Inverse Kinematic Study of the ^{26g}Al$(d,p)^{27}$Al Reaction and Implications for Destruction of ^{26}Al in Wolf-Rayet and Asymptotic Giant Branch Stars

V. Margerin,[1] G. Lotay,[1,2,3,*] P. J. Woods,[1] M. Aliotta,[1] G. Christian,[4] B. Davids,[4] T. Davinson,[1] D. T. Doherty,[1,†] J. Fallis,[4] D. Howell,[4] O. S. Kirsebom,[4,‡] D. J. Mountford,[1] A. Rojas,[4] C. Ruiz,[4] and J. A. Tostevin[2]

[1]*School of Physics and Astronomy, University of Edinburgh, Edinburgh, EH9 3FD, United Kingdom*

[2]*Department of Physics, University of Surrey, Guildford GU2 7XH, United Kingdom*

[3]*National Physical Laboratory, Teddington, Middlesex TW11 0LW, United Kingdom*

[4]*TRIUMF, Vancouver, British Columbia V6T 2A3, Canada*

(Received 27 March 2015; published 5 August 2015)

In Wolf-Rayet and asymptotic giant branch (AGB) stars, the ^{26g}Al$(p,\gamma)^{27}$Si reaction is expected to govern the destruction of the cosmic γ-ray emitting nucleus ^{26}Al. The rate of this reaction, however, is highly uncertain due to the unknown properties of key resonances in the temperature regime of hydrogen burning. We present a high-resolution inverse kinematic study of the ^{26g}Al$(d,p)^{27}$Al reaction as a method for constraining the strengths of key astrophysical resonances in the ^{26g}Al$(p,\gamma)^{27}$Si reaction. In particular, the results indicate that the resonance at $E_r = 127$ keV in ^{27}Si determines the entire ^{26g}Al$(p,\gamma)^{27}$Si reaction rate over almost the complete temperature range of Wolf-Rayet stars and AGB stars.

DOI: 10.1103/PhysRevLett.115.062701 PACS numbers: 25.60.-t, 25.45.Hi, 26.20.Np

Observations of cosmic γ rays throughout the interstellar medium (ISM) by the latest generation of space-based telescopes have provided new insights into astrophysical processes occurring during the life cycles of stars [1–3]. A first key milestone was the detection by the HEAO-3 satellite of a diffuse γ-ray line in the equatorial plane of the Galaxy at 1.809 MeV, associated with the ground-state decay of ^{26g}Al $(t_{1/2} \sim 7.2 \times 10^5$ yr) [4], which showed nucleosynthesis is an ongoing process in the Milky Way. However, because of the poor angular resolution and sensitivity of the instrument, no spatial information on the source of the 1.809 MeV emission line could be obtained [4]. More recently, the COMPTEL and INTEGRAL satellite missions have been able to measure the distribution of the ^{26g}Al cosmic γ-ray line across the Milky Way [5–7]. Those studies measured overall abundances of ^{26}Al and reported irregular emission across the Galactic plane, indicating that ^{26}Al source regions corotate with the Galaxy, pointing to high-mass progenitors as the favored production sites. In particular, it is expected that Galactic ^{26}Al is produced predominantly either during the hydrogen burning phase of massive Wolf-Rayet (WR) stars that pollute the ISM with the products of hydrogen burning, via a strong stellar wind, or their resulting core collapse supernova phase [5]. Additional contributions to the observed Galactic abundance have been suggested to come from asymptotic giant branch (AGB) stars and classical novae [8,9]. The existence of radioactive ^{26}Al in the Galaxy may also be traced through excesses of its daughter nucleus ^{26}Mg in meteoritic material. Excesses of ^{26}Mg were found in calcium and aluminum inclusions of the Allende meteorite, inferring a relatively large ^{26}Al:^{27}Al ratio present in the Solar System at the time of its formation [10]. A much-debated question relates to the origin of ^{26}Al in the early Solar System [11]. It has been suggested that energy released by *in situ* decay of ^{26}Al in protoplanetary disks orbiting young stars may cause melting of icy planetesimals, thereby influencing the conditions required of planetary systems to support life [12].

