PHYSICAL REVIEW C **88**, 031306(R) (2013)

Excited 0^+ states in ^{62}Zn populated via the ^{64}Zn(p,t)^{62}Zn reaction

K. G. Leach,[1,*] P. E. Garrett,[1,2] C. E. Svensson,[1] I. S. Towner,[3] G. C. Ball,[4] V. Bildstein,[1] B. A. Brown,[5,6] A. Diaz Varela,[1]
R. Dunlop,[1] T. Faestermann,[7] R. Hertenberger,[8] D. J. Jamieson,[1] R. Krücken,[4,7] S. Triambak,[1,†] and H.-F. Wirth[8]
[1]*Department of Physics, University of Guelph, Guelph, Ontario N1G 2W1, Canada*
[2]*Excellence Cluster Universe, Boltzmannstraße 2, D-85748 Garching, Germany*
[3]*Cyclotron Institute, Texas A&M University, College Station, Texas 77843-3366, USA*
[4]*TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada*
[5]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[6]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[7]*Physik Department, Technische Universität München, D-85748 Garching, Germany*
[8]*Fakultät für Physik, Ludwig-Maximilians-Universität München, D-85748 Garching, Germany*

(Received 19 June 2013; published 11 September 2013)

A search for excited 0^+ states in ^{62}Zn was conducted via the ^{64}Zn$(p,t)^{62}$Zn reaction. Four such states in ^{62}Zn were observed up to an excitation energy of 5.4 MeV. The measured angular distribution for the previously assigned 0_2^+ state at 2342 keV is consistent with a 2^+ assignment, and thus the first excited 0^+ state is now assigned at 3043 keV. Due to the energy scaling in the currently adopted formalism for isospin-mixing corrections in superallowed Fermi β decay, δ_{C1} for ^{62}Ga is reduced by nearly a factor of two. This result shifts the theoretical value closer to previous experimental determinations of the same quantity through ^{62}Ga superallowed β-decay branching-ratio measurements.

DOI: 10.1103/PhysRevC.88.031306 PACS number(s): 21.60.Cs, 25.40.Hs, 24.80.+y, 27.50.+e

Superallowed $0^+ \rightarrow 0^+$ nuclear β-decay data currently provide the most precise determination of the vector coupling constant for weak interactions, G_V [1,2]. The extraction of G_V from these data is vital to determine the up-down element of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix, $V_{\rm ud}$ [2]. In order to obtain $V_{\rm ud}$ from the high-precision superallowed data, corrections to the nucleus-dependent β-decay ft values for these nuclei must be made [2]:

$$\mathcal{F}t \equiv ft(1+\delta_R)(1-\delta_C) = \frac{2\pi^3\hbar^7\ell n(2)}{2G_V^2 m_e^5 c^4(1+\Delta_R)}, \quad (1)$$

where δ_R is a transition-dependent radiative correction, Δ_R is a transition-independent radiative correction, and δ_C is a nucleus-dependent isospin-symmetry-breaking (ISB) correction. Although small ($\sim$1%), these corrections are crucial due to the very precise experimental ft values [1], obtained through measurements of the β-decay half-lives, branching ratios, and Q-values for superallowed decays. The current uncertainty for G_V is, in fact, dominated by the precision of these theoretical corrections; most notably the transition-independent radiative correction Δ_R [3] and the ISB corrections [2]. Although there has been a great deal of recent theoretical work regarding the ISB calculations [4–11], precision Standard Model tests generally adopt the formalism and refinements developed by Towner and Hardy [1,12]. Their current method uses a separation of δ_C into a sum of two terms, one which results from different configuration mixing between the parent and daughter states in the superallowed decay (δ_{C1}), and one that corrects for the imperfect radial overlap between the initial and final spatial nuclear wave functions (δ_{C2}). If the shell-model effective interaction was truly isospin invariant, the parent and daughter analog-state wave functions would be identical and the selection rules on the isospin ladder operator formalism for Fermi β transitions would hold exactly. This would also lead to all β transitions to nonanalog 0^+ states in the daughter nucleus being strictly forbidden [13]. The addition of charge-dependent terms into the Hamiltonian causes the isospin symmetry to be broken and the Fermi matrix element to deviate slightly from its exact-symmetry limit value. This symmetry breaking also implies that small branches to the excited, nonanalog 0^+ states in the daughter nucleus are possible, if they are energetically accessible within the β-decay Q-value window.

