PHYSICAL REVIEW C **82**, 054313 (2010)

Influence of the $\nu g_{9/2}$ orbital on level structures of neutron-rich $^{61,62}\mathrm{Mn}_{36,37}$

C. J. Chiara,[1,2] I. Stefanescu,[1,2] N. Hoteling,[1,2,*] W. B. Walters,[1] R. V. F. Janssens,[2] R. Broda,[3] M. P. Carpenter,[2] B. Fornal,[3]
A. A. Hecht,[1,2,†] W. Królas,[3,4] T. Lauritsen,[2] T. Pawłat,[3] D. Seweryniak,[2] X. Wang,[2,5,‡] A. Wöhr,[1,2,5] J. Wrzesiński,[3] and S. Zhu[2]
[1]Department of Chemistry and Biochemistry, University of Maryland, College Park, Maryland 20742, USA
[2]Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA
[3]Niewodniczański Institute of Nuclear Physics PAN, Radzikowskiego 152, PL-31-342 Kraków, Poland
[4]Joint Institute for Heavy Ion Research, Oak Ridge, Tennessee 37831, USA
[5]Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA

(Received 17 September 2010; published 18 November 2010)

Level structures in $^{61,62}\mathrm{Mn}_{36,37}$ were studied with Gammasphere in the reaction of a 430-MeV ^{64}Ni beam and a thick ^{238}U target. The newly identified levels decrease in excitation energy compared to the analogous structures in the lighter Mn isotopes and behave similarly to states in the corresponding Fe isotones that involve $g_{9/2}$ neutron excitations. This behavior illustrates the importance of the inclusion of the $\nu g_{9/2}$ orbital in any realistic shell-model calculations in this region.

DOI: 10.1103/PhysRevC.82.054313 PACS number(s): 23.20.Lv, 21.10.Pc, 27.50.+e

I. INTRODUCTION

The study of the structure of $Z = 25$ Mn isotopes has been useful in identifying the important role played in nuclear structure by three-particle cluster configurations—in this case, the three-hole $\pi f_{7/2}^{-3}$ states—described as three valence particles or holes coupled to a quadrupole vibrational field [1]. The neutron-rich Mn nuclei have the added advantage that the $20 < Z \leqslant 28$ shell has no other valence proton orbital available at low energies to add complexity to the observed level schemes. Hence, the evolution of the three-proton cluster structure with the number of valence neutrons provides insight into the interactions between $f_{7/2}$ protons and fpg neutrons. A comprehensive description of clustering, featuring Mn nuclei, has been published by Paar [1].

Extensive level schemes with spins as high as $(16)\hbar$ and $(27/2)\hbar$ for $^{57-60}$Mn have recently been reported by Steppenbeck *et al.* [2]. These nuclei were populated at Gammasphere with the reaction of a 130-MeV ^{48}Ca beam with ^{13,14}C targets. In another recent investigation, γ rays in $^{59-63}$Mn have been reported by Valiente-Dobón *et al.* [3] from an experiment in which mass gating by the magnetic spectrometer PRISMA was used to associate transitions with fragments produced in the reactions of a 460-MeV ^{70}Zn beam with a ^{238}U target. Shell-model calculations were presented in both works that provided reasonable agreement with the observed levels for nuclei with $N \leqslant 34$. However, questions were raised regarding the possible influence of the occupancy of the $g_{9/2}$ neutron orbital as N exceeds 34 and approaches 40. Additional low-spin states in ^{61}Mn were recently reported by Crawford *et al.* [4] from a study of the β-delayed γ rays from ^{61}Cr decay. In ^{62}Mn, low-spin levels from the β decay of ^{62}Cr were reported by Gaudefroy *et al.* [5], and an isomeric [$t_{1/2} = 95(2)$ ns] 113-keV transition was identified in a fragmentation reaction by Daugas *et al.* [6].