Key uncertainties relate to the nuclear reaction rates responsible for the production and destruction of ^{26}Al in stellar environments [13,14]. In the case of hydrogen burning scenarios such as Wolf-Rayet stars and AGB stars, it is the uncertainties in the ^{26g}Al$(p,\gamma)^{27}$Si destruction reaction that dominate. A recent sensitivity study by Parikh *et al.* [15] has considered the importance of these uncertainties and has drawn attention to the need for experimental constraints on the rate of the ^{26g}Al$(p,\gamma)^{27}$Si reaction. However, difficulty primarily arises in this regard because ^{26}Al is radioactive. Direct (p,γ) measurements of a resonance at 189 keV have been made using both a radioactive target of ^{26}Al [16] and a radioactive ion beam of ^{26}Al [17], reporting resonance strengths of 55(9) and 35(7) μeV, respectively. More recent spectroscopic studies of ^{27}Si indicate that a lower-energy s-wave resonance at 127 keV could play the dominant role in the destruction of ^{26}Al in Wolf-Rayet stars and AGB stars, where burning occurs at relatively low temperatures in the Gamow peak ($T \sim 0.03$–0.10 GK) [18]. However, direct measurements of the reaction at this lower energy are not practicable with presently available ^{26}Al beam intensities, due to the rapid reduction in the cross section with beam energy below the Coulomb barrier, and an indirect approach is mandated to estimate the resonance strength. In earlier work, Vogelaar *et al.* [19] used a radioactive target of ^{26}Al to perform a ^{26}Al$(^3$He$,d)^{27}$Si transfer reaction study. However, there were large impurities of ^{27}Al ($> 90\%$) in the target, and only an upper limit of 0.002 could be placed on the proton spectroscopic factor C^2S for the 7590 keV excited state of ^{27}Si corresponding to the 127 keV resonance [19].

In a recent paper by Parikh *et al.* [15], the effect of a range of possible strengths from 0 to 1 μeV (which would correspond to an almost pure single particle state) for the 127 keV resonance on ^{26}Al nucleosynthesis was considered. By using the complete range of values for the 127 keV $^{26g}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$ destruction resonance, Parikh *et al.* found variations in the synthesized abundance of ^{26}Al in AGB stars by up to a factor of 6, as well as even up to 40% in novae, which are relatively high-temperature astrophysical environments ($T = 0.1$–0.4 GK). Furthermore, an additional sensitivity study of the effect of the $^{26g}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$ reaction rate variations for $T < 0.05$ GK by Iliadis *et al.* [14] found that an increase in the rate by a factor of 100, corresponding to a 127 keV resonance strength of ~ 1 μeV, would result in a reduction in the amount of ^{26}Al synthesized by a factor of ~ 300. In this Letter, we present a method for experimentally constraining the largely uncertain strength of the 127 keV resonance by performing a high-resolution study of the $^{26g}\mathrm{Al}(d,p)^{27}\mathrm{Al}$ transfer reaction in inverse kinematics. By determining the neutron spectroscopic factor for the analog state in ^{27}Al, we conclude the 127 keV resonance will dominate the $^{26g}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$ destruction reaction rate at burning temperatures for Wolf-Rayet and AGB stars.

