PHYSICAL REVIEW C, VOLUME 65, 021302(R)

^{100}Sn core excitations in ^{102}In

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(Received 14 October 2001; published 16 January 2002)

Nuclei in the vicinity of the doubly-magic ^{100}Sn nucleus have been studied, and an extended level scheme for ^{102}In has been established. The level structure comprises both the negative parity states involving the $\nu h_{11/2}$ orbital, and levels due to the breakup of the doubly-magic ^{100}Sn core. Results of a large-scale shell model calculation, using realistic and empirical effective interactions with ^{88}Sr as a core, are in very good agreement with the experimental data.

DOI: 10.1103/PhysRevC.65.021302 PACS number(s): 21.10.−k, 21.60.Cs, 23.20.Lv, 27.60.+j

Studies of doubly-magic nuclei and of their neighbors have always attracted much attention. These nuclei provide important information about the single-particle energies and two-body matrix elements needed for microscopic calculations. The heaviest self-conjugate, doubly-magic nucleus is ^{100}Sn. As such, ^{100}Sn and its neighbors provide a unique opportunity to test effective interactions between protons and neutrons occupying similar high-j orbitals. However, being located far from the valley of β stability, no direct experimental spectroscopic information about ^{100}Sn and its immediate neighbors is available currently. In this region, the nucleus providing the most direct information about the interaction of protons below the $Z=50$ shell closure with neutrons above the $N=50$ shell is ^{100}In. However, no excited states are currently known in this nucleus either. The lightest indium isotope with known excited states is the neighboring ^{101}In nucleus [1,2], and the closest odd-odd nuclei to ^{100}Sn with known excited states are ^{102}In [3] and ^{98}Ag [4]. In this Rapid Communication, we present extensive experimental data on high spin states in ^{102}In. These data convey important information about proton-neutron interactions, as well as about the breakup of the doubly-magic ^{100}Sn core. Our experimental results agree rather well with recent Euroball data [5].

Nuclei near ^{100}Sn were studied in an experiment at the ATLAS accelerator at Argonne National Laboratory using the ^{58}Ni$+^{50}$Cr reaction at 225 MeV with a 2.1 mg/cm^2 thick target. The ^{50}Cr target had an isotopic enrichment of more than 99% and was backed by 10 mg/cm^2 Au in order to stop the residual nuclei. The experiment was performed with the GAMMASPHERE Ge-detector array [6]. The experimental setup consisted of 78 Ge detectors, the Microball [7], which is comprised of 95 CsI scintillators for the detection of light charged particles, and the Neutron Shell, an array of 30 liquid scintillators [8]. The neutron detectors covered a solid angle of about 1π in the forward direction. The average detection and identification efficiencies for protons, α particles, and neutrons were 78%, 47%, and 27%, respectively. In the analysis, the data were sorted into particle-gated γ-ray spectra and γ-γ coincidence matrices. Further experimental details are given in Ref. [1].

In a previous study [3], six γ rays with respective energies of 145, 190, 302, 442, 835, and 1137 keV were placed in a partial ^{102}In level scheme, and four additional γ rays were tentatively assigned to this nucleus as well. In the present experiment, all these γ rays were also observed in the spectrum corresponding to ^{102}In residues (see Fig. 1). This spectrum was generated by requiring the coincident detection of one α particle, zero or one proton, and at least one neutron. Gamma rays detected in coincidence with the previously known ones are also marked in Fig. 1 and they all belong to ^{102}In. Energies, relative intensities, and A_2 angular distribution coefficients of these γ rays are listed in Table I. The multipolarity of the γ rays was deduced from the measured angular distributions assuming stretched dipole, quadrupole, and mixed $M1/E2$ transitions. This information, together with the coincidence relationships between the γ rays assigned to ^{102}In, forms the basis for the partial level scheme shown in Fig. 2. In a few cases, where the A_2 coefficients allowed for more than one spin-parity assignment, we relied on additional experimental information (e.g., branching ratios and the presence or absence of other linking transitions) to propose the quantum numbers presented in the level scheme.

