Band crossings in ^{166}Ta

D. J. Hartley,[1] R. V. F. Janssens,[2] L. L. Riedinger,[3] M. A. Riley,[4] X. Wang,[4] A. Aguilar,[4,*] M. P. Carpenter,[2] C. J. Chiara,[2,5,6] P. Chowdhury,[7] I. G. Darby,[3] U. Garg,[8] Q. A. Ijaz,[9] F. G. Kondev,[5] S. Lakshmi,[7] T. Lauritsen,[2] W. C. Ma,[9] E. A. McCutchan,[2] S. Mukhopadhyay,[8,†] E. P. Seyfried,[1] U. Shirwadkar,[7] I. Stefanescu,[2,6] S. K. Tandel,[7] J. R. Vanhoy,[1] and S. Zhu[2]

[1]*Department of Physics, U.S. Naval Academy, Annapolis, Maryland 21402, USA*
[2]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[3]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*
[4]*Department of Physics, Florida State University, Tallahassee, Florida 32306, USA*
[5]*Nuclear Engineering Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[6]*Department of Chemistry and Biochemistry, University of Maryland, College Park, Maryland 20742, USA*
[7]*Department of Physics, University of Massachusetts Lowell, Lowell, Massachusetts 01854, USA*
[8]*Department of Physics, University of Notre Dame, South Bend, Indiana 46556, USA*
[9]*Department of Physics, Mississippi State University, Mississippi State, Mississippi 39762, USA*

(Received 27 September 2010; published 23 November 2010)

High-spin states in the odd-odd nucleus ^{166}Ta are investigated through the $5n$ channel of the ^{51}V + ^{120}Sn reaction. Four new bands are observed and linked into the previous level scheme. Configurations for the bands are proposed, based on measured alignments and $B(M1)/B(E2)$ transition strength ratios.

DOI: 10.1103/PhysRevC.82.057302 PACS number(s): 21.10.Re, 23.20.Lv, 27.70.+q

In a recent experiment that focused on the exotic wobbling phenomenon in ^{167}Ta [1], a significant amount of new data for the odd-odd nucleus ^{166}Ta was obtained as a by-product of the reaction. This Brief Report discusses the five rotational sequences now established in ^{166}Ta and proposes configurations for each of the bands. The investigation of this nucleus coincides with our recent work on heavier odd-odd tantalum nuclei: ^{170}Ta [2] and ^{168}Ta [3].

The ^{120}Sn(^{51}V,5n) reaction channel was used to populate the high-spin states in ^{166}Ta. The ATLAS facility at Argonne National Laboratory provided a 235-MeV ^{51}V beam, and Gammasphere [4] detected the radiation with 101 Compton-suppressed germanium detectors. Two stacked, self-supporting ^{120}Sn targets with thicknesses of 500 μg/cm^2 were placed in the middle of Gammasphere. Approximately 2×10^9 fourfold or greater coincidence events were recorded and sorted into a Blue database [5]. Radware [6] cubes and hypercubes were constructed from this database, and an angular-correlation analysis was also performed that is identical to that described in Ref. [2].

Only two studies previously reported excited states in ^{166}Ta. Hild *et al.* [7] investigated the feeding of ^{166}Ta levels from electron-capture decay of ^{166}W. A $(2)^+$ spin-parity assignment was proposed for the ground state, and four low-spin levels were identified. Zheng *et al.* [8] more recently observed a single rotational band that was assigned to ^{166}Ta based on x-γ coincidences and on an excitation function. This structure is presented in the level scheme of Fig. 1 as band 1. The tentative spin assignments proposed in Ref. [8] were based upon systematics and were adopted here as well.

Band 1 has been extended from $I = 24$ to 42 as seen in the level scheme (Fig. 1) and the spectra given in Fig. 2(a). Although Ref. [8] suggested that the 148-keV line decaying from the 11^- state is an in-band $E2$ transition, our normalized angular-correlation ratio of 0.63(6) is consistent with the transition being dipole ($\Delta I = 1$) in nature. Thus, the 148-keV γ ray presumably feeds an $I = 10$ level, as drawn in Fig. 1. The odd parity for band 1 was assigned in Ref. [8] based upon the proposed configuration of $\pi h_{11/2}\nu i_{13/2}$. Because both of these orbitals lie near the Fermi surface, it is logical that they would couple to form the yrast sequence in ^{166}Ta. The alignment behavior of band 1, displayed in Fig. 3(a), is also in agreement with this assignment. When Harris parameters of $\mathcal{J}_0 = 20\ \hbar^2$/MeV and $\mathcal{J}_1 = 40\ \hbar^4$/MeV^3 are applied, the initial alignment of band 1 is approximately 7.5 $\hbar$. The $h_{11/2}$ quasiproton and $i_{13/2}$ quasineutron are associated with 1.6 and 6.0 $\hbar$ initial alignments, respectively, consistent with the alignment for band 1.