The measurement was carried out using the TUDA silicon strip detector reaction chamber [20] at the ISAC-II radioactive beams facility at TRIUMF. An intense ~ 1 pnA radioactive ion beam of ^{26}Al produced by impinging 500 MeV protons on a SiC target was accelerated to 6 MeV/u and used to bombard an ~ 50 $\mu\mathrm{g/cm}^2$ thick $(\mathrm{CD}_2)_n$ target for 108 hr, in order to populate excited states in the nucleus ^{27}Al via the $^{26}\mathrm{Al}(d,p)$ transfer reaction. Based on β-decay measurements, the relative ground state to isomeric state composition of the ^{26}Al beam was found to be $\sim 17000:1$. Consequently, the population of excited states in ^{27}Al by the isomeric component of the beam is expected to be negligible. In this study, TUDA was specially configured to give ultrahigh-resolution performance at backward angles [forward angles in the center of mass (c.m.)] where low-ℓ ($\ell \leq 2$) transfers of astrophysical interest peak—high resolution is mandated because of the relatively high level density at excitation energies ~ 7–8 MeV. As such, two Micron Semiconductor Ltd S2-type silicon strip detectors of ~ 500 μm thickness [21] segmented into 48 annular strips and 16 rear sectors were placed upstream of the target position at distances of ~ 21 and ~ 75 cm, respectively, covering an angular range in the center of mass of $\theta_{\mathrm{c.m.}} \sim 0.5°$–$12°$. This results in an excitation energy resolution (~ 40 keV FWHM; see Fig. 1) representing state-of-the-art performance for inverse transfer reaction studies with radioactive beams. Here, the excitation energy resolution is dominated by the effects of the target thickness and the transverse emittance of the beam. Typical $(\mathrm{CD}_2)_n$ target thicknesses of 57(9) $\mu\mathrm{g/cm}^2$ were used for this study. An initial thickness for each target was determined by comparing the measured energy loss of α particles from a triple-α source with SRIM energy loss calculations [22]. The deuterium content of the target was then closely monitored by regularly checking the ratio of the beam current recorded in an electrically suppressed Faraday cup to the intensity recorded in the S2 detectors of the most strongly populated excited state in ^{27}Al at 3004 keV (see Fig. 1). Typically, each target was used for ~ 25 hr and replaced once there was a reduction to $\sim 1/3$ of its initial deuterium content. This procedure provided an absolute normalization from which cross-section measurements could be obtained, where errors relating to beam intensity and deuterium content degradation contribute $\sim 5\%$ each to the overall normalization uncertainty. Finally, an energy calibration was performed by fitting observed proton peaks to well-known excited states in ^{27}Al at 3004.2(8), 4510.3(5), 5499.8(8), 5667.3(12), 6512.2(11), and 6947.9(19) keV [23], while spectroscopic factors C^2S were extracted from the relationship between the measured differential cross section and those obtained from adiabatic distorted-wave approximation (ADWA) calculations using the code TWOFNR [24]. The Johnson-Tandy adiabatic model deuteron distorting potential [25] was calculated using the deuteron wave function of the Argonne AV18 np interaction [26] and the Koning-Delaroche [27] global nucleon-nucleus optical potential, which is also used for the proton distortion in the final state. The radii of the potentials that bind the transferred neutron were obtained by the Hartree-Fock (HF) methodology detailed in Ref. [28], except for the (HF-unbound) $2p$-wave orbitals for which radius and diffuseness parameters of 1.25 and 0.65 fm were used. These deduced ^{27}Al spectroscopic factors were then adopted for the analog states in the mirror nucleus ^{27}Si—the C^2S of mirror analog states are expected to agree to within 20% [29,30]. The excitation energy spectrum for $E_x = 0$–8200 keV in ^{27}Al is shown in Fig. 1, while an expanded view of the energy region $E_x = 7700$–8200 keV is shown in Fig. 2. It is clear from Figs. 1 and 2 that excited levels in ^{27}Al corresponding to low-ℓ transfers on the 5^+ ground state of ^{26}Al are highly selectively populated by the (d,p) transfer mechanism, highlighting its suitability for studying mirror states of astrophysical importance. In this Letter, we will focus on those states that are of critical importance for the astrophysical $^{26g}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$ reaction rate in WR and AGB stars; a detailed study of all states populated in the $^{26}\mathrm{Al}(d,p)$ transfer reaction will be reported later in a full paper.

Figure 3(a) shows the angular distribution for the most strongly populated $9/2^+$ state at 3004(2) keV in ^{27}Al which is predicted to be a relatively pure shell model

