^{26}Si excited states via one-neutron removal from a ^{27}Si radioactive ion beam

J. Chen, A. A. Chen, A. M. Amthor, D. Bazin, A. D. Becerril, A. Gade, D. Galaviz, T. Glasmacher, D. Kahl, G. Lorusso, M. Matos, C. V. Ouellet, J. Pereira, H. Schatz, K. Smith, B. Wales, D. Weisshaar, and R. G. T. Zegers

Phys. Rev. C **85**, 045809 — Published 26 April 2012

DOI: 10.1103/PhysRevC.85.045809

^{26}Si excited states via one-neutron removal from a ^{27}Si radioactive ion beam

J. Chen,[1,*] A. A. Chen,[1] A. M. Amthor,[2,3,4,†] D. Bazin,[2] A. D. Becerril,[2,3,4] A. Gade,[2,3] D. Galaviz,[2,4,‡] T. Glasmacher,[2,3] D. Kahl,[1,§] G. Lorusso,[2,3,4] M. Matos,[2,4] C. V. Ouellet,[1,¶] J. Pereira,[2,4] H. Schatz,[2,3,4] K. Smith,[2,3,4] B. Wales,[1,**] D. Weisshaar,[2] and R. G. T. Zegers[2,3,4]

[1]*Department of Physics and Astronomy, McMaster University, Hamilton, Ontario L8S 4M1, Canada*
[2]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[4]*Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, Michigan 48824, USA*

(Dated: April 17, 2012)

A study of ^{26}Si states by neutron removal from a fast radioactive beam of ^{27}Si has been performed for the first time. A beam of ^{27}Si of energy 84.3 MeV/nucleon impinged on a polypropylene foil (C_3H_6) of 180 mg/cm^2 in thickness. De-excitation γ-rays were detected with a highly-segmented germanium detector array, in coincidence with the ^{26}Si recoils, and the corresponding ^{26}Si level energies were determined. In comparing our results to two previous γ-ray spectroscopic studies of ^{26}Si level structures, we find good agreement with a recent measurement of the ^{12}C(^{16}O, $2n\gamma$)^{26}Si reaction. Our results support the use of excitation energies from that study in helping determine the important resonance energies for the thermonuclear ^{25}Al(p, γ)^{26}Si reaction rate. We do not observe a bound state at 4093 keV reported in an earlier study of the ^{24}Mg(^{3}He, $n\gamma$)^{26}Si reaction.

PACS numbers: 23.20.Lv, 26.30.-k, 25.40.Lw, 27.30.+t, 25.60.Je

I. INTRODUCTION

In classical nova explosions, the ^{25}Al(p, γ)^{26}Si reaction ($Q_p = 5513.7(5)$ keV [1]) plays an important role in the synthesis of the γ-emitter ^{26}Al, whose 1.809-MeV decay line is an ongoing target for γ-ray astronomy [2]. While massive stars are likely the main sources of the observed galactic ^{26}Al [3–5], contributions from classical novae cannot be discounted [6]. The main reaction sequence leading to the synthesis of ^{26g}Al is ^{24}Mg(p,γ)^{25}Al(β^+, ν)^{25}Mg(p,γ)^{26g}Al. However, José *et al.* [6] concluded that the ^{25}Al(p,γ)^{26}Si reaction significantly affects the final ^{26}Al yield, since ^{26}Si decays to the isomeric first-excited state of ^{26}Al, which decays to ^{26g}Mg, thus bypassing the production of ^{26g}Al.

The ^{25}Al(p,γ)^{26}Si reaction is also important in type I x-ray bursts ($T_{peak} \sim 1.5$ GK), in which the rp- and αp-process are the dominant nucleosynthesis pathways [7, 8]. Burst simulations show that ^{25}Al(p,γ)^{26}Si is active within the rp-process in the burst's ignition and convective regions [7], and furthermore the reaction has been identified as one of the strongest contributors to the energy generation as the peak temperatures in the burst are approached [9]. Lastly, bottlenecks in the reaction flow at "waiting-point" nuclei have been shown to affect the burst's light-curve structure and evolution [10]. In this context, the ^{25}Al(p,γ)^{26}Si reaction connects the waiting-point nuclei ^{22}Mg and ^{26}Si through the reaction sequence ^{22}Mg(α,p)^{25}Al(p,γ)^{26}Si(α,p)^{29}P, leading finally to the waiting point at ^{30}S, which has been suggested as an explanation for the double-peaked structure in the light-curves of certain x-ray bursts [10].

