Energy spectrum for α decays occurring after a recoil implantation in the same pixel of the DSSD with recoil-α correlation times up to 10 s. The ^{173}Pt and ^{172}Pt decay lines are present because of impurities in the target.

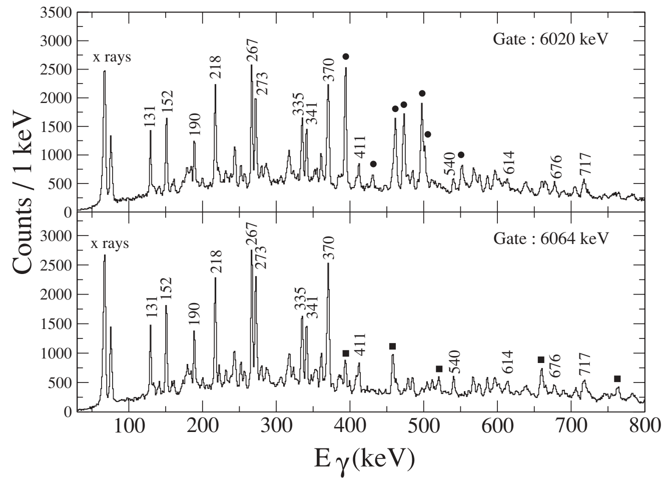

FIG. 2. Prompt γ ray spectra from the decay of excited states in ^{170}Ir correlated with the 6007-keV (top panel) and 6053-keV (bottom panel) α decay lines. Strong contaminant peaks from ^{174}Pt and ^{169}Ir are marked by filled circles and squares, respectively. The spectra are produced by using a search time limit of 2 s between a recoil implant and its subsequent α decay.

TABLE I. The γ rays assigned to the structure built on the isomeric state of ^{170}Ir. Gamma-ray intensities (with statistical uncertainties given within parentheses) have been adjusted for detector efficiencies and normalized to the intensity of the strongest transition (370 keV). Doublet γ-ray transitions are indicated with stars.

Energy (keV)	Relative intensity	Energy (keV)	Relative intensity
131.5(2)	50(6)	360.8(7)	24(6)
142.9(3)	⩽8	370.1(1)*	100(8)
152.5(2)	56(6)	388.0(9)	14(4)
160.4(3)	⩽5	398.4(4)	⩽5
174.9(3)	⩽5	407.6(3)	⩽9
180.9(4)	14(4)	411.4(3)	22(6)
190.3(4)	32(5)	539.5(2)	16(5)
218.4(2)	61(7)	565.9(3)	21(7)
232.7(2)	⩽7	573.7(3)	15(7)
244.0(3)	22(5)	584.8(3)	20(7)
252.7(3)	12(4)	594.9(2)	24(6)
259.8(8)	⩽6	600.3(3)	15(5)
267.3(1)	80(7)	613.6(8)	18(6)
272.7(1)	66(6)	636.2(8)	⩽8
279.9(2)	11(4)	665.8(3)	12(7)
287.8(2)	11(4)	675.9(3)	21(7)
306.2(4)	⩽5	704.5(3)	14(6)
317.6(4)	26(6)	716.7(3)	34(7)
323.2(2)	12(5)	723.5(3)	12(6)
335.0(2)*	55(7)	744.9(3)	14(6)
340.9(2)	43(6)	753.5(7)	⩽10
354.5(2)	14(4)	782.0(3)	14(6)

to ^{170}Ir. The results confirm the 152- and 190-keV γ rays previously assigned to ^{170}Ir by Goon [2]. However, the 65-keV γ ray [3] cannot be unambiguously confirmed because of its overlap with the Ir X rays.

A search for prompt γ rays feeding the ground state of ^{170}Ir was carried out by requiring a delayed coincidence with α particles with energies around 5815 keV, corresponding to the tentatively assigned α decay of the ground state [15]. The contaminating γ rays were found to be from a few strong reaction channels, most notably ^{167}Os, ^{171}Ir, and ^{169}Os, or from the decay of ^{172}Ir [2], which was produced in reactions with heavier Sn isotopes in the target. Hence, no γ rays could be assigned as feeding the ground state of ^{170}Ir in this work.

The use of α-recoil correlated γ-γ coincidences enabled us to extract the partial level scheme for ^{170}Ir, shown in Fig. 3. The limited statistics and the presence of energy doublets meant that only about a third of the observed γ rays listed in Table I could be placed in the level scheme. The low statistics also precluded firm multipolarity assignment by means of angular distribution measurements. Our results confirm one of the three previously reported levels ($x + 152$), which is placed in the structure that builds on the α-decaying isomeric state [2]. Spectra gated by the 267- and the 341-keV γ-ray transitions are shown in Fig. 4.