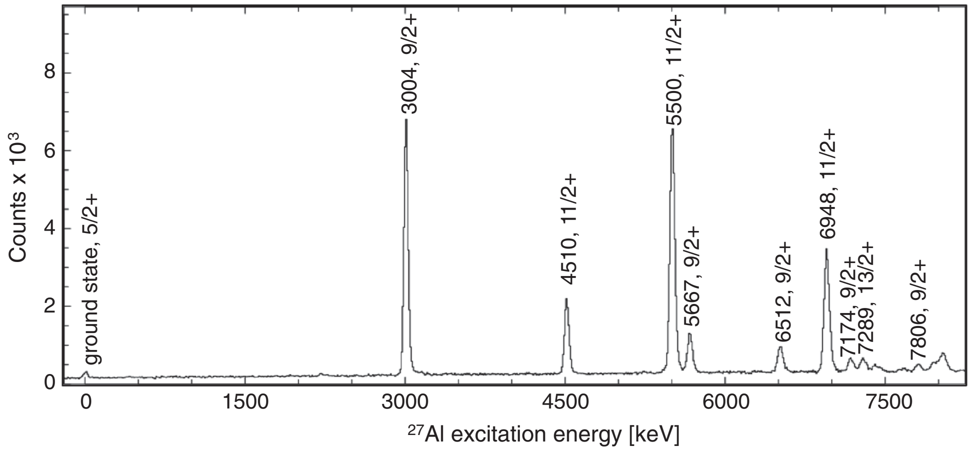

FIG. 1. Excitation energy spectrum of ^{27}Al obtained from the ^{26g}Al(d,p) transfer reaction at $\theta_{\mathrm{c.m.}} \sim 0.5°$–$12°$. Fusion-evaporated protons from reactions on carbon in the target produce a continuous background distribution. This is subtracted in the determination of cross sections.

configuration dominated by $\ell = 0$ transfer [31]. This distribution is, indeed, well reproduced by the ADWA calculation with pure $\ell = 0$ transfer and a high spectroscopic factor, $C^2S = 0.49(2)$. Figure 3(b) shows the angular distribution for the $9/2^+$ 7806(3) keV state, which corresponds to the mirror analog of the 127 keV resonance at an excitation energy of 7590 keV in ^{27}Si [18]. From comparison with TWOFNR calculations, it is evident that the most forward angle component is predominantly $\ell = 0$ transfer, while an additional $\ell = 2$ component is required in order to accurately reproduce the full distribution at less forward angles. A best fit is obtained combining $\ell = 0$ and 2 transfers with C^2S $(\ell = 0)$ of $9.3(19) \times 10^{-3}$ and C^2S $(\ell = 2)$ of $6.8(14) \times 10^{-2}$ for the 7806 keV state (errors quoted on spectroscopic factors represent experimental uncertainties). This is significantly higher than the upper limit of 2.2×10^{-3} [19] for $\ell = 0$ proton capture to the 7590 resonant state in ^{27}Si in the ^{26}Al$(^3\mathrm{He}, d)^{27}$Si study of Vogelaar *et al.* [19]. However, we note that Parikh *et al.* [15] point out that the experimental limit of C^2S $(\ell = 0)$ may be compatible with values up to a maximum of $\sim 11 \times 10^{-3}$ for the 7590 keV state in ^{27}Si when the smallest scattering angle is discarded from the Vogelaar *et al.* data [19]. The present result is, therefore, within the upper range of the value suggested by Parikh *et al.* [15], and using a C^2S $(\ell = 0)$ of $9.3(19) \times 10^{-3}$ implies a strength of 0.025(5) μeV for the 127 keV resonance in the ^{26g}Al$(p,\gamma)^{27}$Si reaction (the error quoted for the strength represents a statistical error; there is also an uncertainty of ~20% associated with possible differences between spectroscopic factors of analog states). It should be noted that in the energy region of interest for the 7806 keV level in ^{27}Al, there are two potential excited states at 7790.4(7) [32] and 7798(2) keV [23], which have been previously assigned as $5/2^+$ and $3/2^+$, respectively [32]. We performed a detailed fit analysis of the 7806 keV peak and looked for potential excess counts contributing to the differential cross section around the energy region 7790 and 7798 keV. We found that the peak was entirely consistent with a single-state structure at an energy of 7806(3) keV, in agreement with the value of 7807.2(10) keV reported in the γ-ray spectroscopy study of ^{27}Al by Lotay *et al.* [32]. This indicates there is no significant contribution to the observed differential cross section for the 7806 keV state from these two neighboring excited levels. The 7790 keV state in ^{27}Al has been assigned to a mirror analog in ^{27}Si, corresponding to a $5/2^+$ resonance at 68 keV in the ^{26g}Al$(p,\gamma)^{27}$Si reaction [32]. Based on the analysis above, we set an upper limit for C^2S $(\ell = 2)$ of 1.6×10^{-2}, corresponding to a resonance strength of $\omega\gamma < 8 \times 10^{-10}$ μeV.