A previous β-decay study of ^{102}In suggests spin 6 or 7 $\hbar$ for the ground state [9]. $J^{\pi}=6^{+}$ is adopted here, a value which is the same as that of the ^{104}In ground state and which was also assumed in Ref. [3]. Due to this uncertainty, all quantum numbers in the level scheme are indicated as tentative, even though their relative values remain rather firm.

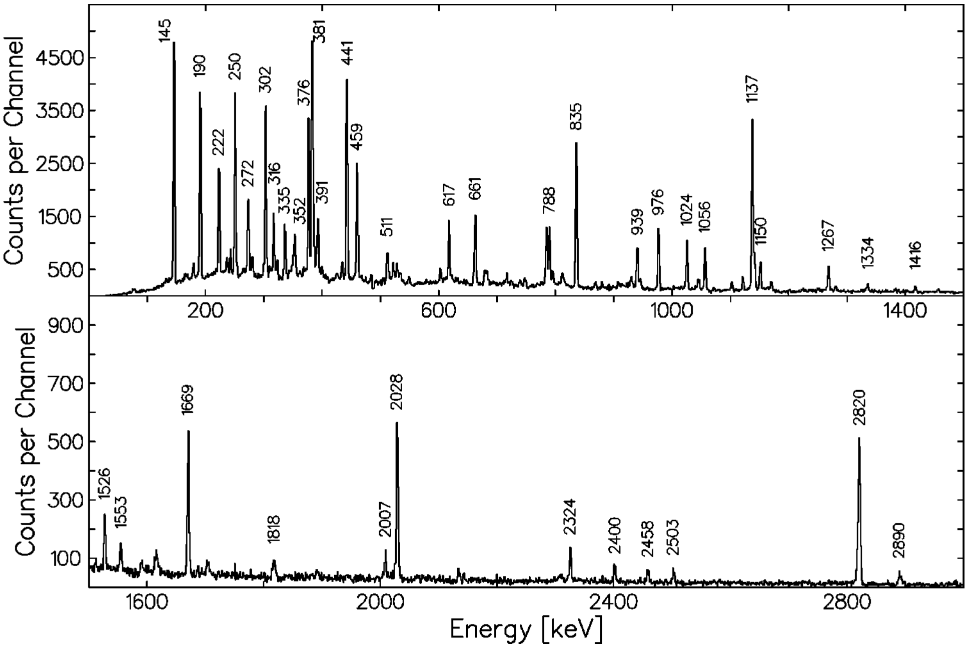

FIG. 1. Background subtracted γ-γ coincidence spectrum gated with one α particle, zero or one proton, and at least one neutron in coincidence with one of the 145, 302, 381, 441, 835, or 1137 keV γ rays.

This level scheme agrees with the previously published one [3], except for the ordering of the 190 and 442 keV transitions which was changed based on several new linking transitions that firmly establish the proper level sequence. As linear polarizations of the γ rays have not been measured, the parities of the levels in Fig. 2 are not established experimentally. Nonetheless, we have used several plausibility arguments to deduce the parities indicated in the level scheme. For example, all low-lying states are assumed to be of positive parity since their configurations involve only positive parity proton and neutron orbitals located just below and above the $N,Z=50$ gaps. The proton $p_{1/2}$ orbit is the only negative parity state near the Fermi surface, but it cannot contribute to the observed states because of its low angular momentum. Furthermore, quadrupole transitions are assumed to be electric in character due to lifetime considerations, and the fact that $M2$ transitions require a change in configuration from one of the low-lying, positive parity orbitals to a higher-lying, negative parity orbital such as the neutron $h_{11/2}$ state. Since such transitions are hindered, they cannot generally compete favorably with the much faster transitions allowed in the level scheme. Therefore, the parity of the band marked as "A" in Fig. 2 is most likely the same as that of the ground state. Negative parity states are expected to occur at higher excitation energies and have, indeed, been observed systematically in heavier odd-mass indium isotopes [10]. (The negative parity of these states has been established experimentally for ^{105}In [11].) According to the systematics, negative parity states become yrast at about 4–5 MeV excitation energy in heavier indium isotopes and this excitation energy increases by about 200 keV for each removed neutron pair [10]. This is because the $\nu h_{11/2}$ orbit, which contributes to the largest parts of the wave functions describing the high spin, negative parity states, moves away from the Fermi surface when approaching the $N=50$ shell closure. Based on these considerations, negative parity is proposed for levels marked as 12^- (3941, 4238, 4046, and 4314 keV) and 13^- (4119 keV) in the sequence marked as "B" in Fig. 2.