II. EXPERIMENTAL DETAILS

Here, data for higher-spin levels in ^{61,62}Mn are presented from deep-inelastic reactions of a 430-MeV ^{64}Ni beam with a 55-mg/cm^2 thick ^{238}U target. The beam from the ATLAS facility at Argonne National Laboratory was directed onto the target in pulses of about 1 ns width every ~410 ns. Emitted γ rays were identified using the Gammasphere array of 100 Compton-suppressed Ge detectors [7]. A minimum of three coincident Compton-suppressed γ rays was required for an event to be recorded. The experimental details have been reported in several recent publications including, in particular, a description of the use of prompt and delayed coincidence events to associate γ rays with isomers [8–10]. Transitions falling within a 40-ns window centered around the beam pulse were designated as "prompt"; those falling within one of the ~400-ns intervals either immediately following the prompt time region or after the subsequent beam pulse were considered to be "delayed". Gamma rays in each event were sorted offline into sets of threefold coincidences according to their prompt or delayed designations. Three-dimensional histograms (cubes) were then incremented at the energies E_γ of these coincident γ rays. Four such cubes were created, labeled PPP (all three γ rays prompt), PPD (two prompt and one delayed), PDD (one prompt and two delayed), and DDD (all three delayed). In the PDD and DDD cubes, the delayed transitions were further required to be within 40 ns of each other to reduce the contributions from random coincidence events.

III. RESULTS AND DISCUSSION

A. ^{61}Mn

Figure 1(a) shows the spectrum from a double gate in the PPP cube on the 157- and 1125-keV γ rays reported for ^{61}Mn

---

[*] Present address: Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA.

[†] Present address: Department of Chemical and Nuclear Engineering, University of New Mexico, Albuquerque, New Mexico 87131-0001, USA.

[‡] Present address: Department of Physics, Florida State University, Tallahassee, Florida 32306-4350, USA.

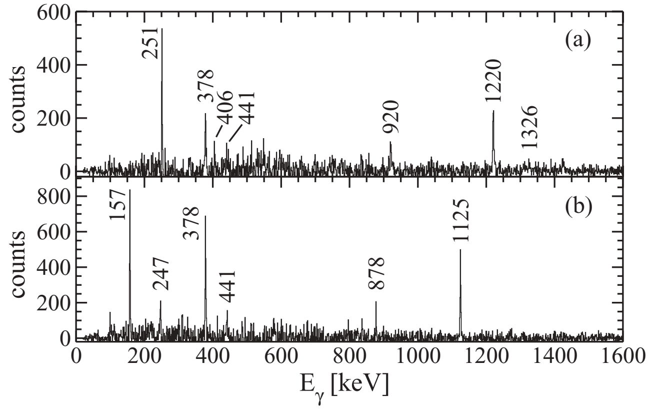

FIG. 1. Coincidence spectra double gated on transitions at (a) 157 and 1125 keV and (b) 1220 and 251 keV in the PPP cube. ^{61}Mn transitions are marked with their energies in keV.

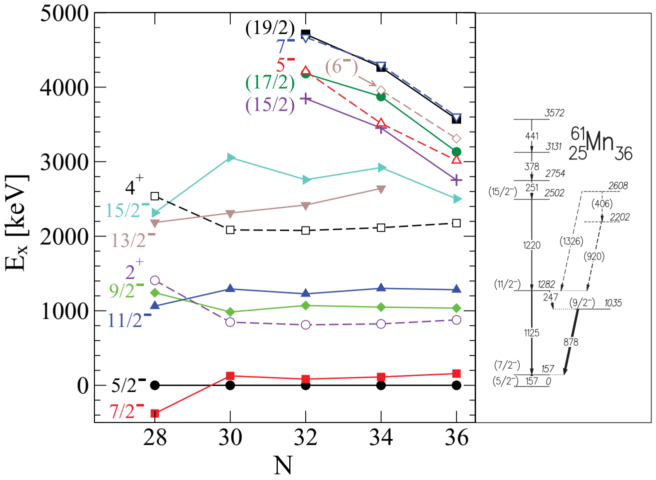

FIG. 2. (Color online) Level-energy systematics for odd-*A* Mn isotopes (filled symbols, solid lines) and their even-*A* Fe isotones (open symbols, dashed lines). See text for details. Data are from Ref. [11] and references therein ($^{54-62}$Fe$_{28-36}$), Refs. [12,13] (^{53,55}Mn$_{28,30}$), and Ref. [2] (^{57,59}Mn$_{32,34}$). The levels for ^{61}Mn$_{36}$ are from the decay scheme on the right, deduced in the present work.