For all of the 0^+ states in a given model space with the same total isospin, the effect of this mixing is to deplete the analog transition strength by the sum of the mixing into all of the nonanalog states,

$$\delta_{C1} \approx \sum_n \delta_{C1}^n, \quad (2)$$

where n is a counting index for excited 0^+ states. In most cases, the bulk of the mixing is associated with the first few excited nonanalog 0^+ states [12]. The configuration mixing generates nonanalog Fermi β-decay branches, which allows for the direct measurement of the δ_{C1}^n from the observed β-decay branching ratios, B_n, to the excited 0^+ states [14],

$$\delta_{C1}^n \approx \left(\frac{f_0}{f_n}\right) B_n \frac{(1-\delta_{C1})}{B_0} \approx \left(\frac{f_0}{f_n}\right) B_n, \quad (3)$$

where f_0 and f_n are the phase-space integrals for decay to the ground state and $n^{\rm th}$ excited 0^+ state, respectively.

---

[*] Present address: TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada; kleach@triumf.ca

[†] Present address: Department of Physics & Astrophysics, University of Delhi, Delhi 110 007, India.

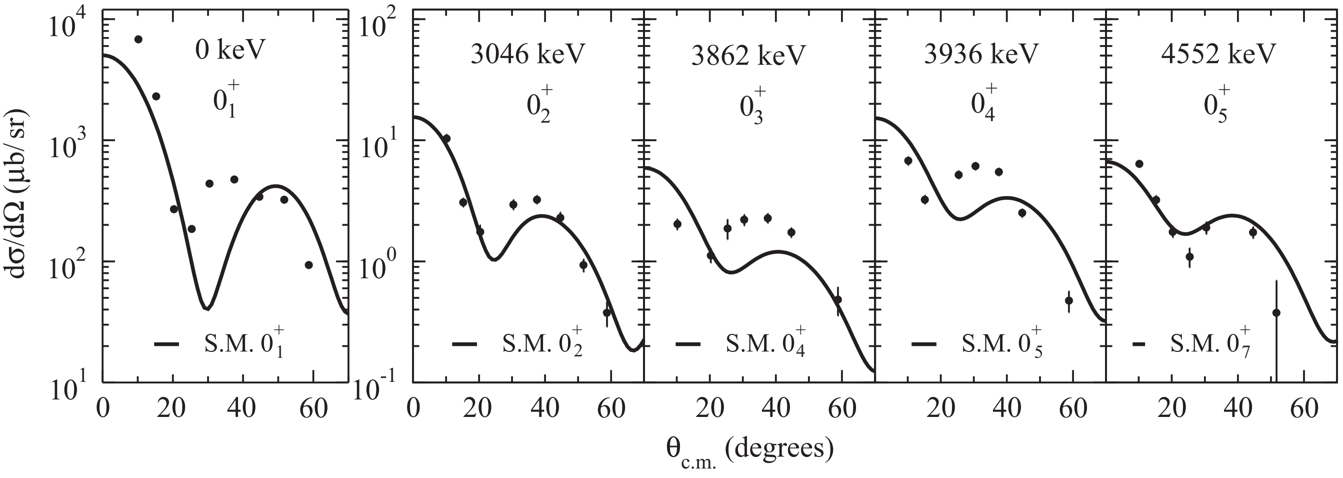

FIG. 1. Experimental angular distributions for the five observed 0^+ states in ^{62}Zn from this work. The data are compared to one- + two-step DWBA calculations using shell-model wave functions for each respective final state, and in most cases the experimental uncertainties are smaller than the data points. Due to the large cross-section disparity between the ground state and the excited states, the 0_1^+ state is displayed on a different scale. The curves are normalized to the data in order to provide a better shape comparison. A discussion on the assignment of each state and a comparison with previous experimental data are given in the text.