A large-scale shell model calculation was performed for ^{102}In. The calculation uses ^{88}Sr as a closed shell core with an effective interaction based on the CD-Bonn nucleon-nucleon interaction [12]. The effective two-body interaction is in turn used in a shell model calculation for valence neutrons in the single-particle orbits $2s_{1/2}$, $1d_{5/2}$, $1d_{3/2}$, $0g_{7/2}$, and $0h_{11/2}$ and valence protons in the single-particle orbits $0g_{9/2}$ and $1p_{1/2}$ [13]. Reference [14] describes how the effective interaction was obtained for nuclei near $A\sim100$. The results of the calculation are compared with the experimental levels in Fig. 3. The agreement between the calculated and experimental excitation energies up to the 3858 keV experimental level is very good, apart from the second $J^\pi=11^-$ state as discussed below. In the above model space, ^{102}In has three valence neutrons and 11 valence protons, which is equivalent to a single proton hole in the doubly-magic ^{100}Sn core. For all calculated levels shown in Fig. 3, this proton hole remains in the $g_{9/2}$ orbit. Therefore, the only proton contribution to the calculated level scheme of ^{102}In comes through proton-neutron interactions. The calculation favors a $J^\pi=6^+$ assignment for the ground state. In this state, the three valence neutrons occupy mainly the $d_{5/2}$ orbit, while about 40% of the wave function amplitude comes from the contribution of the $g_{7/2}$ level. All other orbitals have an insignificant contribution to the wave function of the ground state. Surprisingly, all levels up to the $J^\pi=10_2^+$ state have a very similar configuration in the calculation. The 10_2^+ level is the lowest observed level for which the $d_{5/2}$ and $g_{7/2}$ orbits switch their occupation numbers. The larger wave function difference results in a lower mixing between the 10_1^+ and 10_2^+ levels. This in turn leads to two close lying 10^+ states, in agreement with the experimental observation. However, all other nonyrast states are calculated too high in energy, and we expect that the $g_{7/2}$ orbit has a larger contribution than calculated to their

TABLE I. Energies, relative γ-ray intensities, and angular distribution coefficients for γ rays assigned to ^{102}In.