Because of the existence of many close-lying peaks in the α spectra, the unambiguous identification of additional α decays from ^{170}Ir was not possible solely by requiring

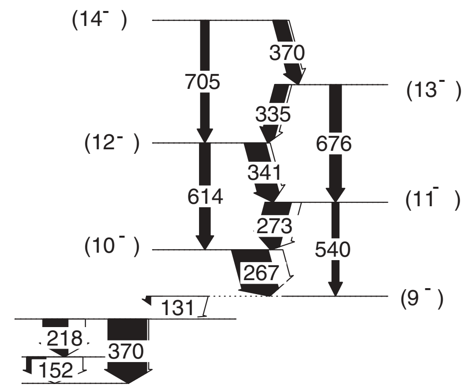

FIG. 3. Partial level scheme of ^{170}Ir.

mother-daughter correlations. We therefore made an attempt to search for additional fine structure in the α decay of the high-spin isomeric state by gating on some of the prompt γ-ray transitions that could be associated with its previously known decay branches. Figure 5 shows the α-energy spectrum resulting from correlation between a number of pairs of strong coincident prompt γ rays belonging to ^{170}Ir with subsequent recoil-correlated α decays in the focal plane (i.e., "inverse tagging"). In this spectrum the two previously known α peaks belonging to the isomeric α-decaying state in ^{170}Ir can be clearly seen, together with two new peaks appearing at energies of 5951(10) and 6121(10) keV. The tagged γ-ray spectra gated on the two new observed α lines are shown in Fig. 6. However, we cannot exclude that the α peak at 6121(10) keV is formed by summing the energies of internal conversion electrons to the α-particle energies of 6007(10) and 6053(10) keV, since the DSSDs can detect conversion electrons as well as α particles (see the following).

The α decay of a nucleus via several branches, all emanating from the same state, is not a new feature in this mass region and it is not uncommon for α-decaying odd-odd nuclei. For instance, the nucleus ^{178}Tl, which is the grandmother of ^{170}Ir, has been found to have four different α decays depopulating

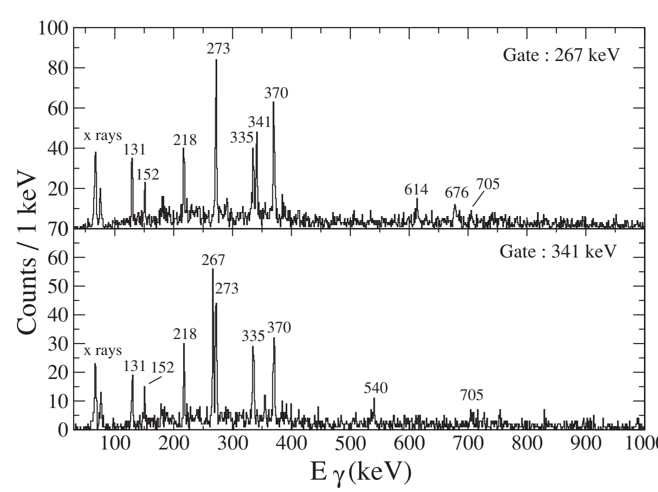

FIG. 4. Spectra gated by the 267-keV (top) and 341-keV (bottom) γ-ray transitions (see the text for more details).

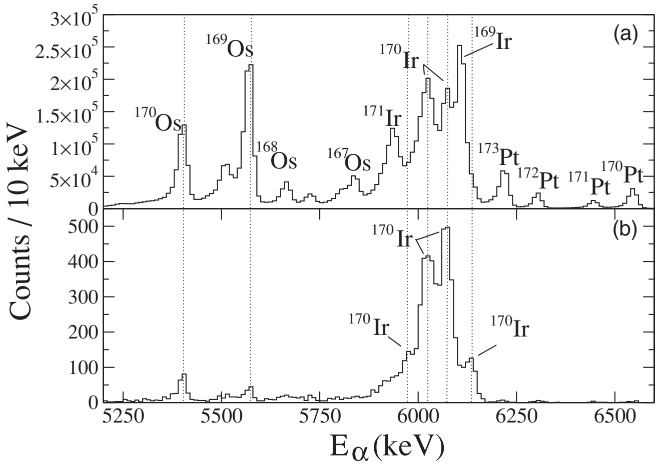

FIG. 5. (a) Energy spectrum for α decays occurring after recoil implantation in the same pixel of the DSSD, with a recoil-α correlation time of up to 3 s (a). (b) The α-decay energy spectrum resulting from correlations between the prompt coincidence of pairs of γ rays identified as belonging to ^{170}Ir and recoils is imposed (see the text for details).

the ground state [15]. Similar α-decay fine structure has been observed in ^{174}Au, the mother of ^{170}Ir, which has been reported to have three α-decay branches originating from an isomeric state [2]. Similar observations have been reported in the heavier gold isotopes, $^{181-185}$Au [19].

The half lives of the α-decay branches in ^{170}Ir were independently determined by using the maximum-likelihood method. Time differences between cleanly correlated recoils and α particles were obtained by including only the α decays that were correlated with certain combinations of strong coincident γ rays belonging to ^{170}Ir. The resulting half-lives were measured to be 802^{+30}_{-28} ms for the α decay with $E_\alpha = 6007(10)$ keV, 826^{+30}_{-28} ms for $E_\alpha = 6053(10)$ keV, 830^{+58}_{-53} ms for $E_\alpha = 5951(10)$ keV, and 801^{+63}_{-57} ms for the tentative α decay with $E_\alpha = 6121(10)$ keV. Since the γ-ray spectra correlated with these α particles display the same peaks and the differences in half-lives are within the experimental uncertainties, all four α-decay branches most likely originate from the same state, which is assigned a half-life of 811(18) ms.