The calculations of δ_{C1} are highly sensitive to the specific model that is used, and it is important that the Hamiltonian is able to generate an accurate representation of the 0^+-state spectrum. The authors of Ref. [12] admit that this is not always possible, especially in the heavier superallowed decays and near closed shells, where some of the 0^+ states tend to exhibit strong deformation associated with multiparticle-multihole excitations across the shell gap. Therefore, two strategies are employed in an attempt to reduce the model dependencies.

The first method is to scale the δ_{C1} values by the square of the ratio between the theoretical and experimental 0_2^+-state energies,

$$\frac{(\Delta E)^2_{\mathrm{SM}}}{(\Delta E)^2_{\mathrm{exp.}}}. \tag{4}$$

The second method was adopted from Ref. [15], where the charge-dependent part of the effective interaction is constrained such that the coefficients of the IMME [16] are properly reproduced. It is the former of these two methods that is of particular interest to the work presented here, since it requires accurate experimental information regarding the 0_2^+ state energy.

Previous superallowed β-decay branching ratio measurements [17–20] have suggested that the shell-model δ_{C1} calculations [12,13] may overpredict the nonanalog β-decay branching ratios to some of these excited 0^+ states. One of the most heavily studied cases for testing ISB calculations in recent years is that of ^{62}Ga [18,21–24], which has a fractional uncertainty of <0.05% for its experimental *ft* value [1], approaching the precision of the best cases in the *sd* shell [25]. In particular, the measurements of Ref. [18] suggested significantly smaller nonanalog Fermi branches to the low-lying 0^+ states of ^{62}Zn than predicted by theory. However, if a 0^+ state in the daughter nucleus is misidentified, conclusions regarding the isospin-mixing corrections from these data will be incorrect. Since final-state J^π information is often inconclusive from β-decay data (due to the nonexclusivity of the selection rules for β and γ decay), a direct characterization of these states is required to remove ambiguities associated with these measurements.

One of the most conclusive ways to locate excited 0^+ states in nuclei is through two-neutron transfer reactions. The angular distributions for $L = 0$ transfers from such experiments are very distinctive, and typically the strongest transition is ground-state-to-ground state, due to the significant pairing component of the Hamiltonian. However, excited 0^+ states can also be observed in these reactions, even if the cross sections are several orders of magnitude smaller than that of the ground state. Therefore, a ^{64}Zn(p,t) experiment was performed to locate excited 0^+ states in ^{62}Zn and to determine their excitation energies more accurately.

The experiment was performed at the Maier-Leibnitz-Laboratorium (MLL) of Ludwig-Maximilians-Universität (LMU) and Technische Universität München (TUM) in Garching, Germany. A ~1-μA beam of protons was accelerated to 24 MeV using the MP tandem Van de Graaff accelerator and was incident on a 99.3(1)% isotopically pure, ~120 μg/cm^2 ^{64}Zn target with a 13 μg/cm^2 carbon backing. The reaction products were momentum analyzed using a Q3D magnetic spectrograph, and the resulting particles were detected at the focal plane using a cathode-strip detector [26]. Outgoing tritons were observed at nine angles between 10° and 60°, up to an excitation energy in ^{62}Zn of 5.4 MeV, using eight primary momentum settings of the Q3D. A 0° Faraday cup inside the target chamber was used to determine the number of beam particles incident on the ^{64}Zn target by integrating the total current. Using this information, cross sections were calculated and angular distributions were extracted.

An examination of the peak position as a function of angle was also performed to eliminate possible reactions products from isotopic and other similar-mass impurities within the target. For the < 1% isotopic target impurities of ^{68,66}Zn, the

TABLE I. Excitation energies of the observed 0^+ states in ^{62}Zn from this work compared to previous data and the shell-model states up to 5 MeV. All listed energies are in keV.

Experiment		Theory		
Ref. [27]	This work	MSDI3	GXPF1	GXPF1A
g.s.	g.s.	g.s.	g.s.	g.s.
2341.95(23)		2263	2320	2094
		2874		2811
3042.9(8)	3045.5(4)	3071		3457
	3862(2)	3513	3706	3682
4008.4(7)	3936(6)	3833		3991
				4444
4620(20)	4552(9)	4551	4729	4643

reaction Q-value differences put the g.s. transfers into ^{66,64}Zn below channel 0 and were therefore outside the observed momentum range. A search for excited states populated in these reactions was also performed, and as expected, none were observed.