by Valiente-Dobón *et al.* [3]. Several lines not observed in Ref. [3] have been identified. The spectrum from a double gate on two of these, the 1220- and 251-keV transitions, is given in Fig. 1(b). From such coincidence spectra, the ^{61}Mn level scheme on the right side of Fig. 2 was constructed. This confirms the level scheme proposed in Ref. [3] (maximum energy 1282 keV) and extends it with the identification of four (tentatively six) new states. The transitions at 1220, 251, 378, and 441 keV are found to be coincident with each other and with the previously known γ rays below the 1282-keV level. The 406-, 920-, and 1326-keV lines appear in some gates, but they could not be verified for all expected coincidences; hence, they are tentatively placed in the level scheme.

The spin and parity (I^π) quantum numbers in ^{61}Mn for states at 1282 keV and below were tentatively assigned in Ref. [3], based on the systematics of low-lying structures in the lighter odd-*A* Mn isotopes. The I^π assignments in ^{57,59}Mn were later confirmed by angular-distribution and directional-correlation measurements in Ref. [2]. An angular-correlation (AC) analysis, as described in Ref. [8], was attempted for the present ^{61}Mn data. The results were not sufficiently sensitive to further constrain the I^π quantum numbers beyond the tentative assignments for the low-lying states, nor could any assignments be made for the states above 2502 keV (or the tentative 2202- and 2608-keV levels). However, the data are consistent with the 1125-, 1220-, and 251-keV γ rays having $E2$, $E2$, and $\Delta I = 0$ $E1$ multipolarities, respectively, lending support to the assignments of $I^\pi = (11/2^-)$ and $(15/2^-)$ to the 1282- and 2502-keV levels, and suggesting spin (15/2) for the 2754-keV state. The $(15/2^-)$ assignment for the 2502-keV state is strengthened by the absence of a possible crossover transition to the $(9/2^-)$ level.

The $5/2^-$ to $15/2^-$ yrast levels for the odd-*A* Mn isotopes with $N \geqslant 28$ are plotted in Fig. 2. In addition, the 15/2, 17/2, and 19/2 levels of band *A* in ^{57,59}Mn (with the spins being tentative in the latter) from Ref. [2] and the states above the $(15/2^-)$ level in the current work for ^{61}Mn are also shown. For this discussion, somewhat speculative spins for the new states in ^{61}Mn are taken to be (15/2) at 2754 keV, (17/2) at 3131 keV, and (19/2) at 3572 keV, based on the AC of the 251-keV γ ray and, following the systematics of the lighter isotopes, the expectation of such a dipole band structure feeding the yrast $15/2^-$ state. Above $N = 28$, the $5/2^-$ to $11/2^-$ states are remarkably stable in energy as a function of N, whereas the higher-lying levels can be seen to decrease in energy rather rapidly. As discussed in Ref. [1], the $5/2^-$ to $11/2^-$ states are expected to be part of the $\pi f_{7/2}^{-3}$ multiplet for the $Z = 25$ Mn isotopes. In fact, a comparison of these levels with the 2^+ and 4^+ states in the corresponding $Z = 26$ Fe isotones (plotted with dashed lines in Fig. 2), which can be viewed as the core to which the odd $f_{7/2}$ proton hole couples, also shows very similar stability in energy versus N for these sets of states.