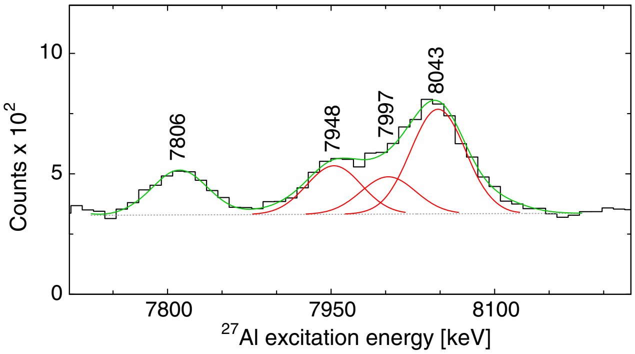

FIG. 2 (color online). Expanded view of the excitation energy spectrum showing astrophysically important mirror states in the energy region $E_x = 7700$–8200 keV. The green line shows a cumulative fit to the data. The red lines indicate the individual fits for the 7948, 7997, and 8043 keV levels with fixed peak widths, and the background is displayed by the dotted line.

Figure 4 shows the contributions of individual resonances to the ^{26g}Al$(p,\gamma)^{27}$Si stellar reaction rate, incorporating

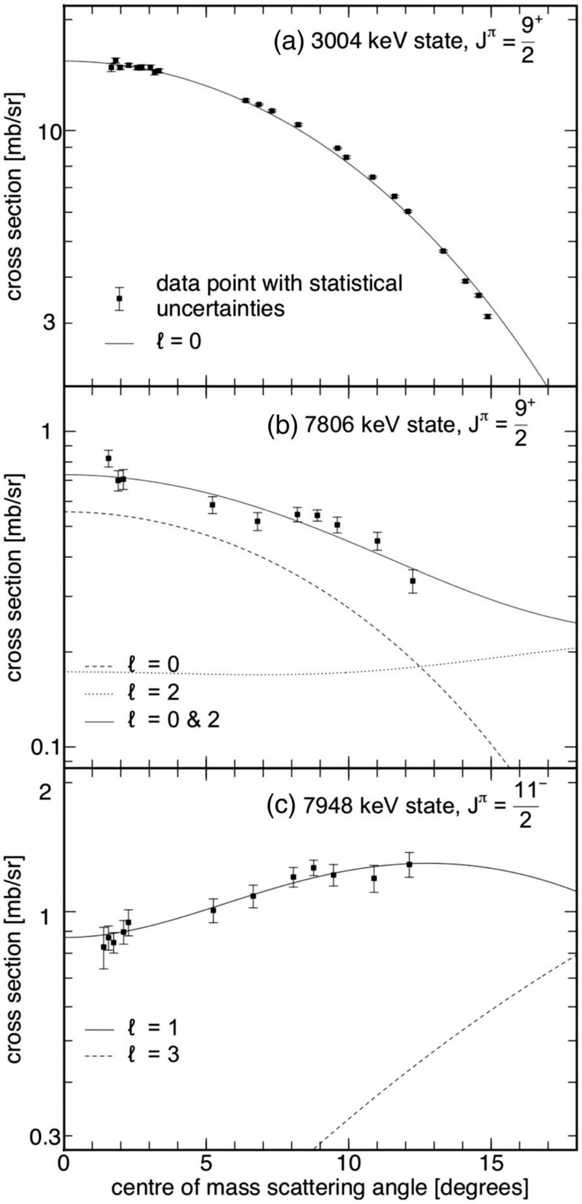

FIG. 3. Angular distributions together with ADWA fits for excited states in ^{27}Al at (a) 3004(2), (b) 7806(3), and (c) 7948(3) keV. The dominant systematic uncertainty in extracting cross sections relates to errors involved in determining the initial target thickness.

the present results, an average value of 45^{+19}_{-17} μeV for the strength of the 188.9(6) keV resonance [18] and strong resonances at 276.3(4) and 368.5(4) keV in ^{27}Si [33] (resonance energies are taken from Ref. [32]). It is clear from Fig. 4 that the 127 keV resonance now dominates the reaction over almost the entire temperature range of WR stars and AGB stars ($T \sim 0.04$–0.10 GK). Furthermore, by significantly constraining the proton spectroscopic factor for the 127 keV resonance compared to the full range considered in Parikh *et al.* [15], we conclude that its contribution in novae environments is likely to be negligible.

