RAPID COMMUNICATIONS

PHYSICAL REVIEW C **96**, 032801(R) (2017)

New portal to the $^{15}O(\alpha,\gamma)^{19}Ne$ resonance triggering CNO-cycle breakout

C. Wrede,[1,2,*] B. E. Glassman,[1,2,†] D. Pérez-Loureiro,[2,‡] J. M. Allen,[3] D. W. Bardayan,[3] M. B. Bennett,[1,2] B. A. Brown,[1,2] K. A. Chipps,[4,5] M. Febbraro,[4,5] C. Fry,[1,2] M. R. Hall,[3] O. Hall,[3] S. N. Liddick,[2,6] P. O'Malley,[3] W.-J. Ong,[1,2] S. D. Pain,[4] S. B. Schwartz,[1,2] P. Shidling,[7] H. Sims,[8] P. Thompson,[4,5] and H. Zhang[1,2]

[1]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[2]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[4]*Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[5]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*
[6]*Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, USA*
[7]*Cyclotron Institute, Texas A & M University College Station, Texas 77843, USA*
[8]*University of Surrey, GU2 7XH, Guildford, UK*

(Received 14 February 2017; published 29 September 2017)

The $^{15}O(\alpha,\gamma)^{19}Ne$ reaction is expected to trigger the initial path for breakout from the CNO hydrogen-burning cycles to the rapid proton capture (rp) process in type I x-ray bursts on accreting neutron stars. The thermonuclear reaction rate has a major impact on models of type I x-ray burst observables and it depends on the small α-particle branching ratio, Γ_α/Γ, of the 4.03 MeV state in ^{19}Ne. Attempts to measure Γ_α/Γ by populating the 4.03 MeV state using nuclear reactions have only led to strong upper limits. In the present work, we report the first experimental evidence that the 4.03 MeV ^{19}Ne state is populated in ^{20}Mg β-delayed proton emission. This new channel has the potential to provide the necessary sensitivity to detect a finite value of Γ_α/Γ.

DOI: 10.1103/PhysRevC.96.032801

Introduction. Thermonuclear runaways can occur periodically on the surface of a neutron star that is accreting matter from a hydrogen-rich companion star in a close binary system. These events are frequently observed using space-based x-ray telescopes and classified as type I x-ray bursts [1]. Models show that hydrogen burning through the hot carbon-nitrogen-oxygen nucleosynthesis cycles occurs during the initial stages of the burst while temperatures are sufficiently low that the elemental composition of the material is contained below mass number $A = 20$ [2]. Once sufficiently high temperatures of $\approx$0.4 GK are reached, the rate of the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction ($Q = 3528.5 \pm 0.5$ keV [3]) is expected to become high enough to trigger a nucleosynthesis breakout path from the hot CNO cycles to higher masses, initiating a chain of rapid proton captures and β decays known as the rp process [4]. The $^{15}O(\alpha,\gamma)^{19}Ne$ reaction rate is expected to determine the temperature and density at which the breakout occurs [2] and, therefore, varying the rate in models of these events can lead to dramatic differences in the predicted x-ray burst light curves and nucleosynthesis ashes [5–8]. A reliable $^{15}O(\alpha,\gamma)^{19}Ne$ reaction rate for use in the simulations is needed to extract meaningful physics and astrophysics from observations of these extreme cosmic laboratories.

Unfortunately, the thermonuclear $^{15}O(\alpha,\gamma)^{19}Ne$ reaction rate has a large experimental uncertainty [7]. While it has been determined that a single resonance at $E_{\text{c.m.}} = 505.8 \pm 1.0$ keV [3,7,9,10] corresponding to a ^{19}Ne excited state at 4.03 MeV ($J^\pi = 3/2^+$ [7]) dominates the reaction rate, the strength of the resonance, $\omega\gamma$, is unknown. It is not currently possible to measure that resonance strength directly because a ^{15}O ($T_{1/2} = 122$ s) rare-isotope beam of sufficient intensity is not available to bombard a helium target and measure the yield. Fortunately, the resonance strength can be constructed by combining measurements of the level lifetime τ and the small α-particle branching ratio Γ_α/Γ using the following expression:

$$\omega\gamma = \frac{2\hbar}{\tau}\frac{\Gamma_\alpha}{\Gamma}\left(1 - \frac{\Gamma_\alpha}{\Gamma}\right) \approx \frac{2\hbar}{\tau}\frac{\Gamma_\alpha}{\Gamma}. \qquad (1)$$