In contrast to the flat behavior of the low-lying states, the higher-lying ones are found to decrease rapidly in energy as N increases, much like the 5^-, (6^-), and 7^- levels in the neighboring Fe nuclei (Fig. 2). The negative-parity states in the neutron-rich even-even Fe isotopes must arise from the excitation of an fp-shell neutron into the $g_{9/2}$ subshell, as discussed in Ref. [11]. The subsequent coupling of an $f_{7/2}$ proton hole to these core states would yield positive-parity levels in the odd-*A* Mn isotones. Indeed, we suggest that band *A* in ^{57,59}Mn [2] and the structure above the 2502-keV $(15/2^-)$ state in ^{61}Mn could be positive-parity levels arising from the coupling of an $f_{7/2}$ proton hole with the 5^-, (6^-), and 7^- levels in the ^{58,60,62}Fe core nuclei, thereby explaining the similar systematic behavior as a function of neutron number. Thus, the effects of the possible occupancy of the $g_{9/2}$ neutron level as $N = 40$ is approached can be seen in the neutron-rich Mn nuclei as well as in the neighboring Fe cores reported in Ref. [11].

An additional feature worth noting is that the $(15/2^-)$ level at 2502 keV in ^{61}Mn comes down in energy by several hundred keV relative to ^{59}Mn (2922 keV). With presumed negative parity, this state cannot be attributed to the excitation of a single neutron into the $g_{9/2}$ subshell. A $\nu g_{9/2}^2$ component to the configuration would, however, yield the proper parity.

This becomes energetically feasible as $N = 40$ is approached, as was shown in Ref. [11] for the neutron-rich Fe isotopes. Specifically, the 6^+ and 8^+ levels are found to vary little in energy as a function of neutron number until, respectively, $N = 38$ and 36 are reached (Fig. 9 in Ref. [11]). Furthermore, a sizable $\nu g_{9/2}^2$ contribution to the wave function was found even for the lower-spin states in ^{62}Fe, whereas there was a minimal such contribution in ^{60}Fe (Fig. 10 in Ref. [11]). Therefore, even if the proposed parities of band *A* in ^{57,59}Mn and the new high-lying states in ^{61}Mn are negative, it seems plausible that the observed decrease in energy is associated with the occupation of $g_{9/2}$ neutron orbitals.

B. ^{62}Mn

For ^{62}Mn, Valiente-Dobón *et al.* [3] reported five γ rays at 109, 155, 196, 225, and 541 keV. A spectrum double gated on the 109- and 196-keV transitions in the PPP cube of the present data can be found in Fig. 3(a). Lines at 225 and 541 keV are visible. Double gates on other pairs of these transitions reveal the mutual coincidence of the 109-, 196-, 225-, and 541-keV γ rays; the 155-keV transition identified in Ref. [3] was not observed in the present work.

As noted earlier, an isomeric transition at 113 keV was reported for ^{62}Mn with a 95-ns half-life [6]. To search for coincidences across this isomer, a double gate on the prompt 109- and 196-keV transitions was again applied, this time in the PPD cube. The delayed spectrum in Fig. 3(b) was produced, where a prominent line can be seen at 114 keV. A double gate on the delayed 114-keV γ ray and one of the prompt 109-, 196-, or 225-keV lines yields the spectrum in Fig. 3(c), in which the latter gating transitions appear along with the prompt 541-keV line. The results are consistent with these fast γ rays populating a high-spin isomer that, in turn, decays via the isomeric 114-keV transition to the proposed β-decaying excited state. The level scheme for ^{62}Mn deduced from these data is presented in Fig. 4. The ordering of the transitions above the 95-ns state, guided in part by the sequences in ^{58,60}Mn, is consistent with the relative intensities measured in Ref. [3]. The absence of the 155-keV γ ray identified in Ref. [3] may imply that it is a low-lying transition from a short cascade that is not seen here because of the threefold coincidence requirement imposed during the data acquisition. A 156-keV transition was also reported for ^{62}Mn in the β-decay work by Gaudefroy *et al.* [5], supporting this interpretation.