In the temperature regime characteristic of explosive hydrogen burning, the thermonuclear ^{25}Al(p,γ)^{26}Si reaction rate is dominated by contributions from isolated and narrow ^{25}Al+p resonances of ^{26}Si. Since a direct measurement of the ^{25}Al(p,γ)^{26}Si reaction is presently untenable due to insufficiently intense beams of ^{25}Al, transfer reactions and in-beam gamma-ray spectroscopic studies have been used extensively to determine indirectly the important level properties of ^{26}Si, such as resonance energies and spin-parity assignments [1, 11–25]. The rate has been re-evaluated recently [23, 26–28], and Ref. [23] in particular provides a comprehensive overview of recent experimental work and a new set of adopted ^{26}Si level energies.

Experiments using γ-ray spectroscopy have played an important role in this effort to date. The earliest such experiments were a study of the ^{24}Mg(^{3}He, $n\gamma$)^{26}Si reaction by Bell *et al.* [11], and of the ^{12}C(^{16}O, $2n\gamma$)^{26}Si reaction by Seweryniak *et al.* [20]. Excitation energies from Bell *et al.* [11] had been widely used in the energy calibration of other experiments, which determined the energies of astrophysically important resonances in the E_x~5.9-MeV region. However, some of these level energies were measured by Seweryniak *et al.* to disagree by up to ~10 standard deviations, resulting in significant changes to some of the excitation energies [27].

---

*Present address: Nuclear Engineering Division, Argonne National Laboratory, Argonne, Illinois 60439, USA
†Present address: Grand Accelerateur National d'Ions Lourds, Bd. Henri Becquerel, BP 55027, F-14076 Caen, Cedex 5, France
‡Present address: Centro de Física Nuclear da Universidade de Lisboa, Av. Prof. Gama Pinto 2, 1649-003 Lisbon, Portugal
§Present address: Center for Nuclear Study (CNS), University of Tokyo, Wako Branch at RIKEN, Wako, Saitama 351-0198, Japan
¶Present address: Department of Physics, Carleton University, Ottawa, Ontario K1S 5B6, Canada
**Present address: Department of Physics and Astronomy, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada

Furthermore, Bell *et al.* [11] discovered two states at $E_x(^{26}\mathrm{Si}) = 3842$ and 4093 keV. These states, however, were not observed in the ^{12}C(^{16}O, $2n\gamma$)^{26}Si measurement [20], which reported a ^{26}Si level scheme apparently complete up to the proton threshold, based on mirror assignments to states in ^{26}Mg.

More recently, in a new measurement of the ^{24}Mg(^{3}He, $n\gamma$)^{26}Si in which neutrons were detected in coincidence with decay γ-rays [36], a potentially important new state was found at 5888 keV via its decay cascade, which was not observed in either Ref. [20] or Ref. [11].

Thus, further studies are needed to clarify these issues, and to search for γ-ray transitions from other ^{26}Si proton-unbound states. In particular, transfer reactions involving radioactive ion beams can be helpful and have not been extensively utilized so far. To this end, we present results for the first time from a γ-ray spectroscopic study of ^{26}Si levels by neutron removal from a fast radioactive beam of ^{27}Si.