Three successful measurements of the level lifetime using the Doppler shift attenuation method have yielded consistent finite values that are sufficiently precise for this astrophysical application [10–12]. However, attempts to measure the branching ratio by populating the 4.03 MeV state using nuclear reactions have proved to be more challenging, leading only to strong upper limits [7] of $\Gamma_\alpha/\Gamma < 6 \times 10^{-4}$ [13], $\Gamma_\alpha/\Gamma < 4.3 \times 10^{-4}$ [14], and $\Gamma_\alpha/\Gamma = (2.9 \pm 2.1) \times 10^{-4}$ [15]. In the present work, we introduce and substantiate a novel approach to measure the branching ratio of the 4.03 MeV ^{19}Ne state via nuclear β decay. This new β decay portal has the potential to provide more sensitive measurements than reaction-based methods.

Considering that ^{19}Na is unbound to proton emission, causing it to decay on strong-interaction time scales, its β decay cannot be used to populate the 4.03 MeV state of ^{19}Ne. This may be the reason that β decay, in general, has apparently been overlooked as an experimental method to investigate the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction rate. However, the 4.03 MeV state of ^{19}Ne is energetically accessible in the β-delayed proton

*wrede@nscl.msu.edu
†glassman@nscl.msu.edu
‡perezlou@nscl.msu.edu

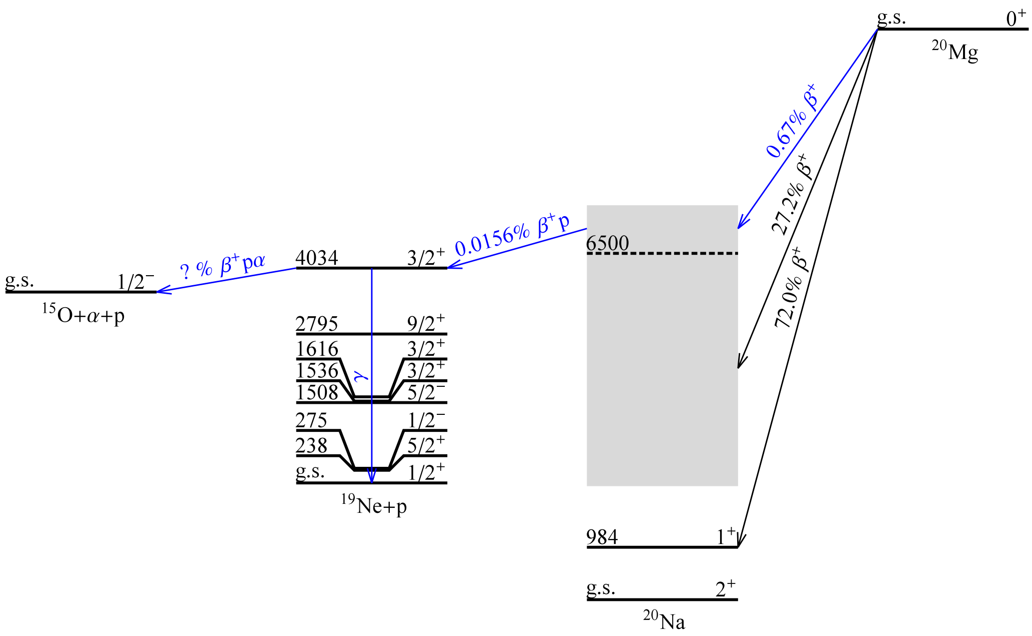

FIG. 1. Simplified ^{20}Mg ($T_{1/2} = 91.4$ ms [16], $Q_{EC} = 10627$ keV [3,17,18]) β decay scheme focusing on the transitions relevant to the present work (blue online). Energies are shown in units of keV. The proton separation energy of ^{20}Na is 2190 keV and the α-particle separation energy of ^{19}Ne is 3529 keV [3]. Branches are given as intensities in percent of ^{20}Mg β decays. The values for the ^{20}Mg($\beta^+\nu$)^{20}Na branches are adopted from Ref. [16] and the value for the ^{20}Na*(p)^{19}Ne$^*_{4033}$ branch shown is from the present work.

decay of ^{20}Mg ($T_{1/2} = 91.4$ ms [16], $Q_{EC} = 10.627$ MeV [3,17,18]) through ^{20}Na and, therefore, it may be populated with significant intensity (Fig. 1) [19], but it has never been detected. The β-delayed proton decay of ^{20}Mg is already known [16,20] to populate low-lying states of ^{19}Ne including the ground state and the first five excited states up to an excitation energy of 1.62 MeV. In order to be energetically allowed, ^{20}Mg decay to the seventh excited state of ^{19}Ne at 4.03 MeV would have to proceed through ^{20}Na states above 6223 keV excitation energy. While these ^{20}Na states include the strongly populated isospin $T = 2$ isobaric