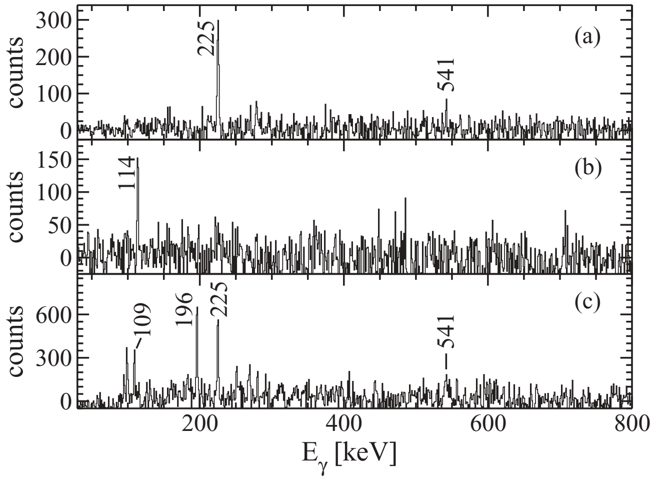

FIG. 3. Coincidence spectra double gated on prompt transitions at 109 and 196 keV in the (a) PPP and (b) PPD cubes. (c) Sum of spectra double gated on the delayed 114-keV transition and the prompt 109-, 196-, or 225-keV transition in the PPD cube. ^{62}Mn transitions are marked with their energies in keV.

A similar analysis was attempted for ^{60}Mn: In a recent survey of isomers produced in the high-energy fragmentation of ^{238}U, an observed γ ray with a half-life of 1.0(3) μs and an energy of 114 keV was assigned to ^{60}Mn [17]. Double gates were set in the PPD cube on the 114-keV line and the prompt γ rays reported in Ref. [2] (and observed in the PPP cube) for ^{60}Mn; none of the other lines reported for ^{60}Mn were observed. Although the total ~800-ns delayed time region in this experiment implies that only about 35% of the coincidence events would be observed across a 1.0-μs isomer, this should have been sufficient for some of these events to be recorded. As argued earlier for the 155-keV γ ray in ^{62}Mn, the 114-keV line in ^{60}Mn may be part of a short, low-lying cascade that did not satisfy the threefold coincidence trigger. Indeed, the authors of Ref. [17] speculate, based on the calculations in Ref. [18], that this transition could decay from a 3^+ state directly to the 1^+ ground state or from a 2^+ level to the 271-keV, 4^+ isomer; in either case, if the state is not strongly fed by high-spin band structures, it would not be observed in the present data.

The yrast dipole band structures [up to spin (8)] and low-energy levels determined by Steppenbeck *et al.* [2] for ^{58,60}Mn are given in Fig. 4. Transitions between the low-lying states have been omitted for clarity, as the emphasis here is on the decay within and out of the dipole band. These level schemes are compared to the results for ^{62}Mn from Ref. [3] and the present work, and to the levels proposed for ^{64}Mn in Ref. [14]. $M3$ transitions between the ^{58,60}Mn isomers were reported by Schmidt-Ott *et al.* [19]. Liddick *et al.* [18] subsequently interpreted the results of the decay of ^{60}Cr to ^{60}Mn to rule out a 0^+ assignment in favor of 1^+ for the lower-lying β-decaying isomers in ^{58,60}Mn, and they adopted 4^+ for the higher-lying ones. These assignments are consistent with the results of the decay of ^{62}Cr to ^{62}Mn, where 1^+ and $(3^+, 4^+)$ were also proposed for the β-decaying isomers [14]. The latter was further restricted to (4^+) in Ref. [11]. Little evidence exists for the ordering of the 196- and 225-keV γ rays in ^{62}Mn; hence, they have been arranged in a sequence similar to those in ^{58,60}Mn. Steppenbeck *et al.* [2] proposed tentative spins, but no parities, for the ^{58,60}Mn sequences beginning with the spin-(4) levels. These cascades are distinguished by relatively large yrast strengths, as well as by the absence of possible $E2$ crossover transitions from the spin-(8), -(7), and -(6) levels. Hence, it is proposed that they could be negative-parity levels arising from the $I^\pi = 1^-$ to 8^-, $\pi f_{7/2}^{-1} \nu g_{9/2}^{+1}$ multiplet. (It is worth noting that an analogous case illustrating the absence of crossover $E2$ transitions within a proton-neutron particle-hole multiplet is found among the $I^\pi = 1^+$ to 6^+ levels in ^{90}Nb, where only $M1$ transitions are observed [20,21].) The bands in ^{58,60}Mn could extend beyond the $I = (8)$ states by recoupling the remaining proton holes (i.e., the $\pi f_{7/2}^{-3} \nu g_{9/2}^{+1}$ configuration).