To further investigate the fine structure in the α decay of the isomeric state in ^{170}Ir, events were studied for which recoil-correlated α decays in the DSSDs were followed by γ rays detected by the germanium detector at the RITU focal plane position. Figure 7 illustrates the γ-ray spectra gated on the different α-decay branches from the isomeric state in ^{170}Ir and on the α decay of ^{171}Ir, and a proposed level scheme for ^{166}Re is shown in Fig. 8.

The α decay of ^{171}Ir is in coincidence with Re X rays [Fig. 7(a)] and with the previously identified 92-keV γ ray [20] belonging to the $\pi h_{11/2}$ band of ^{167}Re [21], the α decay daughter of ^{171}Ir. The tentative 6121-keV α line is not in coincidence with any clear γ-ray transitions [see Fig. 7(b)], nor is it in coincidence with Re K X rays of appreciable intensity. This tentative decay branch could therefore directly populate the corresponding isomeric state in the ^{166}Re daughter nucleus. However, since the X-ray energies originating from the Re L shells are lower than 12 keV, they would not be registered by the germanium detector. The possibility that the 6121-keV α line is formed

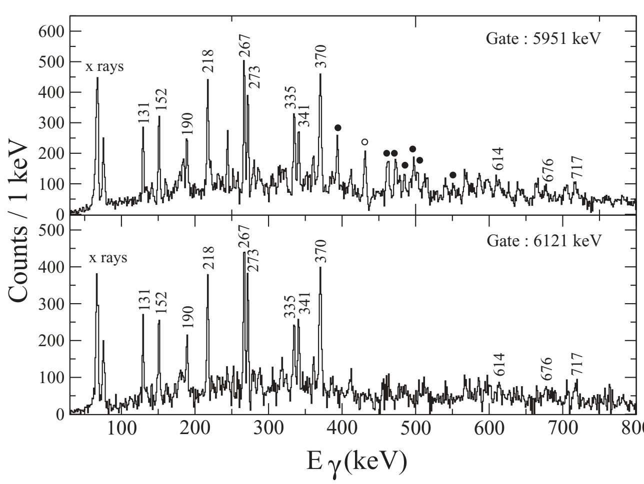

FIG. 6. Recoil α-gated prompt-γ-ray spectra for the new α lines associated with the decay of ^{170}Ir. The spectra were partially cleaned by subtracting a fraction of similarly produced spectra from α gates on peaks that partially overlap with the α decays of ^{170}Ir. The filled circles indicate contamination from ^{174}Pt from overlapping α gates. The open circle indicates contamination from ^{166}Os, which has a ground-state α-decay energy within the range of this gate.

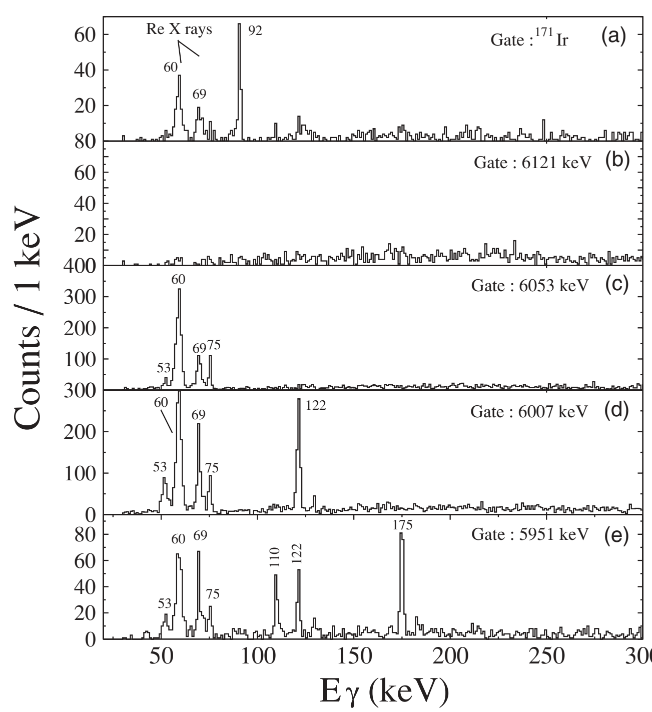

FIG. 7. Gamma-ray spectra obtained from a germanium detector placed at the focal plane of RITU, gated on the α decay of ^{171}Ir and on the α-decay branches of the high-spin isomeric state in ^{170}Ir indicated in Figs. 5 and 6.