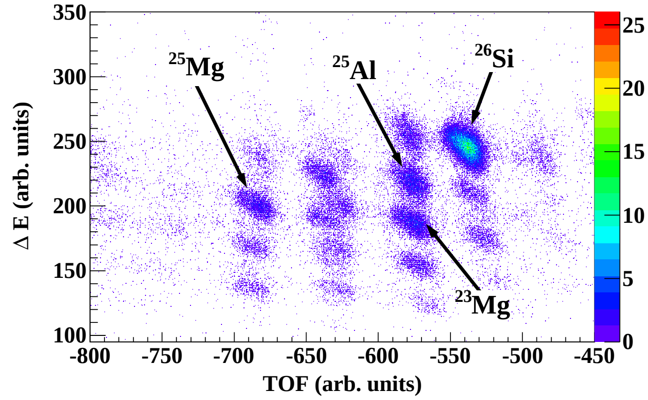

FIG. 1: (Color online) Two-dimensional histogram of ΔE vs. time-of-flight through the S800 for ions detected at the S800 focal plane, following interactions with the polypropelene target. The ^{26}Si recoils of interest and other strong particle groups are indicated.

II. EXPERIMENT DETAILS

The experiment was performed at the National Superconducting Cyclotron Laboratory, with a technique similar to that of Ref. [29]. The secondary radioactive beam of ^{27}Si ($t_{1/2}$ = 4.16 sec) was produced using the A1900 fragment separator [30] by fragmenting a 150 MeV/nucleon ^{36}Ar (q = 18+) primary beam on a 940-mg/cm^2 ^{9}Be target. The momentum acceptance was restricted to $\Delta p/p = 0.5\%$. The ^{27}Si beam had 84.3 MeV/nucleon and an intensity of $\approx 10^6$ particles/s.

Excited states in ^{26}Si were populated by neutron removal reactions on ^{26}Si in a 180-mg/cm^2 polypropylene foil serving as a secondary target, at the target position of the S800 spectrograph [31]. The ^{26}Si recoils were transported to detectors at the S800 focal plane for measurements of energy and time-of-flight (TOF). The energy losses and residual energy were measured by a 16-segment ionization chamber and a plastic scintillator, respectively. The ^{26}Si recoils were identified by their time-of-flight between a poly-crystalline diamond strip detector (upstream from the polypropylene target) and the plastic scintillator, plotted against their energy losses (ΔE) in the ionization chamber, as shown in Figure 1.

The γ-rays from the de-excitation of states in the ^{26}Si recoils were detected with the Segmented Germanium Array (SeGA) [32], which surrounded the S800 target position. SeGA comprised 17 high-purity Germanium detectors mounted in two rings at $\theta_{lab} = 37°$ (7 detectors) and 90° (10 detectors) with respect to the beam direction, and located 20 cm downstream from the target. Each detector consists of 32 segments, providing accurate measurements of the γ-ray detection points, allowing for event-by-event Doppler reconstruction of the measured energies. The in-beam energy resolution was determined to be 2% at 1796 keV after Doppler correction, while the in-beam efficiency was 2% at the same energy. The array's energy calibration was performed with known γ-ray transitions from standard ^{56}Co, ^{152}Eu and ^{226}Ra sources. Data were taken over a period of 150 hours, yielding $\sim 10^5$ ^{26}Si–γ-ray coincidence events.

III. DATA ANALYSIS

The mean midtarget ^{26}Si velocity (β) was used in the Doppler correction. This velocity was determined with an iterative Doppler-reconstruction technique in which β and the target position are adjusted in the offline analysis to align the strong 1796-keV transition with its known energy for all SeGA detection angles. A second determination of β, whose result was consistent with the first, used the mean post-target ^{26}Si momentum determined with the S800 spectrometer, combined with target energy-loss calculations. A value of β = 0.393(8) was adopted. The dominant contributions to the uncertainty in β are uncertainties in the γ emission point in the target, the energy loss calculation, and the beam energy spread. The Doppler-corrected γ-ray spectrum is shown in Figure 2.