Energy (keV)	Relative intensity	Ang. distr. coeff. A_2	Ang. distr. coeff. A_4	Energy (keV)	Relative intensity	Ang. distr. coeff. A_2	Ang. distr. coeff. A_4
144.9(2)	72(2)	−0.1(1)	−0.2(2)	834.7(2)	30(2)	0.0(1)	
163.2(3)	1.2(2)			924.5(4)	1.2(2)		
165.2(4)	0.5(2)			929.4(3)	7.0(2)		
178.3(3)	2.8(2)	−0.0(2)		939.1(3)	8.7(5)	−0.3(1)	
189.9(2)	21.4(7)	0.00(8)		975.9(2)	12.4(5)	0.15(2)	−0.06(3)
222.0(2)	11.7(5)	−0.12(9)		1024.1(3)	8.7(5)	−0.0(1)	
223.0(5)	0.5(2)			1044.1(3)	2.8(2)	0.2(2)	
241.5(3)	2.6(2)	−0.1(2)		1055.6(3)	7.7(5)	−0.1(1)	
249.6(2)	16.7(7)	−0.1(2)		1120.0(4)	1.9(2)	0.1(2)	
272.0(2)	9.2(2)	−0.1(1)		1136.6(2)	61(2)	0.25(3)	0.02(4)
302.1(2)	19(1)	−0.10(9)		1140.9(4)	4.5(5)	−0.3(1)	
315.8(3)	6.8(2)	−0.2(1)		1150.2(3)	5.9(2)	0.1(1)	
334.8(3)	6.6(2)	−0.2(1)		1267.0(3)	5.2(5)	−0.2(1)	
352.1(3)	28(2)			1279.0(3)	1.4(2)	−0.8(4)	
375.7(2)	17.4(5)	−0.17(6)	0.07(8)	1333.8(4)	2.6(5)	0.1(3)	
381.4(2)	43(1)	−0.12(4)	−0.02(5)	1416.3(4)	2.3(5)	0.2(3)	
383.7(2)	12.0(5)	−0.4(3)		1526.0(4)	2.3(2)	0.1(2)	
391.2(3)	7.0(2)	−0.4(1)		1553.1(5)	1.2(2)	−0.5(3)	
433.1(3)	1.4(2)	0.1(2)		1589.4(3)	0.7(2)		
441.3(2)	43(1)	−0.17(3)	0.06(4)	1669.2(3)	5.9(2)	0.1(1)	
458.9(2)	12.3(5)	−0.14(9)		1669.8(3)	2.1(2)		
520.3(3)	4.7(2)			1818.4(3)	0.7(2)		
601.5(4)	1.4(2)	0.3(2)		2007.0(5)	1.6(2)	−0.2(2)	
616.7(3)	8.2(5)	−0.2(1)		2027.9(3)	9.2(5)	−0.2(1)	0.1(1)
628.0(3)	3.1(2)			2324.4(4)	2.3(2)	−0.3(3)	
661.1(2)	9.2(5)	0.01(9)		2400.4(5)	1.4(2)	−0.1(2)	
678.0(3)	2.8(2)	−0.2(2)		2458.1(4)	0.9(2)		
681.5(4)	2.6(2)	−0.1(2)		2502.5(6)	1.2(2)	0.6(4)	
715.7(3)	2.1(2)			2819.7(3)	12.0(7)	0.41(6)	−0.1(1)
788.4(3)	10.6(5)	0.3(1)		2889.8(6)	1.2(2)	0.7(3)	
794.6(4)	2.6(2)	−0.3(2)		3015.0(6)	1.2(2)	0.3(3)	
810.9(3)	3.1(2)						

wave functions. This is especially true for the 11_2^+ state that is calculated more than 1 MeV too high. The interaction used in the calculation probably gives too strong an attraction between the $g_{9/2}$ protons and the $g_{7/2}$ neutrons. The nice one-to-one correspondence between the experimental and calculated positive parity states ends with the 13_1^+ state, which corresponds to the highest spin that can be reached by coupling one proton hole in the $g_{9/2}$ orbit with three neutrons in $d_{5/2}$ and $g_{7/2}$ orbits. The wave function of this state is, therefore, $\pi(g_{9/2})^{-1}\nu d_{5/2}(g_{7/2})^2$.

The shell-model calculation using an effective interaction based on the CD-Bonn potential gives also a good agreement for the ordering of the experimental states with negative parity. However, their relative position with respect to the positive parity spectrum was found to be too high in excitation energy by almost 4 MeV. By making the high spin, negative parity matrix elements (essentially those involving the $\pi g_{9/2}\nu h_{11/2}$ configuration) more attractive by up to 2 MeV, it was possible to achieve good agreement between experiment and theory for the negative parity states as well. All negative parity levels shown in Fig. 3 have a wave function configuration with the proton hole in the $g_{9/2}$ orbital and one neutron in the $h_{11/2}$ orbit, with the remaining neutron pair distributed mainly over the $d_{5/2}$ and $g_{7/2}$ states. The highest spin state

TABLE II. Comparison of level spacings in ^{103}In with those of the core-excited states in ^{102}In that can be interpreted as a neutron $g_{9/2}$ hole coupled to a ^{103}In core.