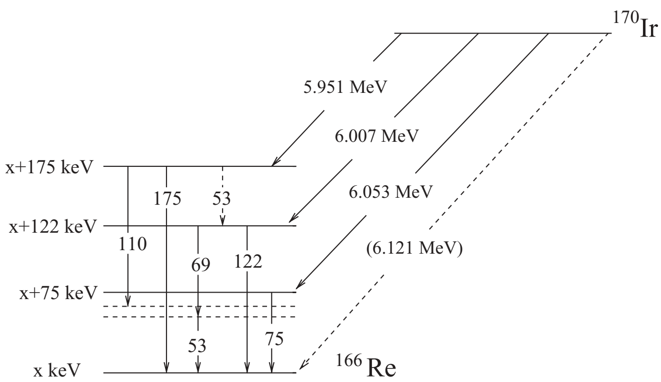

FIG. 8. Tentative level structure of ^{166}Re deduced from the α-decay study of ^{170}Ir.

by summing the energies of conversion electrons with those of the detected α particles therefore cannot be ruled out (see the following). In addition, the α- and β-decay studies on $^{172–174}$Ir by Schmidt-Ott *et al.* [20] revealed no α decays emanating from the isomeric states in these nuclei that directly populate the isomeric states in $^{168–170}$Re. The 6053-keV α decay is found to be in coincidence with a 75-keV γ-ray transition, in addition to the Re X rays [Fig. 7(c)]. This indicates that the 6053-keV α decay is likely to feed a state that is excited at least 75 keV above the α-decaying isomeric state in ^{166}Re. Considering that the 92-keV γ ray in ^{167}Re has $M1$ character and the X rays observed in the ^{171}Ir gate originate from the conversion of the 92-keV γ ray, we can assign an $M1$ character to the 75-keV γ ray transition as well. The 53-keV peak visible in the $E_\alpha = 6053$ keV gate could originate from the 6007-keV α decay, if the 69-keV γ ray is L-converted. The added signals from the conversion electrons to the α energy of 6007 keV then fall into the 6053-keV α gate (see the following). Figure 7(d) shows that the α decay with energy 6007 keV is strongly coincident with a 122-keV γ ray as well as with γ rays at 75, 53, and 69 keV (the latter overlapping one of the Re X-ray peaks). We propose 122 keV $+\, x$ as an excited state in ^{166}Re fed by this α decay, where x is the excitation energy of the isomeric state. The population of the 75-keV state may occur through a single heavily converted 47-keV transition. Since the energies of the 53- and 69-keV γ rays add to 122 keV, they probably form a cascade de-exciting the same state. However, the ordering of the 69- and 53-keV transitions cannot be determined. Since the relative intensities of the 75-keV γ ray and the K_α 60-keV X ray in spectra gated by the 6053- and 6007-keV α decays are approximately the same, one can conclude that the 122-keV transition probably has an $E1$ character as it has no significant contribution to the X-ray intensities via internal conversion. The 122-keV γ ray as well as γ rays at 110 and 175 are in coincidence with the 5951-keV α line [see Fig. 7(e)], suggesting another state at 175 keV above the ^{166}Re α-decaying isomer. Since the energies of the 122- and the 53-keV γ rays add to 175 keV, there may be two 53-keV transitions, with one of them significantly more converted than the other. The relative intensity of the 53-keV peak compared to that of the 122-keV peak in the spectra gated by the 5951- and 6007-keV α decays is, however, approximately the same. If one assumes stretched dipole transitions, the $M1$ transition would be around 20 times more converted than an $E1$ transition at this energy. Therefore we tentatively assign an $M1$ character to the upper and $E1$ multipolarity to the lower 53-keV transition. We also tentatively assign $M1$ character to the 69-keV γ ray, which is consistent with the tentative multipolarities assigned to the parallel transitions. Although there is uncertainty in the placement of the 110-keV γ ray, it is tentatively assigned to depopulate the $x + 175$ keV level, forming a cascade together with a 65-keV transition (which may be a highly converted $M1$ transition) to the α-decaying isomeric state at x keV. The same argument that was used to propose the assignment of $E1$ character to the 122-keV γ ray transition is valid for assigning an $E1$ character also to the 110- and 175-keV γ-ray transitions. Returning now to the tentative α-decay branch at 6121 keV we find that there are γ-ray transitions fed by the 6007- and 6053-keV decays that might produce such a peak as an artifact via summing the energies of conversion electrons to the α particles. However, only L-conversion is possible since K-conversion does not have enough energy to create the 6121-keV peak. Furthermore, K X rays are not seen in coincidence with the 6121-keV α decay. For instance, since the electron binding energies are 71.6 and 12.5 keV for the K and L shells in Re, respectively, contributions to the 6121-keV peak can be formed mainly by adding electron conversions with energy 75 – 12.5 keV to the 6053-keV α particle or 122 – 12.5 keV to the 6007-keV α particle.

The energies of the α particles from the decay of ^{170}Ir that populate excited states in ^{166}Re are measured in the α spectrum obtained by requiring coincidences with γ-ray transitions that de-excite the corresponding state populated in the daughter nucleus. This avoids the summing of conversion electron energies to the α particle energies. The energy difference between the most energetic α lines, 6121(10) and 5951(10) keV, corresponds to a Q_α difference of 174(20) keV, which is in agreement with the most energetic γ ray found to be coincident with the 5951-keV α decay (175 keV). Similar agreement is seen for the Q_α difference between the 6121- and 6007-keV α decays, which is 117(20) keV, and the 122-keV γ ray, which is in coincidence with the 6007-keV α decay. The Q_α difference between the 6121(10) and 6053(10)-keV α decays amounts to 70(20) keV, which is in good agreement with the 75-keV γ-ray energy. Disregarding the tentative α peak at 6121 keV, we see that the agreement between the other Q_α differences and the energy level differences are still valid. The Q_α difference between 6053 and 6007 keV is 47 keV, which is in excellent agreement with the differences between the 122- and 75-keV energy levels. Similar agreement is seen for the Q_α difference between the 6007- and 5951-keV α decays, which is 57 keV, and the level energy difference between the 175- and 122-keV decays, which is 53 keV.