analog state (IAS) at 6498 keV [16,20,21], it is unlikely that the IAS would have a significant proton branch to feed the 4.03 MeV state: proton emission from the IAS is isospin forbidden and the c.m. energy for the transition to the 4.03 MeV ^{19}Ne state is only 275 keV, so it should also be suppressed by the Coulomb barrier. Let us, therefore, consider the other ^{20}Na states that are sufficiently high in energy to emit protons to populate the 4.03 MeV state of ^{19}Ne and sufficiently low in energy to be populated in ^{20}Mg β decay. The ^{20}Mg β decay feeding of $T = 1$ ^{20}Na states above 6223 keV was recently measured to be $0.67 \pm 0.09\%$ using ^{20}Mg β-delayed proton decay [16]. If even a small fraction of this ^{20}Na feeding would undergo proton emission to populate the 4.03 MeV ^{19}Ne level then a variety of experimental techniques could be used to provide sensitive measurements of Γ_α/Γ. We have carried out an experiment to search for the population of the 4.03 MeV state of ^{19}Ne via the β-delayed proton-γ decay of ^{20}Mg.

Experiment. The experiment [21] was carried out at Michigan State University's National Superconducting Cyclotron Laboratory (NSCL) and employed a procedure similar to that of our previous β decay experiments [22–26]. A fast radioactive ^{20}Mg beam was produced using projectile fragmentation of a 170 MeV/u, 60 pnA ^{24}Mg primary beam from the Coupled Cyclotron Facility. The beam impinged upon a 961 mg/cm^2 ^{9}Be target, which transmitted the ^{20}Mg reaction products to the A1900 fragment separator. The A1900 separated ^{20}Mg ions from other fragmentation products by magnetic rigidity [27]. Rates of up to 4000 ^{20}Mg ions s^{-1} were delivered to the experimental setup. Beam ions were cleanly identified by combining the time of flight with energy loss. The energy loss was measured using a 300-μm-thick silicon detector located ≈70 cm upstream of the counting station. The time of flight was measured over a 25 m path between a plastic scintillator at the focal plane of the A1900 and the Si detector. In order to mitigate radiation damage to the Si detector, it was extracted while running with the full ^{20}Mg beam intensity. These production runs were interleaved with attenuated beam-intensity runs during which the Si detector was inserted for particle identification. The average composition of the beam delivered to the experiment was found to be 34% ^{20}Mg with the contaminant isotones ^{18}Ne ($T_{1/2} = 1.7$ s, 24%), ^{17}F ($T_{1/2} = 64$ s, 12%), ^{16}O (stable, 22%), and ^{15}N (stable, 8%) (these values have been refined since [21]).