J^π ^{102}In vs ^{103}In	Energy (keV) ^{102}In	Energy (keV) ^{103}In
13^+ vs $17/2^+$	0	0
14^+ vs $19/2^+$	459	315
15^+ vs $21/2^+$	1120	1131
16^+ vs $23/2^+$	1504	1453
17^+ vs $25/2^+$	1895	1892
17^- vs $25/2^-$	2726	2795

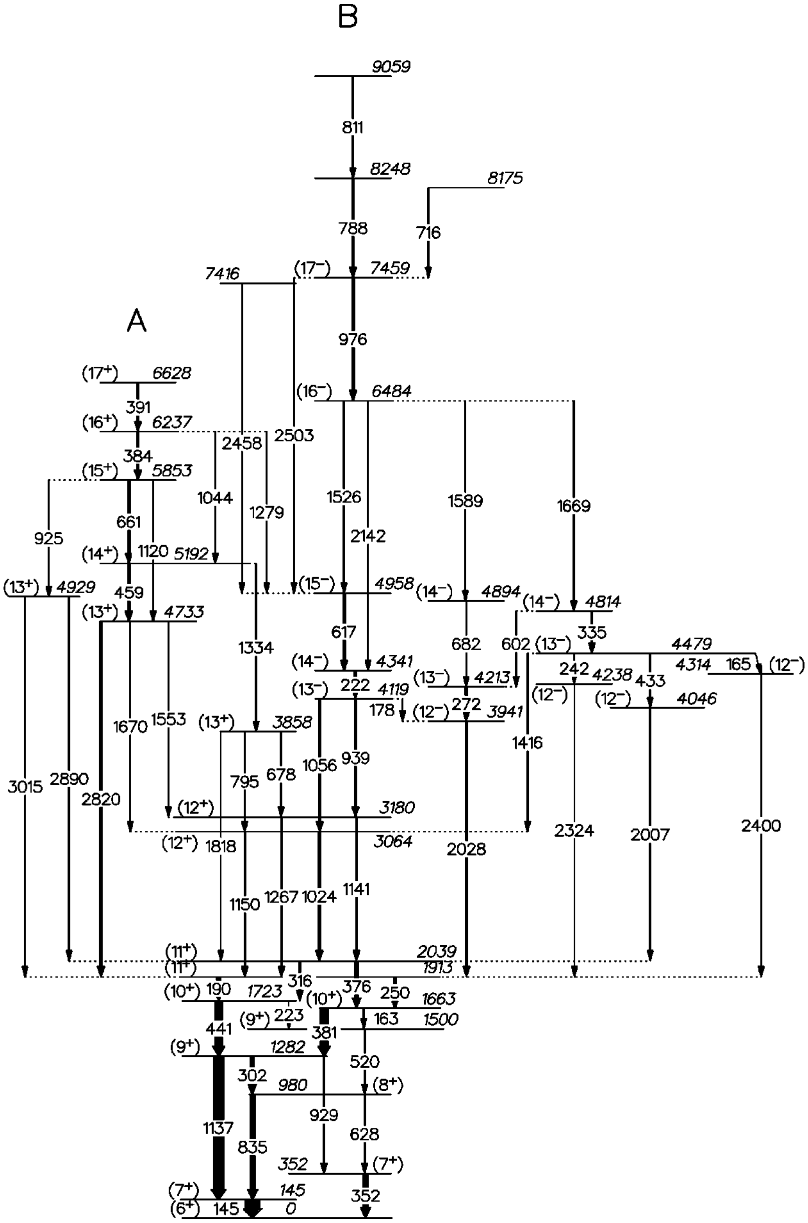

FIG. 2. Experimental level scheme of ^{102}In as derived from the present measurements. The widths of the arrows are proportional to the intensity of the transitions observed in the experiment. The white parts of the arrows correspond to the contribution of internal conversion.