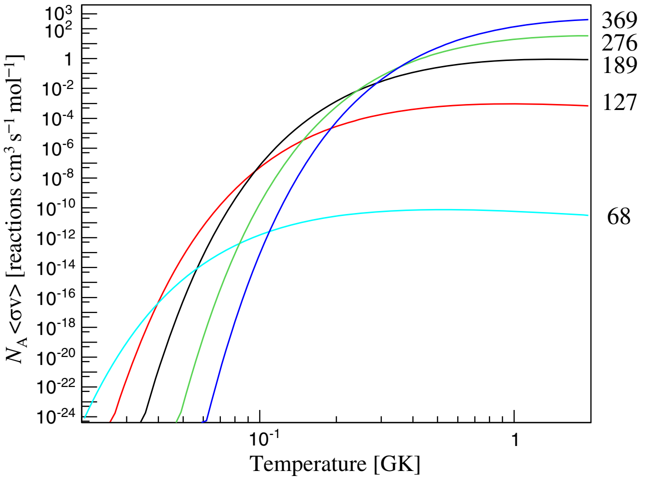

FIG. 4 (color online). Contribution of individual resonances to the ^{26g}Al$(p,\gamma)^{27}$Si stellar reaction rate. Resonance energies in keV are given on the right-hand side of the figure. The errors on the energies and strengths of resonances used to derive the reaction rates are given in the text. As discussed in the text, the contribution of the 68 keV resonance represents an upper limit.

It can be seen from Fig. 4 that for the region immediately above ~0.1 GK, corresponding to the lower temperature range for hydrogen burning in novae, the 189 keV resonance (7652 keV excitation energy), is the strongest single contributing state to ^{26}Al destruction. Lotay *et al.* [18] paired this state with a mirror analog level at 7948 keV in ^{27}Al [23], with angular distribution measurements of γ decays giving a clear 11/2 spin assignment for the 7652 keV level in ^{27}Si. The angular distribution and ADWA fit for the 7948(3) keV excited state in ^{27}Al is shown in Fig. 3(c). As can be seen, the angular distribution is well fitted by a pure $\ell = 1$ transfer with C^2S ($\ell = 1$) of 0.14(3) and is inconsistent with $\ell = 0, 2$ transfer, supportive of an $11/2^-$ assignment. Such high values for C^2S for negative parity states at high excitation energies in *sd*-shell nuclei have been associated with relatively pure single particle configurations [34]. Using this value to obtain an implied strength for the 189 keV resonance gives 52(11) μeV, which is in excellent agreement with the two direct measurements of 55(9) [16] and 35(7) μeV [17].

In summary, we have performed a high-resolution study of the ^{26}Al$(d,p)^{27}$Al transfer reaction in inverse kinematics and have, for the first time, placed experimental constraints on the proton spectroscopic factor C^2S of the key 127 keV resonance in the ^{26g}Al$(p,\gamma)^{27}$Si reaction. This has resulted in stringent restrictions on the rate at which this reaction occurs and clearly points to the dominant role of the 127 keV resonance in the destruction of the cosmic γ-ray emitting isotope ^{26}Al in Wolf-Rayet and AGB stars. In order to reduce further uncertainties in the reaction, we would encourage a ^{26}Al$(^3$He$,d)^{27}$Si study to obtain a direct measurement of the proton spectroscopic factor of the 127 keV resonance in ^{27}Si.

The authors wish to thank the ISAC operations and technical staff at TRIUMF, as well as P. Morrall (STFC Daresbury Laboratory, UK) for the preparation of targets. The UK authors acknowledge support by STFC.

Note added.—Recently, a complementary $^{26}\mathrm{Al}(d,p)$ study by Pain *et al.* [35] was published in Physical Review Letters. The results presented here are entirely independent of that work.

---

[*] Corresponding author.
g.lotay@surrey.ac.uk
[†] Present address: CEA Saclay, Gif-sur-Yvette 91400, France.
[‡] Present address: Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus, Denmark.