IV. DISCUSSION

For neutron-deficient odd-odd nuclei below the $Z = 82$ closed proton shell and with neutron numbers above $N = 82$, a strong proton-neutron residual interaction may favor the occupation of the $d_{3/2}$ rather than the $s_{1/2}$ proton orbital in near-spherical nuclei [22,23]. For the nuclei ^{166}Ir and ^{170}Au the $\pi d_{3/2} \otimes \nu f_{7/2}$ and $\pi h_{11/2} \otimes \nu f_{7/2}$ configurations have therefore been proposed for the α-decaying ground and isomeric states, respectively. According to the Nordheim rules, this leads for spherical nuclei to $I^\pi = 2^-$ for the ground state and $I^\pi = 9^+$ for the high-spin isomeric state in these nuclei. It was also suggested that ^{170}Ir may have an analogous structure [22]. However, even for weakly deformed shapes, significant mixing between the single-particle states will occur. Schmidt-Ott *et al.* [20] have tentatively assigned the spin-parities $I^\pi = 7^+$ and $I^\pi = 3^+$ to the isomeric and ground states in ^{172,174}Ir, respectively, based on the observed β decays to states in the ground-state bands of the even-even isobars. These assignments are consistent with coupling of deformed proton and neutron configurations near the Fermi level. For instance, in ^{172}Ir, the high-spin isomeric (7^+) state can be explained by occupation of the $\pi 11/2^-[505]$ and $\nu 3/2^-[521]$ Nilsson orbitals. This interpretation is also valid for the high-spin isomeric state observed in ^{170}Ir. It is consistent with the observations of similar rotational-like band structures in the neighboring ^{169}Ir [24] and ^{171}Ir [25] isotopes, assigned to be built on the $\pi 11/2^-[505]$ configuration at weakly deformed, triaxial shapes. A consideration of the available proton orbitals near the Fermi surface indicates that there is no other candidate for the proton component of the strongly coupled yrast band in ^{170}Ir among the available orbitals near the Fermi surface. An interesting feature in the even-Z odd-N nuclei in this region is the collective rotational-like yrast bands built on γ-decaying $\nu i_{13/2}$ spin isomers. For the closest isotones of ^{170}Ir, $^{169}_{76}$Os, and $^{171}_{78}$Pt, these states lie at a few hundred keV excitation energy above the ground state [26]. These observations indicate that the occupation of the $i_{13/2}$ neutron orbital is favored at intermediate spins in these nuclei.

In Fig. 9 the rotational alignments are plotted for the observed rotational band in ^{170}Ir and the $h_{11/2}$ band in ^{171}Ir [25]. The kink observed at $\hbar\omega \approx 0.3$ MeV for ^{171}Ir can be

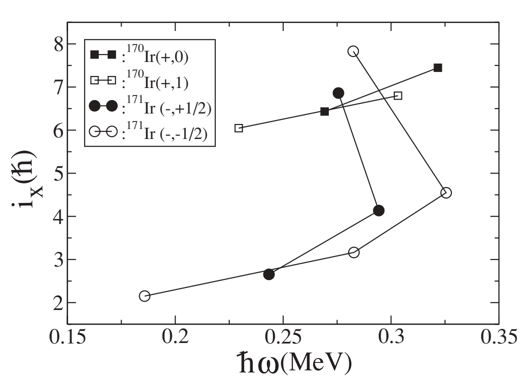

FIG. 9. Aligned angular momentum values for the $h_{11/2}$ band in ^{171}Ir [25], and the observed rotational band in ^{170}Ir obtained from the present work. The Harris parameters used are $J_0 = 10$ MeV$^{-1}\hbar^2$ and $J_1 = 50$ MeV$^{-3}\hbar^4$, which are taken from Ref. [25]. The signatures $-1/2$ and $+1/2$ in ^{171}Ir are indicated by open and filled circles, respectively, and the filled and open squares represent the signatures 0 and 1 in ^{170}Ir. In both cases the K value is taken to be 5.5. For ^{170}Ir the bandhead spin is taken as $I = 9$.