The crossing frequency of ~0.33 MeV, and the alignment gain of ~8 $\hbar$, in band 1 tracks those observed in the $\nu i_{13/2}$ structure in ^{165}Hf [9] and the $\pi h_{11/2}\nu i_{13/2}$ bands of ^{168,170}Ta [2,3]. This crossing is typically referred to as the BC alignment, where the second and third lowest $i_{13/2}$ quasineutrons align. The observation of the BC crossing in band 1 confirms the presence of the $i_{13/2}$ quasineutron, and the nature of the quasiproton can be determined by inspection of the $B(M1)/B(E2)$ ratios. Figure 4(a) displays the experimental ratios for band 1 extracted from the measured branching ratios. Theoretical calculations based upon the $B(M1)$ estimates from the geometrical model [10] and the rotational form of the $B(E2)$ strengths [11] were performed and compared to the experimental values in Fig. 4. Parameters used for the calculation of the $B(M1)$ strengths are given in Table I, along with $g_R = Z/A = 0.44$, and a quadrupole moment of 5.3 e b [12] for the $B(E2)$ calculations. There is good agreement with the data assuming the $\pi h_{11/2}\nu i_{13/2}$

*Present address: Department of Radiation Oncology, University of Pennsylvania, Philadelphia, PA 19104, USA.
†Present address: Department of Physics, Mississippi State University, Mississippi State, MS 39762, USA.