[1] S. A. Grebenev, A. A. Lutovinov, S. S. Tsygankov, and C. Winkler, Nature **490**, 373 (2012).
[2] E. Churazov *et al.*, Nature **512**, 406 (2014).
[3] R. Diehl, T. Siegert, W. Hillebrandt, S. A. Grebenev, J. Greiner, M. Krause, M. Kromer, K. Maeda, F. Ropke, and S. Taubenberger, Science **345**, 1162 (2014).
[4] W. A. Mahoney, J. C. Ling, A. S. Jacobson, and R. E. Lingenfelter, Astrophys. J. **262**, 742 (1982).
[5] R. Diehl *et al.*, Nature **439**, 45 (2006).
[6] R. Diehl *et al.*, Astron. Astrophys. **298**, 445 (1995).
[7] W. Wang *et al.*, Astron. Astrophys. **496**, 713 (2009).
[8] L. Siess and M. Arnould, Astron. Astrophys. **489**, 395 (2008).
[9] J. Jose, M. Hernanz, and A. Coc, Astrophys. J. **479**, L55 (1997).
[10] T. Lee, D. A. Papanastassiou, and G. J. Wasserburg, Astrophys. J. **211**, L107 (1977).
[11] G. Wasserburg, M. Busso, R. Gallino, and K. M. Nollett, Nucl. Phys. **A777**, 5 (2006).
[12] G. Srinivasan, J. N. Goswami, and N. Bhandari, Science **284**, 1348 (1999).
[13] M. A. van Raai, M. Lugaro, A. I. Karakas, and C. Iliadis, Astron. Astrophys. **478**, 521 (2008).
[14] C. Iliadis, A. E. Champagne, A. Chieffi, and M. Limongi, Astrophys. J. Suppl. Ser. **193**, 16 (2011).
[15] A. Parikh, J. Jose, A. Karakas, C. Ruiz, and K. Wimmer, Phys. Rev. C **90**, 038801 (2014).
[16] R. B. Vogelaar, Ph.D. thesis, California Institute of Technology 1989.
[17] C. Ruiz *et al.*, Phys. Rev. Lett. **96**, 252501 (2006).
[18] G. Lotay, P. J. Woods, D. Seweryniak, M. P. Carpenter, R. V. F. Janssens, and S. Zhu, Phys. Rev. Lett. **102**, 162502 (2009).
[19] R. B. Vogelaar, L. W. Mitchell, R. W. Kavanagh, A. E. Champagne, P. V. Magnus, M. S. Smith, A. J. Howard, P. D. Parker, and H. A. O'Brien, Phys. Rev. C **53**, 1945 (1996).
[20] C. Ruiz *et al.*, Phys. Rev. C **65**, 042801(R) (2002).
[21] http://www.micronsemiconductor.co.uk/.
[22] J. F. Ziegler, M. D. Ziegler, and J. P. Biersack, Nucl. Instrum. Methods Phys. Res., Sect. B **268**, 1818 (2010).
[23] M. Shamsuzzoha Basunia, Nucl. Data Sheets **112**, 1875 (2011).
[24] J. A. Tostevin, University of Surrey version of the code TWOFNR (of M. Toyama, M. Igarashi and N. Kishida) and code FRONT (private communication).
[25] R. C. Johnson and P. C. Tandy, Nucl. Phys. **A235**, 56 (1974).
[26] R. B. Wiringa, V. G. J. Stoks, and R. Schiavilla, Phys. Rev. C **51**, 38 (1995); https://www.phy.anl.gov/theory/research/av18/.
[27] A. J. Koning and J. P. Delaroche, Nucl. Phys. **A713**, 231 (2003).
[28] A. Gade *et al.*, Phys. Rev. C **77**, 044306 (2008).
[29] N. K. Timofeyuk, R. C. Johnson, and A. M. Mukhamedzhanov, Phys. Rev. Lett. **91**, 232501 (2003).
[30] N. K. Timofeyuk, P. Descouvemont, and R. C. Johnson, Eur. Phys. J. A **27**, 269 (2006).
[31] B. A. Brown, (private communication).
[32] G. Lotay, P. J. Woods, D. Seweryniak, M. P. Carpenter, H. M. David, R. V. F. Janssens, and S. Zhu, Phys. Rev. C **84**, 035802 (2011).
[33] L. Buchmann, M. Hilgemeier, A. Krauss, A. Redder, C. Rolfs, H. P. Trautvetter, and T. R. Donoghue, Nucl. Phys. **A415**, 93 (1984).
[34] B. A. Brown, W. A. Richter, and C. Wrede, Phys. Rev. C **89**, 062801(R) (2014).
[35] S. D. Pain *et al.*, Phys. Rev. Lett. **114**, 212501 (2015).