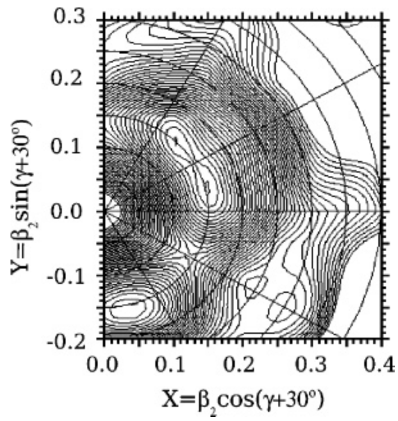

FIG. 10. Calculated total Routhian surfaces at zero rotational frequency for configuration $\pi : (-, -1/2), \nu : (+, +1/2)$. Minima are found at a weakly deformed triaxial shape with $\beta_2 \approx 0.15$ and $\gamma \approx \pm 15°$. Similar minima are found in the calculation for the $\pi : (-, -1/2), \nu : (-, \pm 1/2)$ configurations.

attributed to a paired $(\nu i_{13/2})^2$ band crossing. The rotational band in ^{170}Ir shows no evidence of a similar alignment, which may indicate blocking, although the data do not extend to high enough rotational frequency to draw a firm conclusion of whether the odd valence neutron occupies the $i_{13/2}$ orbital or not. Nonetheless, the relative alignments of the two bands are consistent with such a neutron configuration.

To elucidate the rotational-like structure of ^{170}Ir from a theoretical perspective total Routhian surface (TRS) calculations have been performed using the method described in Ref. [27]. As shown in Fig. 10 the calculations yield a quadrupole deformation of $\beta_2 \approx 0.15$ and $|\gamma| \approx 15°$ for the low-lying yrast states of this nucleus in the energetically most favored configurations. At this deformation the proton levels closest to the Fermi surface are the 11/2[505], 3/2[420], and 1/2[400] Nilsson orbitals emanating from the $h_{11/2}$, $d_{3/2}$, and $s_{1/2}$ spherical subshells, respectively. Neutron levels that are expected to be occupied near the Fermi level are 1/2[660] from the $i_{13/2}$ spherical subshell, 5/2[523] from the $h_{9/2}$ spherical subshell, and the 3/2[521], 5/2[512], and 7/2[503] levels originating from the $f_{7/2}$ spherical subshell. The TRS calculations predict triaxial shapes around $|\gamma| \approx 15°$ and pronounced γ softness. Hence, the triaxial deformation is not well defined and, in addition, shapes with different degree of triaxiality can occur depending on the quasiparticle configuration. The triaxiality introduces significant mixing of the single-particle states. In Fig. 11 single-particle energy levels as a function of the triaxiality parameter γ are shown. Our calculations predict strong mixing between the levels emanating from the $s_{1/2}$ and $d_{3/2}$ spherical proton subshells and the $f_{7/2}$ and $h_{9/2}$ spherical neutron subshells, respectively. The $i_{13/2}$ level close to the Fermi surface has the strongest dependence on γ among the neutron orbitals, favoring triaxial shapes. The $f_{7/2}$ and $h_{9/2}$ neutron levels, in contrast, are relatively flat as a function of γ deformation. The proton levels close to the Fermi surface are to varying degrees affected by a change in γ near prolate shapes. The 11/2[505] and 3/2[420] levels are suppressed in energy by an increase in triaxiality whereas the 1/2[400] level

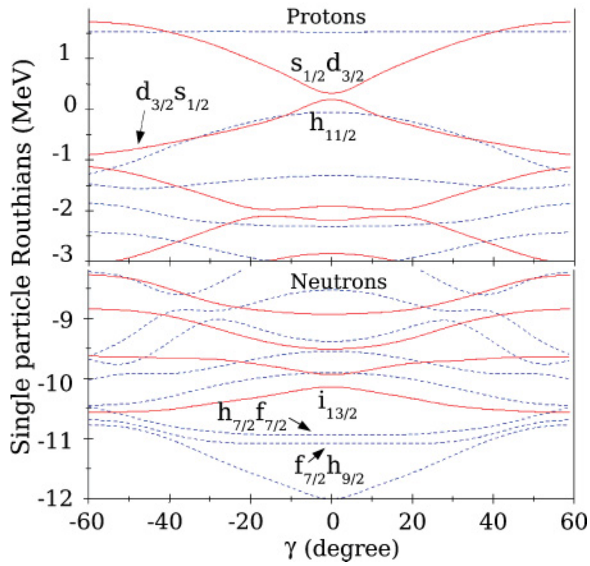

FIG. 11. (Color online) Single-particle energy levels for protons (upper plot) and neutrons (lower plot) as a function of the triaxial deformation parameter γ for $\beta_2 = 0.15$ and $\hbar\omega = 0.0$ MeV. The Fermi surface for protons at $\gamma = 0^\circ$ lies between -0.062 and -1.3126 MeV and for neutrons between -10.1383 and -10.9414 MeV. The solid and dotted curves indicate $(\pi, \alpha) = (+, \pm 1/2)$ and the dashed and dash-dotted curves $(\pi, \alpha) = (-, \pm 1/2)$. (The solid and dotted lines overlap at $\hbar\omega = 0.0$ MeV, as do the dashed and dash-dotted curves.) As can be seen, the level structure near the Fermi surface remains largely the same in the interval $-15 \leqslant \gamma \leqslant 15$.

is pushed up in energy for triaxial shapes. The TRS calculations predict the $\pi h_{11/2} \otimes \nu i_{13/2}$ $[(\pi\frac{11}{2}[505] \otimes \nu(\frac{1}{2}[660])]$ configuration to be favored at intermediate spins and, lacking experimental information on the higher spin states in the band, this configuration is therefore a main candidate for the rotational band in ^{170}Ir. This leads to a tentative spin-parity assignment of $I^\pi = 9^-$ for the bandhead, which is the closest integer to the obtained spin value of 8.83 by coupling a rotation-aligned neutron ($k = 0.5, i = 6.48$) and a deformation-aligned proton ($k = 5.5, i = 0.0$).