The transition energies were determined by fitting Gaussian functions with a quadratic background to the peak profiles. The uncertainties include statistical and systematic uncertainties, added in quadrature. The latter is dominated by the uncertainty in the midtarget recoil velocity mentioned above. The transition energies are shown in Table I. For comparison, results from the γ-ray spectroscopy study of Seweryniak *et al.* [20] are also included. These are a useful benchmark for our work, since they were able to reconstruct a complete level scheme for particle-bound states in ^{26}Si, based

TABLE I: Transition energies and intensities from the present work compared with those from previous γ-ray spectroscopic studies of the ^{12}C(^{16}O, $2n\gamma$)^{26}Si [20] and ^{24}Mg(^{3}He, $n\gamma$)^{26}Si [11] reactions.

J^π	present work		Ref. [20]		Ref. [11]		Adopted	
	E_x (keV)	E_γ (keV)	E_x (keV)	E_γ (keV)	E_x (keV)	E_γ (keV)	E_x (keV)	E_γ (keV)
2_1^+	1797	1796[a]	1797.3(1)	1797.2(1)	1795.9(2)	1795.9(2)	1796.0(3)	1796.4(4)
2_2^+	2785(8)	987(4)	2786.4(2)	988.8(1)	2783.5(4)	987.0(5)	2785.8(3)	987.6(6)
		2787(13)		2785.5(3)		2784.4(10)		2785.4(3)
0_2^+	3330(3)	1533(7)[b]	3336.4(6)	1539.1(5)	3332.5(3)	1536.6(2)	3332.8(4)	1536.7(2)
3_1^+	3753(8)	968(4)	3756.9(2)	970.4(1)	3756(2)	971(3)	3756.2(3)	970.4(1)
		1959(9)		1960.4(2)		1963(4)		1960.4(2)
$4_1^{(+)}$[c]					3842(2)	2046(2)	3842(2)	2046(2)
$(1,2)$[c]					4093(3)	4094(4)	4094(4)	4094(4)
2_3^+	4135(20)		4139.3(7)	1355(2)	4138(1)		4138.3(6)	1355(2)
				2341.9(6)		2342(1)		2341.9(5)
		4135(20)		4141(3)		4135(6)		4140(3)
3_2^+	4190(10)	1405(6)	4187.1(3)	1400.7(2)			4186.9(3)	1400.7(2)
				2391.4(5)				2391.4(5)
4_2^+	4444(9)	1652(8)	4446.2(4)	1657(2)	4445(3)		4445.0(4)	1656.7(19)
		2648(12)		2648.8(3)		2649(3)		2648.8(3)
4_3^+	4803(16)	3006(14)	4798.5(5)	3001.0(4)	4805(2)	3000(8)	4797.2(5)	3001.0(4)
(2_4^+)	4810(12)	2025(9)	4810.7(6)	2024.2(5)	4805(2)	2024(2)	4810.1(6)	2024.2(5)
(0_3^+)			4831.4(10)	2044.9(9)			4830.8(10)	2044.9(9)
2_5^+	5144(14)	2359(11)	5146.7(9)	2360.2(8)			5146.3(8)	2360.2(8)
				3351(2)				3351(2)
4_4^+	5284(9)	839(4)	5288.2(5)	842.1(3)			5287.2(4)	842.1(3)
		1533(7)[b]		1531.1(5)				1531.1(5)
				2503(2)				2503(2)
		3500(17)						3500(17)
4_5^+	5511(10)	1067(5)	5517.2(5)	1071.8(4)			5516.9(4)	1071.8(4)
		1334(6)		1329.4(3)				1329.4(3)
				1764.4(8)		1765(3)		1764.4(8)
				2733(3)				2733(3)
1^+	5659(22)	3862(20)	5677.0(17)	3879.4(17)			5675.7(18)	3879.3(17)

[a]used for calibration.
[b]potential doublet consisting of the 1539.1-keV and 1531.1-keV γ-ray transitions observed in Ref. [20]. The placements of this 1533-keV transition in our decay scheme follow the placements of these two γ-rays in the work of Ref. [20].
[c]from Ref. [11].

on expectations from known levels in the well-studied mirror nucleus ^{26}Mg [33] and from shell-model calculations [34]. The results from the study of Bell *et al.* [11] are also shown.