The focal-plane position spectra of the tritons were calibrated to ^{62}Zn excitation energy using well-known states from the evaluated data [27]. A second-degree polynomial fit was performed to determine the nonlinearity of the Q3D focal plane as a function of outgoing triton energy. Due the lack of known states above 3.8 MeV, an expression for the linear and quadratic parameter-value dependance as a function of triton energy was determined, and the fit parameters were extrapolated in regions where calibration peaks were not available.

The identification of the 0^+ states was performed through a comparison of the extracted angular-distribution data to two-nucleon-transfer reaction calculations performed using the coupled-channel, finite-range distorted-wave Born Approximation (DWBA) software FRESCO [28]. The calculations were performed using the globally determined proton and triton optical-model parameters of CH-89 [29] and Li *et al.* [30], respectively. The proton parameters remained constant for all calculations, with the triton values calculated as a function of outgoing triton energy. The final-state wave functions used in the calculations were extracted from shell-model two-nucleon-amplitude (tna) files, performed using the GXPF1A effective interaction [31] in the full pf model space. Despite the very different microscopic makeup of the generated wave functions for each state (with contributions spread amongst the $p_{1/2}$, $p_{3/2}$, $f_{5/2}$, and $f_{7/2}$ orbitals), the general shape of the angular distributions for $L = 0$ transfers remained very constant, with only a change in the overall magnitude. As a result, the primary feature used for identification of the observed 0^+ states was a characteristic increasing cross section at forward angles (Fig. 1), which distinguished the angular distributions from other L transfers.

Subsequently, four excited 0^+ states were identified in ^{62}Zn, at excitation energies of 3045.5(4), 3862(2), 3936(6), and 4552(9) keV. These states are listed in Table I along with energies from the evaluated data in Ref. [27]. The most notable omission from this list of observed states is a previously assigned 0_2^+ state at 2341.95(23) keV [18,21,32], which does not display a characteristic $L = 0$ angular distribution (Fig. 2). In fact, the peak corresponding to the 2342-keV level displays an $L = 2$ characteristic, and the level is reassigned as a 2^+ state. This assignment may be consistent with the previous 27.5-MeV (p,t) data presented in Ref. [33], where a 2.34-MeV state could not be assigned but appeared to show an $L = 2$ signature. Conversely, $\gamma\gamma$ angular-correlation data from (^{3}He,$2n\gamma$) work [32] leads to a 0^+ assignment, which disagrees with the work presented here. Table I also lists the excitation energies obtained in three different shell-model calculations. The effective interaction MSDI3 is the surface-δ interaction from Ref. [34], and GXPF1 is from Ref. [35] but with the single-particle energies fitted to the ^{57}Ni spectra for use in the present model space. Both interactions use a ^{56}Ni closed-shell core and six nucleons distributed over the $f_{5/2}$, $p_{3/2}$, and $p_{1/2}$ orbitals. The GXPF1A energies arise from the same calculations used to generate the tna files, as previously described.

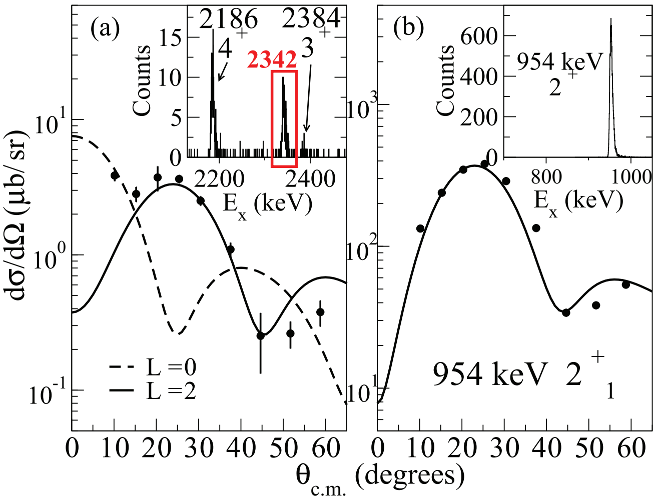

FIG. 2. (Color online) (a) Experimental angular-distribution data for the 2342-keV state, shown with calculated DWBA prediction for $L = 0$ and $L = 2$ transfers. With the exception of the 10° cross section, the 2342-keV state exhibits a nearly identical angular-distribution shape to the well-known 954-keV 2_1^+ state, shown in panel (b) for comparison. The focal-plane position spectrum region of interest for the respective states at 30° are displayed as an inset in the top right corner, where the listed energies are in keV. The assignment of the 2342-keV state is discussed further in the text.