that can be reached with such a configuration is $J^{\pi}=16^{-}$. To justify the modification of the $\pi g_{9/2}\nu h_{11/2}$ interaction, the same negative parity matrix elements as for ^{102}In were also used to calculate the negative parity states in the neighboring nuclei ^{101}In [15] and ^{103}In [10]. The calculation gave a remarkable agreement with experiment for these two nuclei as well.

The experimental states of positive parity above the 3858 keV level do not have calculated counterparts. The only possibility to reach such spins and parities, within the model space used in the calculation, is to promote a neutron pair to the $h_{11/2}$ orbit. However, even after changing the $\pi g_{9/2}\nu h_{11/2}$ effective interaction to reproduce the negative parity states, the $J^{\pi}=13_2^{+}$ to 17^{+} levels were calculated to lie about 2 MeV higher in excitation energy than the experimental ones. Therefore, these states must be associated with excitations across the doubly closed $N=Z=50$ shell. Most likely, they correspond to the excitation of a neutron from the $g_{9/2}$ orbital just below $N=50$ shell gap to the $d_{5/2}$ level just above this gap. This excitation produces a very attractive $(\pi g_{9/2}^{-1}\nu g_{9/2}^{-1})^{9+}$ configuration which is coupled to four neutron particle states. To test the plausibility of this scenario, we have compared the relative energies of the positive and negative parity core-excited states in ^{102}In with their counterparts in ^{103}In [10], as given in Table II. These states (13^{+} to 17^{+} in sequence A, and 17^{-} in sequence B, respectively) may be considered as a neutron $g_{9/2}$ hole coupled to a ^{103}In core. The close similarity of the level spacings and intensity patterns for the states in question provides strong additional support for the proposed configuration and spin-parity assignments.

In summary, the level scheme of ^{102}In, with one proton hole and three neutrons outside the doubly-magic ^{100}Sn core, has been extended to significantly higher spins. Both negative parity levels involving the $\nu h_{11/2}$ orbital and core-excited states requireing the promotion of a neutron across