Events corresponding to γ-γ coincidences were analyzed to re-construct the cascades for our strongly populated states. The background was estimated with gates on regions near the peak in question. This information, with additional guidance from the results of Ref. [20] and the known cascades of analog states in ^{26}Mg, was used to determine the energies and spin-parity assignments of our ^{26}Si states.

IV. RESULTS AND CONCLUSIONS

Although the precision of our measured energies is lower than those of both previous studies [11, 20], our agreement with the results of Ref. [20] is good. While we did not observe the 4831.4-keV level seen by Seweryniak *et al.*, its existence is also firmly established from other studies with transfer reactions (see Ref. [17] and references therein).

Bell *et al.* reported two levels at 3842(2) keV and 4093(3) keV, with the latter observed as a transition to the ground state. Seweryniak *et al.* found no evidence for these two states, and we also did not observe the 4093-keV level. In Bell *et al.*, the level at 3842(2) keV was established from a measurement of 2046 + 1796 keV cascade, which we also did not observe. While we found a peak at 3862(20) keV with a width consistent

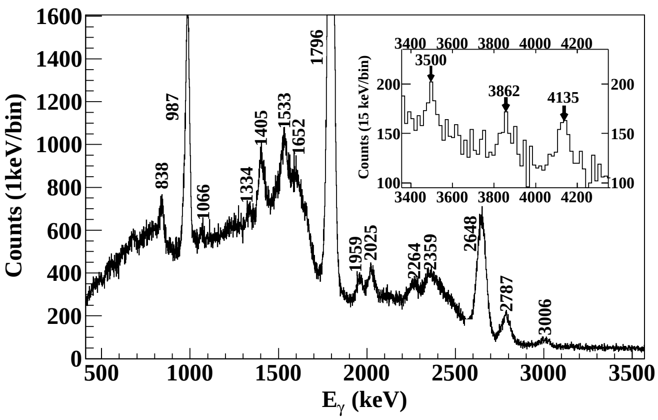

FIG. 2: Doppler corrected γ-ray spectrum. The gamma transition energies are labelled with units of keV (see text for discussion).

with that of a single transition peak, the statistics were insufficient to establish coincidence with the 1797-keV transition. We assume here that this is the case, yielding a proton-unbound state at 5659(11) keV that most likely corresponds to the 5677.0-keV level of Seweryniak *et al.* [20]. Our lower excitation energy suggests that the importance of this resonance to the ^{25}Al(p, γ)^{26}Si, which was already small [23], is reduced even further.

As mentioned earlier, a potential new level at 5888(2) keV was recently reported in a study of the ^{24}Mg(^{3}He, $n\gamma$)^{26}Si reaction by de Séréville *et al.* [36]. Its excitation energy was re-constructed from the observation of coincident γ-ray transitions of 1749(2), 3102(2) and 4091(2) keV to the bound 2^+ states at 4139, 2785 and 1797 keV, respectively. This state falls in the region of astrophysical interest, and its spin-parity assignment is unknown. Since a spin-parity assignment of 3^+ has been firmly assigned to the astrophysically important level at 5923(3) keV (weighted average of 5927(4) keV from Ref. [24] and 5921(3) keV from Ref. [27]), this new level is most likely the 0^+_4 state of ^{26}Si, as suggested by the shell-model calculation of this state's γ branchings by Richter *et al.* [28]. If so, however, this level would not have been populated in our experiment at a statistically significant level, since shell-model calculations [37] indicate a negligible spectroscopic factor for one-neutron removal from this state.

The confirmation of this new level's existence and a determination of its properties will therefore require further experiments. In addition, such experiments will help guide future direct measurements of the ^{25}Al(p, γ)^{26}Si reaction at radioactive ion beam facilities (*e.g.*, Ref. [35]), which require prior precise knowledge of the key resonance energies.

In the meantime, the present work helps clarify some remaining questions related to low-lying ^{26}Si states. Our results also support the ^{26}Si level scheme and mirror assignments derived from the ^{12}C(^{16}O, $2n\gamma$)^{26}Si study [20]; as well as the use of those excitation energies to determine the energies and properties of the important ^{26}Si states to the thermonuclear ^{25}Al(p, γ)^{26}Si reaction rate in explosive hydrogen burning.