Since the assignments for the 2342-keV level of 2^+ from the present data and 0^+ from the (^{3}He,$2n\gamma$) data, appear firm, it can be questioned if there exists a doublet of states at this energy. To explore this, a two-component fit with $L = 0$ and $L = 2$ to the 2342-keV angular-distribution data was performed. While a slight improvement in the agreement with the data was found, the presence of an $L = 0$ contribution is predicated solely on the 10° datum. Furthermore, the observed angular distribution has a minimum at 45°, where the $L = 0$ curve possesses a secondary maximum, in line with the other experimental 0^+ angular distributions (see Fig. 1). If a doublet of levels at 2342 keV with spin and parities of 0^+ and 2^+ were present, it would be expected that the 2^+ state would be more strongly populated in the (^{3}He,$2n\gamma$) compound-nucleus reaction, and

TABLE II. A comparison of the unscaled and scaled isospin-mixing correction terms for ^{62}Ga, using both the previous 0_2^+ excitation energy from Ref. [27] and the value presented here. The result of the new energy scaling lowers the δ_{C1} central value by nearly a factor of two. The adopted values in each case are shown in bold and result from the average of the MSDI3 and GXPF1 calculations. The uncertainties used for the adopted values are described further in the text.

Shell model		Unscaled		Ref. [27]	Previous scaling		This work	New scaling	
Interaction	$E_x(0_2^+)$ (MeV)	δ_{C1}^1 (%)	δ_{C1} (%)	$E_x(0_2^+)$ (MeV)	δ_{C1}^1 (%)	δ_{C1} (%)	$E_x(0_2^+)$ (MeV)	δ_{C1}^1 (%)	δ_{C1} (%)
MSDI3	2.263	0.089	0.350	2.342	0.084	0.329	3.045	0.049	0.193
GXPF1	2.320	0.160	0.221		0.159	0.219		0.093	0.128
		Adopted value			**0.120(40)**	**0.275(55)**		**0.070(35)**	**0.160(70)**

the 0^+ to be more strongly populated in the (p,t) reaction. Thus, while the disagreement with the previous assignment cannot be explained, the hypothesis of a doublet of levels at 2342 keV seems implausible. However, due to the importance of this state for isospin mixing effects in the ^{62}Ga superallowed β-decay system, further experimental work is recommended.

A tentatively assigned 0^+ state at 3042 keV reported in previous superallowed β-decay work [18,21] was also observed in this work, and displayed a characteristic $L = 0$ angular distribution. With the 2^+ assignment of the 2342-keV state, the confirmation of the 3042-keV level as a 0^+ state consequently reassigns it as the first excited 0^+ state. Following this state, previous (p,t) work in Refs. [33,36] report 0^+ states at 4000(10) keV and 3980(20) keV, respectively. It is suggested that these states are the same, and correspond to the state identified at 3936(6) keV in this work.

The highest-lying 0^+ state observed in this work, at 4552(9) keV, likely corresponds to the previously observed 4620(20) keV state in Ref. [33]. A higher lying 0^+ state at 5240(20) keV is reported in the evaluated data; however, the original paper [36] does not show an angular distribution. There is no evidence here to support the assignment of this state; however, it should be noted that the previous (p,t) work was performed using 35-MeV protons [36], and the shape of the angular distributions for the two reactions may be substantially different. Additionally, the observed 0^+ state at 3862 keV is not reported in the literature and is therefore assumed to be new, and subsequently assigned as the 0_3^+ state. All other structure information from this experiment is reported in Ref. [37], including the population of 62 additional states.