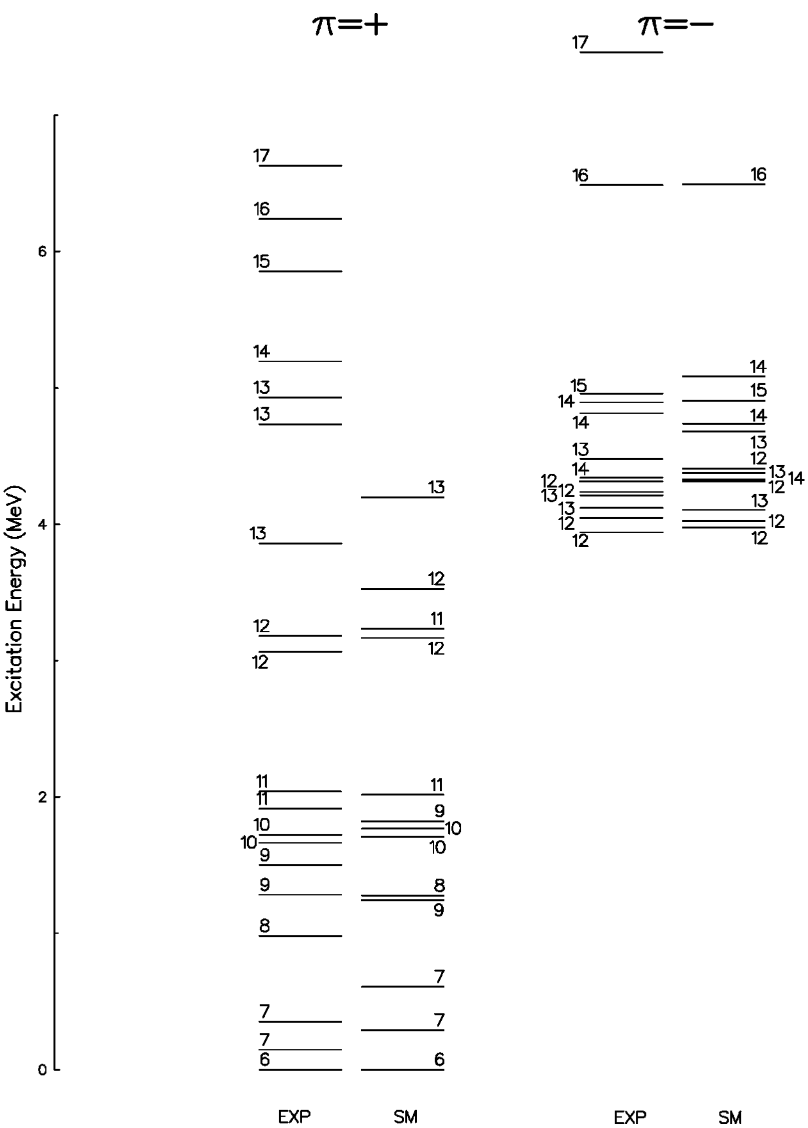

FIG. 3. Comparison of experimental (EXP) and calculated (SM) level energies in ^{102}In. See text for details about the calculations.

the $N=50$ magic gap have been identified. A large-scale shell model calculation using ^{88}Sr as a core and realistic effective interactions gives good agreement with the experimental excitation energies for the states included in the model space.

Oak Ridge National Laboratory is operated by UT-Battelle, LLC for the U.S. Department of Energy under Contract No. DE-AC05-00OR22725. Work at Argonne National Laboratory was supported by the U.S. Department of Energy under Contract No. W-31-109-ENG-38 and at Washington University under Contract No. DE-FG02-88ER40406. This work was supported in part by the Swedish Natural Science Research Council.

[1] M. Lipoglavšek *et al.*, Nucl. Phys. **A682**, 399c (2001).
[2] J. Cederkäll *et al.*, Phys. Rev. C **53**, 1955 (1996).
[3] D. Seweryniak *et al.*, Nucl. Phys. **A589**, 175 (1995).
[4] J. Cederkäll *et al.*, Eur. Phys. J. A **1**, 7 (1998).
[5] D. Sohler *et al.* (to be published).
[6] I.Y. Lee, Nucl. Phys. **A520**, 641c (1990).
[7] D.G. Sarantites *et al.*, Nucl. Instrum. Methods Phys. Res. A **381**, 418 (1996).
[8] D.G. Sarantites (to be published); http://wunmr.wustl.edu/~dgs/NeutronShell/NeutronShell.htm
[9] J. Szerypo *et al.*, Nucl. Phys. **A584**, 221 (1995).
[10] J. Kownacki *et al.*, Nucl. Phys. **A627**, 239 (1997).
[11] T. Ishii *et al.*, Z. Phys. A **343**, 261 (1992); M. Ishii *et al.*, Phys. Scr. **T56**, 89 (1995).
[12] R. Machleidt, F. Sammarruca, and Y. Song, Phys. Rev. C **53**, R1483 (1996).
[13] A. Holt, T. Engeland, M. Hjorth-Jensen, and E. Osnes, Phys. Rev. C **61**, 064318 (2000).
[14] M. Hjorth-Jensen, T.T.S. Kuo, and E. Osnes, Phys. Rep. **261**, 125 (1995); T. Engeland, M. Hjorth-Jensen, and E. Osnes, Phys. Rev. C **61**, 021302(R) (2000).
[15] M. Lipoglavšek *et al.* (to be published).