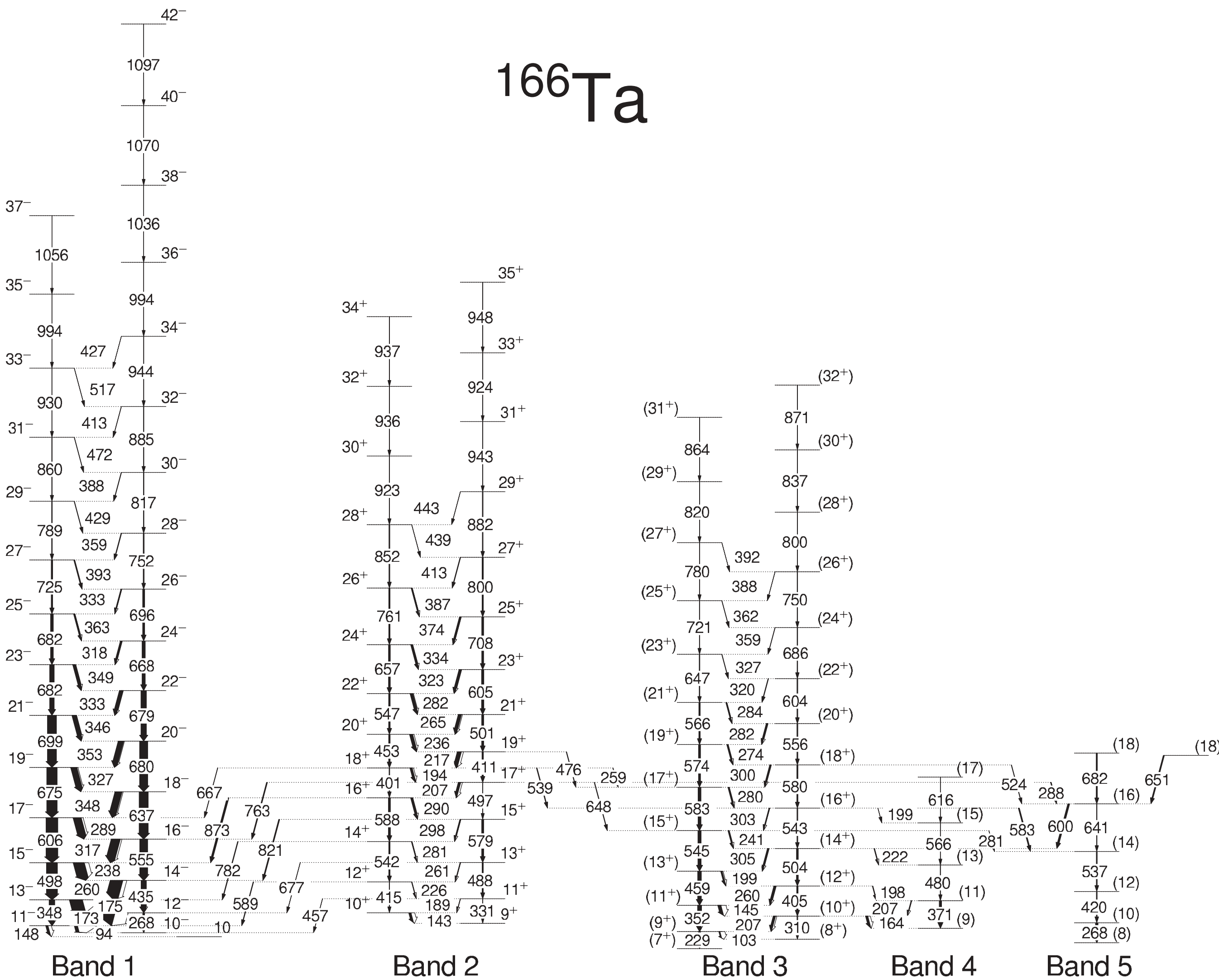

FIG. 1. Level scheme of ^{166}Ta. All spins and parities must be regarded as tentative (see text). The width of the arrows are proportional to the relative γ-ray intensity observed in the experiment.

configuration, although the theoretical values are slightly higher than the experimental ones. This may be due to a higher quadrupole moment than the one assumed, resulting from the presence of the shape-driving $i_{13/2}$ quasineutron. Above spin $I = 20$, two more $i_{13/2}$ quasineutrons were included in the theoretical calculations to represent the BC alignment. Once again, good agreement is achieved and we concur with the $\pi h_{11/2}\nu i_{13/2}$ assignment for band 1. At higher frequencies (>0.45 MeV), there is an apparent alignment gain in the $\alpha = 0$ signature [see Fig. 3(a)], which may correspond to the alignment of the second and third lowest $h_{11/2}$ quasiprotons.

A new structure was observed to strongly feed into band 1 by a series of transitions and is labeled band 2 in Fig. 1. Figure 2(b) displays a spectrum of this strongly coupled band. Angular-correlation ratios for the 782- and 873-keV lines were measured to be 0.50(5) and 0.49(4), respectively, which indicates that these are $\Delta I = 1$ dipole transitions. Based on these results, the spins for band 2 could be assigned as given in Fig. 1. Therefore, band 2 was observed from spin $I = 9$ to 35. A positive parity was assumed, based on the configuration assignment for the sequence.

Figure 3(b) plots the alignment for band 2, where a crossing can be observed at 0.25 MeV with an alignment gain of $\sim$8 $\hbar$. These values are nearly identical to those found in the most favored, odd-parity quasineutron sequence of ^{165}Hf. This ^{165}Hf band likely has an admixture of orbitals of $h_{9/2}$ and $f_{7/2}$ parentage (that is denoted as νE) such that the alignment of the lowest $i_{13/2}$ quasineutrons (the AB alignment) is not blocked, as it is in structures involving the $i_{13/2}$ quasineutron. Thus, the E quasineutron is likely involved in the configuration of band 2. Because the $h_{11/2}$ quasiproton is found to be yrast in neighboring odd-A tantalum nuclei [13,14], the $B(M1)/B(E2)$ theoretical values for the $\pi h_{11/2}\nu E$ configuration were tested against the measured ones in Fig. 4(b). Good agreement between theory and experiment was achieved both before ($I < 17$) and after ($I > 17$) the AB crossing. Thus, band 2 is assigned the $\pi h_{11/2}\nu E$ configuration.

It is worth noting that the additivity of alignment fails for band 2 with the assigned configuration. Only $\sim$1.5 $\hbar$ is