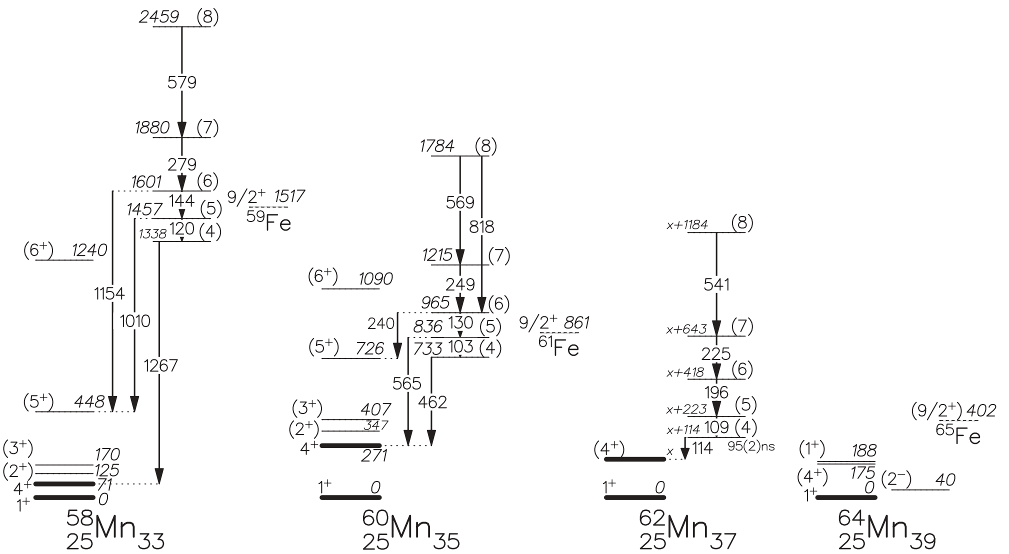

FIG. 4. Level scheme of ^{62}Mn$_{37}$, deduced in this work, in comparison with partial schemes of ^{58,60}Mn$_{33,35}$ from Ref. [2] and ^{64}Mn$_{39}$ from Ref. [14]. The yrast $9/2^+$ states in isotonic ^{59,61,65}Fe$_{33,35,39}$ are from Refs. [12,15], [9], and [16], respectively.

For a particle-hole multiplet, the states with the lowest and highest spins are expected to lie above those with intermediate spins [22]. Hence, the lowest-spin members of the multiplet would be nonyrast and less likely to be observed in fusion-evaporation [2] and deep-inelastic reactions. Additional evidence for a $\pi f_{7/2}^{-1} \nu g_{9/2}^{+1}$ assignment can be drawn from the rapid decrease in excitation energy of the levels in this sequence of $M1$ transitions; consider, for example, the $I = (4)$ members, which decrease from 1338 to 733 to $(x + 114)$ keV as N increases from 33 to 37. This trend is consistent with the positions of the $\nu g_{9/2}$ levels in the respective odd-mass Fe isotones (Fig. 4). The position of the $9/2^+$ level has not been established in ^{63}Fe, but it is known in ^{65}Fe from mass measurements to lie at 402(5) keV [16]. Note that, although the higher-lying isomer in ^{62}Mn is not fixed in energy, the excitation of the dipole band relative to that state has decreased by about 350 keV compared to ^{60}Mn. This lends credence to the hypothesis that the overall excitation energy of the structure has decreased. In the absence of firm excitation energies and spin-parity assignments, the scenario outlined here is admittedly somewhat speculative. However, a rather consistent picture appears to emerge: As with the odd-A Mn isotopes, the $g_{9/2}$ neutron orbital is found to influence the structure of the neutron-rich even-A Mn isotopes as N approaches 40.