An experimental indicator of triaxiality in high-K rotational bands is the energy splitting between signature partner bands. Such effects may be visualized more clearly by plotting the staggering parameter S, defined as [28]

$$S(I) = E(I) - \frac{[E(I+1) + E(I-1)]}{2}. \tag{1}$$

In Fig. 12 experimentally deduced values of the staggering parameter for the rotational bands in ^{170}Ir and ^{171}Ir are plotted as a function of angular momentum. A smaller staggering amplitude (and signature splitting) is observed in ^{170}Ir compared to ^{171}Ir, even though the TRS calculations predict similar degrees of triaxiality ($\gamma \approx 15^\circ$). With an assumed $\pi h_{11/2}(\frac{11}{2}[505]) \otimes \nu i_{13/2}(\frac{1}{2}[660])$ configuration for the observed band structure, this is unexpected since the $i_{13/2}$ neutron, by itself, should drive the nucleus toward a larger triaxial deformation than ^{171}Ir. This result points to an unexpected influence of the odd neutron.

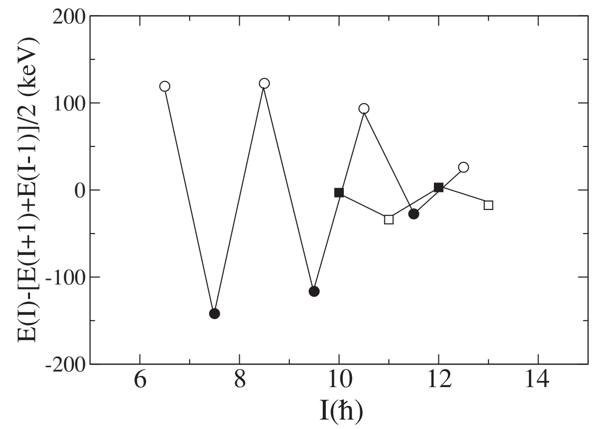

FIG. 12. Energy staggering in the rotational bands of ^{171}Ir and ^{170}Ir. The filled and open squares represent $\alpha = 0$ and $\alpha = 1$, respectively, in ^{170}Ir; filled and open circles correspond to $\alpha = -1/2$ and $\alpha = +1/2$ for ^{171}Ir. For ^{170}Ir the bandhead spin is taken as $I = 9$.

The experimental $B(M1)/B(E2)$ ratios for a strongly coupled rotational band are sensitive to its single-particle configuration. Thus a comparison between the experimental $B(M1)/B(E2)$ ratios and the corresponding theoretical ones can be used as a probe of the single-particle configuration. The experimental $B(M1)/B(E2)$ ratios are deduced by using the well-known formula [29]

$$\frac{B(M1; I \to I-1)}{B(E2; I \to I-2)} = 0.697 \frac{[E_\gamma(E_2; I \to I-2)]^5}{[E_\gamma(M_1; I \to I-1)]^3} \frac{I_\gamma(M_1)}{I_\gamma(E_2)} \frac{1}{\left(1 + \delta^2_{\frac{E2}{M1}}\right)}. \tag{2}$$

The theoretical $B(M1)/B(E2)$ values are obtained by using the Dönau-Frauendorf semiclassical formalism [30]:

$$\frac{B(M1; I \to I-1)}{B(E2; I \to I-2)} = \frac{12}{5Q_0^2 \cos^2(\gamma + 30^\circ)} \left[1 - \frac{K^2}{(I-\frac{1}{2})^2}\right]^{-2} \left[\left(1 - \frac{K^2}{I^2}\right)^{1/2} \times \sum_{n=2}^{2} k_n(g_n - g_R) - \frac{K}{I} \sum_{n=1}^{2} (g_n - g_R) i_n\right]^2. \tag{3}$$

In our calculation the mixing ratio $\delta_{\frac{E2}{M1}}$ is neglected and we use a calculated quadrupole moment, $Q_0 = 6.2$ e b and $\gamma = -15^\circ$ from the TRS calculations. Based on coincidence relationships the intensity values for the doublet transitions, 335 and 370 keV in the rotational band, were estimated to be 52% and 26% of the total intensities of these transitions. As can be seen in Fig. 13 the experimental uncertainties make it difficult to distinguish between the candidate single-particle configurations. However, the best overall agreement between the experimental data and the semiclassical calculations is found for the $\pi h_{11/2}(\frac{11}{2}[505]) \otimes \nu i_{13/2}(\frac{1}{2}[660])$ configuration.