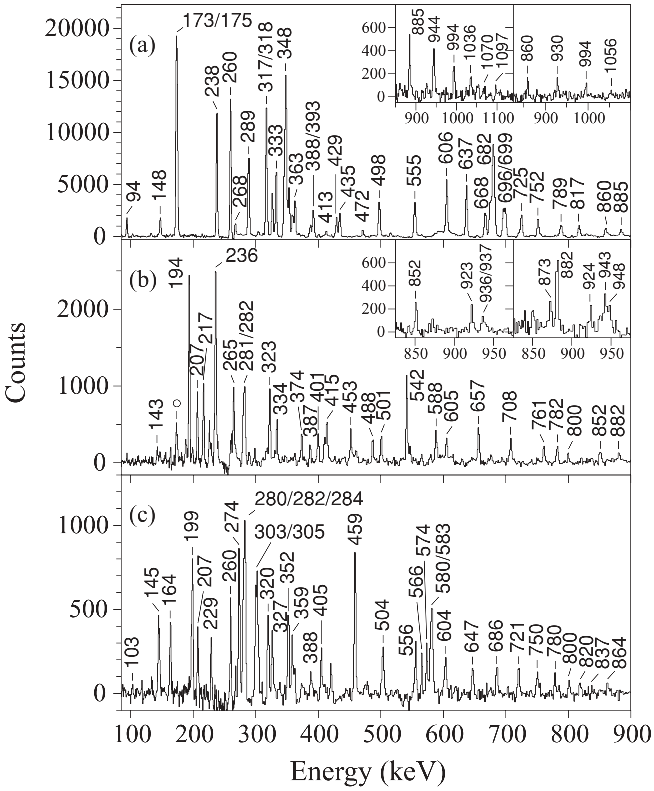

FIG. 2. Example spectra for bands 1, 2, and 3 in ^{166}Ta. (a) Summed spectrum of triple gates with any two $M1$ transitions below $I = 18$ in band 1 with the 680-keV transition. The left and right insets display the highest energy transitions in the $\alpha = 0$ and 1 signatures, respectively. (b) Summed spectrum for band 2 where any two transitions of the 207-, 217-, 265-, or 282-keV lines were gated with the 143- and 588-keV transitions. The peak denoted by a circle is from band 1. The insets were created in a similar gating technique as those in (a) to show the highest transitions in the $\alpha = 0$ (left inset) and $\alpha = 1$ (right inset) sequences. (c) Summed spectrum of band 3 triple gated on any two $M1$ transitions between $I = 16$ and 21 with the 543/545-keV lines.

associated with both the $h_{11/2}$ quasiproton and the E quasineutron. Thus, an initial alignment close to 3 $\hbar$ for band 2, rather than 7 $\hbar$, would be expected. However, the alignment appears to increase with rotational frequency in the νE configuration of ^{165}Hf; this may account for the apparent inconsistency. In addition, a similar deviation was noted for the $\pi h_{11/2}\nu E$ structure in the isotope ^{164}Lu [15]. A high-frequency crossing is present near 0.46 MeV, likely associated with the CD crossing (alignment of the third and fourth lowest $i_{13/2}$ quasineutrons) because a similar crossing was identified [9] near this frequency in the νE configuration of ^{165}Hf [see Fig. 3(b)].

The number of suggested $E1$ transitions linking band 2 to band 1 is unusual, especially considering that no such $E1$ γ rays were reported between the two configurations in ^{164}Lu [15]. The $B(E1)$ strengths for the strongest lines could be deduced by calculating the $B(E1)/B(E2)$ ratios from the extracted branching ratios while assuming the rotational form of the $B(E2)$ rate [11]. From this analysis it is concluded that these are not enhanced $E1$ transitions because the $B(E1)$ rates

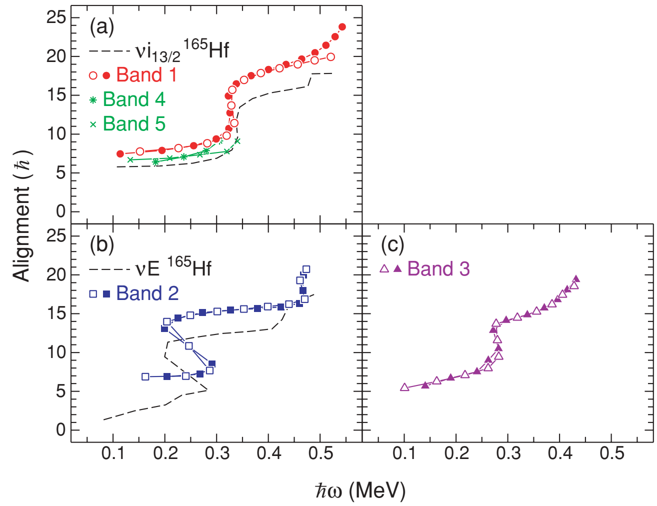

FIG. 3. (Color online) Alignment vs rotational energy for (a) bands 1, 4, and 5; (b) band 2; and (c) band 3 in ^{166}Ta. In (a) and (b), the $\nu i_{13/2}$ and νE bands from ^{165}Hf are shown for reference, respectively.

are found to be 1–2 $\times 10^{-4}$ Weisskopf units, well below those in neighboring nuclei where large $E1$ rates are found [16]. The appearance of the $E1$ transitions is likely a result of the reduced deformation [12] in ^{166}Ta compared with ^{164}Lu that allows the $E1$ γ rays to compete with the collective $E2$ transitions.