Of the observed 0^+ states outlined above, the largest impact to the ISB correction for ^{62}Ga superallowed decay arises from the ~700-keV shift in the ^{62}Zn 0_2^+ excitation energy resulting from the reassignment of the 2342-keV state as 2^+. This change in excitation energy results in a significant shift of the δ_{C1} energy scaling employed by Towner and Hardy [12]. A comparison of this scaling to both the unscaled values and previously scaled values for the ^{62}Ga δ_{C1} correction are given in Table II. When this scaling is applied to both δ_{C1}^1 and δ_{C1}, it lowers both values by nearly a factor of two. The uncertainties on the adopted values consist of (i) the uncertainty that accounts for the choice of effective interaction, equal to half the spread between the MSDI3 and GXPF1 calculations, and (ii) the uncertainty due to the energy scaling, chosen to be half the spread between the unscaled result and the scaled result. The adopted uncertainty that results from this prescription is shown in Table II.

Since the δ_{C1} correction term can be probed directly through observations of nonanalog branches in the β decay of ^{62}Ga, a comparison to previous experimental data can be made. The most stringent constraints placed on the branching ratio to the 3.04-MeV state come from the high-precision β-decay measurements in Ref. [18]. In that work, an upper limit on the branching ratio to this state of 12(5) ppm is reported, which, when combined with the ratio of the phase-space integrals [as described in Eq. (3)], yields an upper limit on δ_{C1}^1 of $\leqslant 0.011(4)\%$. The prediction for δ_{C1}^1 of 0.070(35)% (see Table II) remains significantly higher than the experimental upper limit, but is obviously in better agreement than with the previous energy scaling, which was based on the assumption that the 2342-keV state was the first excited 0^+ state.

For the case of ^{62}Ga, the nonanalog decay strength to the first excited state is not predicted as the largest contributor to δ_{C1} in the MSDI3 interaction, but rather the decay to the third excited 0^+ state, which is calculated to be at 3.04 MeV, as reported in Refs. [12,13]. If the isospin-mixing effects are subsequently shifted up in ^{62}Zn excitation energy, as is suggested by the current work, the MSDI3 shell-model 0_4^+ state may correspond to a 0^+ state at ~3.7- to 3.8-MeV excitation energy, which would contain the large calculated δ_{C1}^3 strength. Experimentally, no candidates for such high-lying nonanalog strength were observed in Ref. [18]; however, with the ^{62}Zn 0^+-state excitation-energy information now included from the work presented here, future measurements may be able to provide improved limits on other possible nonanalog β-decay branches of ^{62}Ga.

In summary, a 24-MeV ^{64}Zn$(p,t)^{62}$Zn experiment was performed to search for excited 0^+ states in the superallowed β-decay daughter nucleus of ^{62}Ga. Four excited 0^+ states were observed in ^{62}Zn, at 3045.5(4), 3862(2), 3936(6), and 4552(9) keV. The angular distribution for a previously assigned 0^+ state at 2342 keV displays good agreement with a calculated $L = 2$ distribution and is therefore reassigned as a 2^+ state. The first excited 0^+ state observed in this work at 3046 keV confirms a tentative 0^+ assignment of a state at 3042 keV reported in previous superallowed β-decay work, and with the reassignment of the 2342-keV state, becomes the first excited 0^+ state. This result changes the energy scaling for the ^{62}Ga isospin-mixing correction and lowers the δ^1_{C1} and δ_{C1} values by nearly a factor of two. This improves the agreement with experimental determinations of δ^1_{C1} from high-precision superallowed β-decay experiments, although the theoretical δ_{C1} corrections do continue to exceed the experimental upper limit.

This work was supported in part by the Natural Sciences and Engineering Research Council of Canada, the Ontario Ministry of Economic Development and Innovation, the DFG Cluster of Excellence "Origin and Structure of the Universe," and NSF Grant No. PHY-1068217. The authors thank the MLL operation staff and J. Loranger for their participation in the experiment.