Srivastava and Mehrotra [23] have recently reported calculations for ^{58,60,62}Mn, utilizing a truncated $fpg_{9/2}$ valence space with a ^{48}Ca core, and allowing up to six excitations into the upper fp-shell orbitals for protons and $g_{9/2}$ orbitals for neutrons. These calculations predict that the lowest of the negative-parity levels in both ^{60,62}Mn have $I = 6$, whereas $I = (4)$ is found experimentally. Furthermore, the excitation energies of the negative-parity states considered in Ref. [23] are generally underpredicted by several hundred keV. (For ^{62}Mn, the energies are relative to the 4^+ isomer.) This behavior perhaps provides some clue as to the adjustments to the fpg interactions that require further exploration in future calculations and the need for full fpg calculations without valence-space truncations.

IV. CONCLUSIONS

In summary, new level structures are reported for ^{61,62}Mn revealing the likely presence of opposite-parity structures arising from the occupancy of the $\nu g_{9/2}$ orbital. For more definitive comparisons between experiment and theory, it would be useful to obtain unambiguous spin and parity assignments for the nuclei discussed here, as well as to determine the relative energies of the isomers in ^{62}Mn. Despite these lapses in available information, these data point to the need for full fpg shell-model calculations to describe these results.

ACKNOWLEDGMENTS

This work was supported in part by the US Department of Energy, Office of Nuclear Physics, under Grant No. DE-FG02-94-ER40834 and Contract No. DE-AC02-06CH11357, and the Polish Ministry of Science under Contracts No. 1P03B05929 and No. NN202103333.

---

[1] V. Paar, Nucl. Phys. A **211**, 29 (1973).
[2] D. Steppenbeck *et al.*, Phys. Rev. C **81**, 014305 (2010).
[3] J. J. Valiente-Dobón *et al.*, Phys. Rev. C **78**, 024302 (2008).
[4] H. L. Crawford *et al.*, Phys. Rev. C **79**, 054320 (2009).
[5] L. Gaudefroy *et al.*, Eur. Phys. J. A **23**, 41 (2005).
[6] J.-M. Daugas *et al.*, Phys. Rev. C **81**, 034304 (2010).
[7] I. Y. Lee, Nucl. Phys. A **520**, 641c (1990).
[8] N. Hoteling *et al.*, Phys. Rev. C **74**, 064313 (2006).

[9] N. Hoteling *et al.*, Phys. Rev. C **77**, 044314 (2008).
[10] I. Stefanescu *et al.*, Phys. Rev. C **79**, 034319 (2009).
[11] N. Hoteling *et al.*, Phys. Rev. C **82**, 044305 (2010).
[12] [http://www.nndc.bnl.gov/ensdf].
[13] Huo Junde, Nucl. Data Sheets **110**, 2689 (2009); **109**, 787 (2008).
[14] L. Gaudefroy, Ph.D. thesis, Université de Paris XI, Orsay, IPNO-T-05-07, 2005.
[15] Coral M. Baglin, Nucl. Data Sheets **95**, 215 (2002).
[16] M. Block *et al.*, Phys. Rev. Lett. **100**, 132501 (2008).
[17] C. M. Folden III *et al.*, Phys. Rev. C **79**, 064318 (2009).
[18] S. N. Liddick *et al.*, Phys. Rev. C **73**, 044322 (2006).
[19] W.-D. Schmidt-Ott *et al.*, in *Proceedings of the 6th International Conference on Nuclei Far from Stability and the 9th International Conference on Atomic Masses and Fundamental Constants*, Bernkastel-Kues, Germany, 19–24 July 1992, Inst. Phys. Conf. Series 132, edited by R. Neugart and A. Wöhr (Institute of Physics, Bristol, 1993), p. 627.
[20] J. A. Cooper, J. M. Hollander, and J. O. Rasmussen, Nucl. Phys. A **109**, 603 (1968).
[21] C. A. Fields, F. W. N. De Boer, J. J. Kraushaar, R. A. Ristinen, L. E. Samuelson, and E. Sugarbaker, Nucl. Phys. A **363**, 311 (1981).
[22] V. Paar, Nucl. Phys. A **331**, 16 (1979).
[23] P. C. Srivastava and I. Mehrotra, Eur. Phys. J. A **45**, 185 (2010).