Another strongly coupled sequence is fed by band 2 and is labeled band 3 in Fig. 1. An example spectrum is provided in Fig. 2(c). Unfortunately, none of the connecting transitions between the two bands was strong enough to perform an angular-correlation analysis. Thus, the spin values for this band must be considered tentative, with the parity based on the proposed configuration.

The alignment for band 3 in Fig. 3(c) exhibits a crossing at 0.28 MeV with an alignment gain of ~8 $\hbar$. This crossing

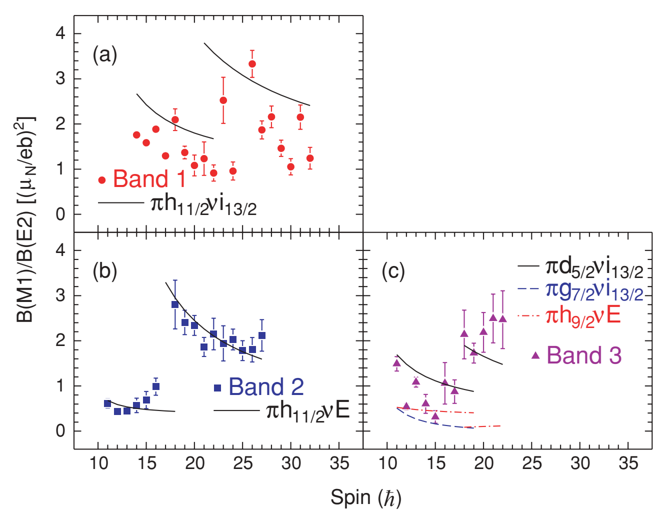

FIG. 4. (Color online) Experimental and theoretical $B(M1)/B(E2)$ ratios for bands (a) 1, (b) 2, and (c) 3 in ^{166}Ta. Theoretical calculations are displayed as lines with the configurations denoted in each panel. At higher spins, the calculations include an additional two $i_{13/2}$ neutrons (see text).

TABLE I. Parameters used in calculating theoretical $B(M1)/B(E2)$ values shown in Fig. 4.

Configuration	g_Ω	K	i_x
$\pi h_{11/2}$	1.30	4.5	1.6
$\pi d_{5/2}$	1.57	2.5	0.0
$\pi g_{7/2}$	0.62	3.5	0.0
$\pi h_{9/2}$	1.30	0.5	3.0
νA	−0.30	2.5	6.0
νE	−0.38	2.5	1.5
νAB	−0.30	0.0	10.0
νBC	−0.30	0.0	8.0

frequency lies between the AB and the BC alignments seen in bands 2 and 1, respectively. It is possible that this is a delayed AB crossing, where the $\pi h_{9/2}$ orbital is involved, as this quasiproton is known to delay crossings [17]. The $B(M1)/B(E2)$ ratios for band 3 were compared with the theoretical values of the $\pi h_{9/2}\nu E$ configuration in Fig. 4(c). Below the crossing ($I < 18$), a reasonable agreement is achieved between theory and experiment. However, above the crossing, the experimental values increase by a factor of 2, while the theoretical values decrease by the same factor. Therefore, the $\pi h_{9/2}\nu E$ assignment does not seem appropriate for band 3.

The $\pi d_{5/2}\nu i_{13/2}$ and $\pi g_{7/2}\nu i_{13/2}$ configurations were also compared in Fig. 4(c). One may observe at low spin that the experimental values lie in between the two configurations. These two quasiproton orbitals are known to mix [2,3]; therefore, a mixing between these even-parity configurations may correctly describe band 3. In addition, above the crossing ($I > 17$), the $\pi d_{5/2}\nu i_{13/2}$ configuration correctly reproduces the larger $B(M1)/B(E2)$ ratios. The $\pi d_{5/2}$ orbital is found to lie lower in energy than the $\pi g_{7/2}$ state in ^{167}Ta [1,14], such that we favor the $\pi d_{5/2}\nu i_{13/2}$ configuration for band 3. It should also be noted that a reduction of the BC crossing frequency was observed for this same configuration in ^{168}Ta [3].