---

[1] J. C. Hardy and I. S. Towner, Phys. Rev. C **79**, 055502 (2009).
[2] I. S. Towner and J. C. Hardy, Rep. Prog. Phys. **73**, 046301 (2010).
[3] W. J. Marciano and A. Sirlin, Phys. Rev. Lett. **96**, 032002 (2006).
[4] G. A. Miller and A. Schwenk, Phys. Rev. C **78**, 035501 (2008); **80**, 064319 (2009).
[5] A. Çalik, M. Gerçeklioğlu, and D. I. Salamov, Z. Naturforsch. A **64**, 865 (2009).
[6] W. Satula, J. Dobaczewski, W. Nazarewicz, and M. Rafalski, Phys. Rev. Lett. **103**, 012502 (2009); **106**, 132502 (2011); W. Satula, J. Dobaczewski, W. Nazarewicz, and T. R. Werner, Phys. Rev. C **86**, 054316 (2012).
[7] H. Liang, N. V. Giai, and J. Meng, Phys. Rev. C **79**, 064316 (2009).
[8] N. Auerbach, Phys. Rev. C **79**, 035502 (2009).
[9] V. Rodin, arXiv:1206.0491[nucl-th].
[10] G. F. Grinyer, C. E. Svensson, and B. A. Brown, Nucl. Instrum. Methods A **622**, 236 (2010).
[11] I. S. Towner and J. C. Hardy, Phys. Rev. C **82**, 065501 (2010).
[12] I. S. Towner and J. C. Hardy, Phys. Rev. C **77**, 025501 (2008).
[13] I. S. Towner and J. C. Hardy, Phys. Rev. C **66**, 035501 (2002).
[14] E. Hagberg *et al.*, Phys. Rev. Lett. **73**, 396 (1994).
[15] W. E. Ormand and B. A. Brown, Nucl. Phys. A **440**, 274 (1985); Phys. Rev. C **52**, 2455 (1995).
[16] J. Britz, A. Pape, and M. S. Antony, Atom. Nucl. Data Tabl. **69**, 125 (1998).
[17] A. Piechaczek *et al.*, Phys. Rev. C **67**, 051305(R) (2003).
[18] P. Finlay *et al.*, Phys. Rev. C **78**, 025502 (2008).
[19] K. G. Leach *et al.*, Phys. Rev. Lett. **100**, 192504 (2008).
[20] R. Dunlop, M.Sc. thesis, University of Guelph, 2012.
[21] B. Hyland *et al.*, Phys. Rev. Lett. **97**, 102501 (2006).
[22] G. F. Grinyer *et al.*, Phys. Rev. C **77**, 015501 (2008).
[23] A. Bey *et al.*, Eur. Phys. J. A **36**, 121 (2008).
[24] K. G. Leach *et al.*, Phys. Rev. C **87**, 064306 (2013).
[25] P. Finlay *et al.*, Phys. Rev. Lett. **106**, 032501 (2011).
[26] H.-F. Wirth *et al.*, *Maier-Leibnitz-Laboratorium Jahresbericht* (2000), p. 71.
[27] A. L. Nichols, B. Singh, and J. K. Tuli, Nucl. Data Sheets **113**, 973 (2012).
[28] I. J. Thompson, FRESCO Coupled-Channel DWBA Program, Version 2.9 (unpublished).
[29] R. L. Varner *et al.*, Phys. Rep. **201**, 57 (1991).
[30] X. Li, C. Liang, and C. Cai, Nucl. Phys. A **789**, 103 (2007).
[31] M. Honma, T. Otsuka, B. A. Brown, and T. Mizusaki, Eur. Phys. J. A **25** (Suppl. 1), 499 (2005).
[32] M. Albers *et al.*, Nucl. Phys. A **847**, 180 (2010).
[33] L. C. Farwell, J. J. Kraushaar, and H. W. Baer, Nucl. Phys. A **186**, 545 (1972).
[34] J. E. Koops and P. W. M. Glaudemans, Z. Phys. A **280**, 181 (1977).
[35] M. Honma, T. Otsuka, B. A. Brown, and T. Mizusaki, Phys. Rev. C **65**, 061301(R) (2002); **69**, 034335 (2004).
[36] R. A. Hinrichs and D. M. Patterson, Phys. Rev. C **10**, 1381 (1974).
[37] K. G. Leach, Ph.D. thesis, University of Guelph, 2012.