ACKNOWLEDGEMENTS

The support of the NSCL technical staff is gratefully acknowledged. This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), and by US National Science Foundation (NSF) Grants PHY-0822648 (Joint Institute for Nuclear Astrophysics) and PHY-0606007 (National Superconducting Cyclotron Laboratory). AAC was supported in part by an Ontario Premier's Research Excellence Award (PREA) and by the DFG cluster of excellence "Origin and Structure of the Universe" (www.universe-cluster.de).

[1] T. Eronen, V.−V. Elomaa, U. Hager, J. Hakala, A. Jokinen, A. Kankainen, T. Kessler, I. D. Moore, S. Rahaman, J. Rissanen *et al.*, Phys. Rev. C **79**, 032802(R) (2009).
[2] R. Diehl, C. Dupraz, K. Bennett, H. Bloemen, W. Hermsen, J. Knödlseder, G. Lichti, D. Morris, J. Ryan, V. Schoenfelder *et al.*, Astron. Astrophys. **298**, 445 (1995).
[3] J. Knödlseder, Astrophys. J. **510**, 915 (1999).
[4] R. Diehl, H. Halloin, K. Kretschmer, G. G. Lichti, V. Schönfelder, A. W. Strong, A. von Kienlin, W. Wang, P. Jean, J. Knödlseder *et al.*, Nature (London) **439**, 45 (2006).
[5] C. Iliadis, A. E. Champagne, A. Chieffi, and M. Limongi, Astrophys. J. Suppl. Ser. **193**, 16 (2011).
[6] J. José, A. Coc, and M. Hernanz, Astrophys. J. **520**, 347 (1999).
[7] J. L. Fisker, H. Schatz, and F.−K. Thielemann, Astrophys. J. Suppl. Ser. **174**, 261 (2008).
[8] A. Parikh, J. José, F, Moreno, and C. Iliadis, Astrophys. J. Suppl. Ser. **178**, 110 (2008).
[9] J. José, F. Moreno, A. Parikh, and C. Iliadis, Astrophys. J. Suppl. Ser. **189**, 204 (2010).
[10] J. L. Fisker, F.−K.Thielemann, and M. Wiescher, Astrophys. J. **608**, L61 (2004).
[11] R. A. I. Bell, J. L'Ecuyer, R. D. Gill, B. C. Robertson, I. S. Towner, and H. J. Rose, Nucl. Phys. A **133**, 337 (1969).
[12] R. A. Paddock, Phys. Rev. C **5**, 485 (1972).
[13] W. Bohne *et al.*, Nucl. Phys. A **378**, 525 (1982).
[14] D. W. Bardayan, J. C. Blackmon, A. E. Champagne, A. K. Drummer, T. Davinson, U. Greife, D. Hill, C. Iliadis,

B. A. Johnson, R. L. Kozub *et al.*, Phys. Rev. C **65**, 032801(R) (2002).

[15] J. A. Caggiano, W. Bradfield-Smith, R. Lewis, P. D. Parker, D. W. Visser, J. P. Greene, K. E. Rehm, D. W. Bardayan, and A. E. Champagne, Phys. Rev. C **65**, 055801 (2002).

[16] J. -C. Thomas, L. Achouri, J. Äystö, R. Béraud, B. Blank, G. Canchel, S. Czajkowski, P. Dendooven, A. Ensallem, J. Giovinazzo *et al.*, Eur. Phys. J. A **21**, 419 (2004).

[17] Y. Parpottas, S. M. Grimes, S. Al-Quraishi, C. R. Brune, T. N. Massey, J. E. Oldendick, A. Salas, and R. T. Wheeler, Phys. Rev. C **70**, 065805 (2004).

[18] A. Parikh, J. A. Caggiano, C. Deibel, J. P. Greene, R. Lewis, P. D. Parker, and C. Wrede, Phys. Rev. C **71**, 055804 (2005).