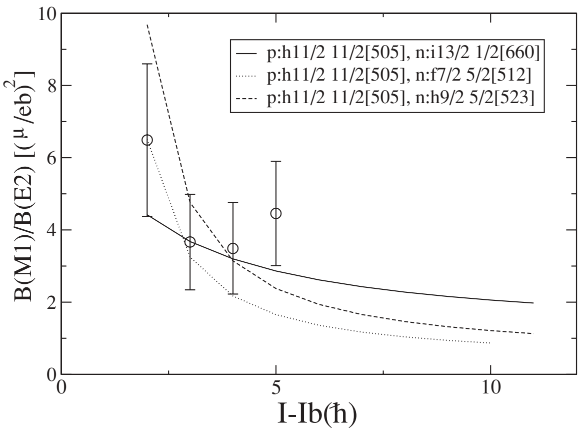

FIG. 13. Measured $B(M1)/B(E2)$ values in the observed rotational band plotted against the spin value relative to the bandhead spin. Calculations using the Dönau-Frauendorf semiclassical formula [30] are shown as lines. From our TRS calculations the value of the quadrupole moment used for the calculation is $Q_0 = 6.2$ e b and $\gamma = -15^\circ$.

V. SUMMARY

In summary, excited states in ^{170}Ir have been identified in an in-beam experiment using the recoil-decay tagging method. The deduced rotational band structure has tentatively been assigned a $\pi h_{11/2}(\frac{11}{2}[505]) \otimes \nu i_{13/2}(\frac{1}{2}[660])$ configuration based on its rotational properties and on predictions from TRS calculations. The data indicate a reduction in signature splitting in ^{170}Ir relative to the $N+1$ isotope ^{171}Ir. This is somewhat unexpected since the calculations predict the $i_{13/2}$ neutron to drive the nucleus toward a larger γ deformation. The α-decay fine structure from the isomeric state that is fed by the rotational band has also been investigated. The energies of the two previously observed α-decay branches have been remeasured, a new decay branch has been identified, and an additional tentative decay branch has been proposed. The α-decay fine structure is confirmed by the observation of α-γ coincidences at the focal plane of the recoil separator. Several new γ rays from the decay of excited states in ^{166}Re were observed in coincidence with these three α-decay branches. Although the low-lying level structure of ^{166}Re could not be delineated in detail, several excited states built on the high-spin isomeric state are suggested by these observations and a tentative level scheme is proposed.

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[1] Y. H. Zhang *et al.*, Eur. Phys. J. A **13**, 429 (2002).
[2] T. M. Goon, Ph.D. thesis, University of Tennessee, Knoxville, 2004.
[3] C. M. Baglin, Nucl. Data Sheets **96**, 611 (2002).
[4] C. W. Beausang *et al.*, Nucl. Instrum. Methods A **313**, 37 (1992).
[5] M. Leino *et al.*, Nucl. Instrum. Methods B **99**, 653 (1995).
[6] M. Leino, Nucl. Instrum. Methods B **126**, 320 (1997).
[7] R. D. Page *et al.*, Nucl. Instrum. Methods Phys. Res. B **204**, 634 (2003).
[8] I. H. Lazarus *et al.*, IEEE Trans. Nucl. Sci. **48**, 567 (2001).
[9] P. Rahkila, Nucl. Instrum. Methods A (to be submitted).
[10] E. S. Paul *et al.*, Phys. Rev. C **51**, 78 (1995).
[11] R. S. Simon *et al.*, Z. Phys. A **325**, 197 (1986).
[12] R. D. Page *et al.*, Phys. Rev. C **53**, 660 (1996).
[13] U. J. Schrewe *et al.*, Z. Phys. A **288**, 189 (1978).
[14] C. Cabot *et al.*, Z. Phys. A **283**, 221 (1977).
[15] M. W. Rowe *et al.*, Phys. Rev. C **65**, 054310 (2002).
[16] G. L. Poli *et al.*, Phys. Rev. C **59**, R2979 (1999).
[17] Y. A. Akovali, Nucl. Data. Sheets **84**, 27 (1998).
[18] T. M. Goon *et al.*, Phys. Rev. C **70**, 014309 (2004).
[19] C. R. Bingham *et al.*, Phys. Rev. C **51**, 125 (1995).
[20] W.-D. Schmidt-Ott *et al.*, Nucl. Phys. **A545**, 676 (1992).
[21] D. Joss *et al.*, Phys. Rev. C **68**, 014303 (2003).
[22] C. N. Davids *et al.*, Phys. Rev. C **55**, 2255 (1997).
[23] K. Livingston *et al.*, Phys. Rev. C **48**, R2151 (1993).
[24] M. Sandzelius *et al.*, Phys. Rev. C **75**, 054321 (2007) .
[25] R. A. Bark *et al.*, Nucl. Phys. **A657**, 113 (1999).
[26] C. Scholey *et al.* (to be published).
[27] W. Nazarewicz *et al.*, Nucl. Phys. **A435**, 397 (1985).
[28] W. Reviol *et al.*, Phys. Rev. C **59**, 1351 (1999).
[29] S. Juutinen *et al.*, Nucl. Phys. **A526**, 346 (1991).
[30] F. Dönau and S. Frauendorf, 1983 in *Proceedings of the Conference on High High Angular Momentum Properties of Nuclei*, edited by N. R. Johnson (Harward Academic, New York, 1983), p. 143; F. Dönau, Nucl. Phys. **A471**, 469 (1987).