Two new decoupled sequences were identified and are labeled as bands 4 and 5 in Fig. 1. Band 4 is exclusively fed by band 3 through several low-energy transitions. Angular-correlation ratios could not be obtained for these γ rays. Consequently, the spins assigned in the level scheme must be considered tentative. Band 5 is fed by both bands 2 and 3, but once again angular-correlation ratios could not be determined for the linking transitions. With the tentative spin assignments, the alignments for bands 4 and 5 are plotted in Fig. 3(a). Both sequences have initial alignments near 7 $\hbar$, which may indicate the presence of the highly aligned $i_{13/2}$ quasineutron. A low-K quasiproton would need to be coupled to the $\nu i_{13/2}$ state to obtain a decoupled structure. Two possibilities are the $h_{9/2}[541]1/2$ and the $d_{3/2}[411]1/2$ orbitals. Because the $h_{9/2}$ quasiproton is also highly aligned (normally associated with ∼3 $\hbar$ of initial alignment), the $\pi h_{9/2}\nu i_{13/2}$ configuration would likely have an initial alignment near 9 $\hbar$. However, the $d_{3/2}$ quasiproton is typically associated with 1 $\hbar$ of alignment or less. Therefore, by additivity of alignment, the $\pi d_{3/2}\nu i_{13/2}$ configuration is favored for both bands 4 and 5, but this assignment must be regarded as tentative at this time.

In summary, the level scheme of the doubly odd nucleus ^{166}Ta was greatly extended with the observation of four new bands. All of the bands are interconnected and the relative energies are known as a result. The $\pi h_{11/2}\nu i_{13/2}$ configuration was confirmed for the previously known structure, and configurations were proposed for the four new sequences. These data were produced as a side channel for the given reaction, and a dedicated, high-statistics experiment would need to be performed to confirm some of the proposed spin and configuration assignments, especially for the weaker bands.

The authors thank the ANL operations staff at Gammasphere and gratefully acknowledge the efforts of J. P. Greene for target preparation. We thank D. C. Radford and H. Q. Jin for their software support. This work is funded by the National Science Foundation under Grants No. PHY-0854815 (USNA), No. PHY-0754674 (FSU), and No. PHY07-58100 (ND), as well as by the US Department of Energy, Office of Nuclear Physics, under Contracts No. DE-AC02-06CH11357 (ANL), No. DE-FG02-94ER40848 (UML), and No. DE-FG02-96ER40983 (UT).

[1] D. J. Hartley *et al.*, Phys. Rev. C **80**, 041304(R) (2009).
[2] A. Aguilar *et al.*, Phys. Rev. C **81**, 064317 (2010).
[3] X. Wang *et al.*, Phys. Rev. C **82**, 034315 (2010).
[4] R. V. F. Janssens and F. S. Stephens, Nucl. Phys. News **6**, 9 (1996).
[5] M. Cromaz *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **462**, 519 (2001).
[6] D. C. Radford, Nucl. Instrum. Methods Phys. Res., Sect. A **361**, 297 (1995).
[7] T. Hild, W.-D. Schmidt-Ott, V. Freystein, F. Meissner, E. Runte, H. Salewski, and R. Michaelsen, Nucl. Phys. A **492**, 237 (1989).
[8] H. Zheng *et al.*, J. Phys. G **23**, 723 (1997).
[9] M. Neffgen, E. M. Beck, H. Hübel, J. C. Bacelar, M. A. Deleplanque, R. M. Diamond, F. S. Stephens, and J. E. Draper, Z. Phys. A **344**, 235 (1993).
[10] F. Dönau, Nucl. Phys. A **471**, 469 (1987).
[11] A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, Reading, MA, 1975), Vol. II.
[12] P. Möller, J. R. Nix, W. D. Myers, and W. J. Swiatecki, At. Data Nucl. Data Tables **59**, 185 (1995).
[13] D. G. Roux *et al.*, Phys. Rev. C **63**, 024303 (2001).
[14] D. J. Hartley *et al.* (unpublished).
[15] X.-H. Wang *et al.*, Nucl. Phys. A **608**, 77 (1996).
[16] G. B. Hagemann, I. Hamamoto, and W. Satula, Phys. Rev. C **47**, 2008 (1993).
[17] H. J. Jensen *et al.*, Nucl. Phys. A **695**, 3 (2001).