[19] D. W. Bardayan, J. A. Howard, J. C. Blackmon, C. R. Brune, K. Y. Chae, W. R. Hix, M. S. Johnson, K. L. Jones, R. L. Kozub, J. F. Liang *et al.*, Phys. Rev. C **74**, 045804 (2006).

[20] D. Seweryniak, P. J. Woods, M. P. Carpenter, T. Davinson, R. V. Janssens, D. G. Jenkins, T. Lauritsen, C. J. Lister, J. Shergur, S. Sinha *et al.*, Phys. Rev. C **75**, 062801(R) (2007).

[21] Y. K. Kwon, C. S. Lee, J. Y. Moon, J. H. Lee, J. Y. Kim, M. K. Cheoun, S. Kubono, N. Iwasa, K. Inafuku, H. Yamaguchi *et al.*, J. Korean Phys. Soc. **53**, 1141 (2008).

[22] P. N. Peplowski, L. T. Baby, I. Wiedenhöver, S. E. Dekat, E. Diffenderfer, D. L. Gay, O. Grubor-Urosevic, P. Höflich, R. A. Kaye, N. Keeley *et al.*, Phys. Rev. C **79**, 032801(R) (2009).

[23] A. Matic, A. M. van den Berg, M. N. Harakeh, H. J. Wörtche, G. P. A. Berg, M. Couder, J. Görres, P. LeBlanc, S. O'Brien, M. Wiescher *et al.*, Phys. Rev. C **82**, 025807 (2010).

[24] K. A. Chipps, D. W. Bardayan, K. Y. Chae, J. A. Cizewski, R. L. Kozub, J. F. Liang, C. Matei, B. H. Moazen, C. D. Nesaraja, P. D. O'Malley *et al.*, Phys. Rev. C **82**, 045803 (2010).

[25] J. Chen, A. A. Chen, G. Amádio, S. Cherubini, H. Fujikawa, S. Hayakawa, J. J. He, N. Iwasa, D. Kahl, L. H. Khiem *et al.*, Phys. Rev. C **85**, 015805 (2012).

[26] C. Iliadis, R. Longland, A. E. Champagne, A. Coc, and R. Fitzgerald, Nucl. Phys. A **378**, 31 (2010).

[27] C. Wrede, Phys. Rev. C **79**, 035803 (2009).

[28] W. A. Richter, B. A. Brown, A. Signoracci, and M. Wiescher, Phys. Rev. C **83**, 065803 (2011).

[29] R. R. C. Clement, D. Bazin, W. Benenson, B. A. Brown, A. L. Cole, M. W. Cooper, P. A. DeYoung, A. Estrade, M. A. Famiano, N. H. Frank *et al.*, Phys. Rev. Lett. **92**, 172502 (2004).

[30] D. J. Morrissey, B. M. Sherrill, M. Steiner, A. Stolz, and I. Wiedenhoever, Nucl. Instrum. Methods Phys. Res. Sect. B **204**, 90 (2003).

[31] D. Bazin, J. A. Caggiano, B. M. Sherrill, J. Yurkon, and A. Zeller, Nucl. Instrum. Methods Phys. Res. Sect. B **204**, 629 (2003).

[32] W. F. Mueller, J. A. Church, T. Glasmacher, D. Gutknecht, G. Hackman, P. G. Hansen, Z. Hua, K. L. Miller, and P. Quirin, Nucl. Instrum. Methods Phys. Res. Sect. A **466**, 492 (2001).

[33] http://www.nndc.bnl.gov/nudat2/

[34] C. Iliadis, L. Buchmann, P. M. Endt, H. Herndl, and M. Wiescher, Phys. Rev. C **53**, 475 (1996).

[35] A. A. Chen *et al.*, TRIUMF EEC Letter of Intent (unpublished) (2011).

[36] N. de Séréville, M. Assié, I. Bahrini, D. Beaumel, M. Chabot, M. Ferraton, S. Fortier, S. Franchoo, S. Giron, F. Hammache *et al.*, PoS (**NIC XI**) 212 (2011).

[37] A. Signoracci and B. Alex Brown, private communication.