The ^{20}Mg ions were implanted to a depth of ≈10 mm in a 25-mm thick plastic scintillator. The scintillator recorded the ion implantations and their subsequent β decays with sufficient energy resolution to discriminate between the two. The Segmented Germanium Array (SeGA) of high-purity Ge detectors [28] surrounded the scintillator in two coaxial 13-cm radius rings consisting of eight detectors apiece and it was used to detect γ rays. Signals were processed using the NSCL digital data acquisition system [29].

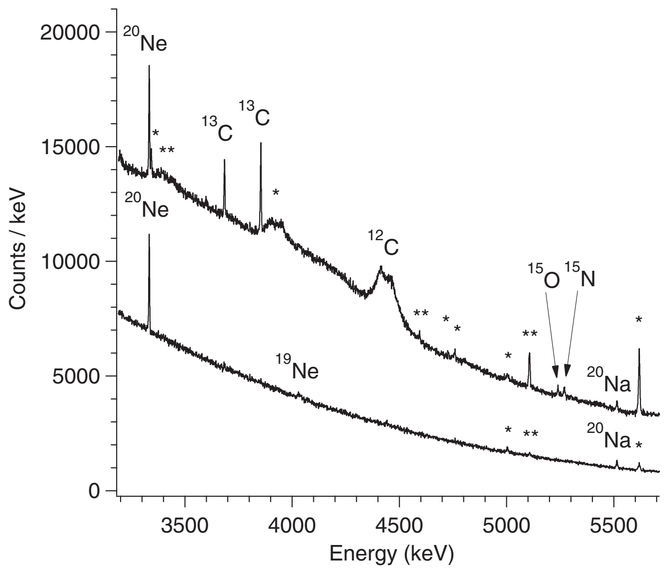

FIG. 2. Energy spectra of SeGA events. The upper spectrum shows all SeGA events in coincidence with events of any energy in the scintillator, including both ion implantations and β decays. This spectrum includes prompt γ rays from nuclear reactions and β-delayed γ rays. The lower spectrum selects events in coincidence with events depositing less than 10 MeV in the scintillator. This spectrum includes β-delayed γ rays and excludes prompt γ rays. γ-ray photopeaks are labeled by the nuclide in which the γ-ray transition occurs. First and second 511-keV γ-ray escape peaks are labeled by one and two asterisks, respectively.

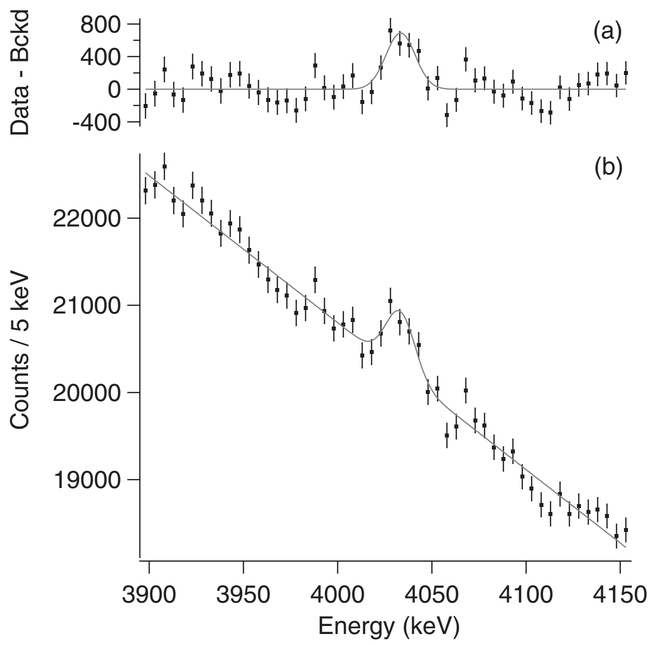

FIG. 3. (b): the points show the energy spectrum of SeGA events in coincidence with events depositing less than 10 MeV in the scintillator. This spectrum includes β-delayed γ rays and excludes prompt γ rays. The spectrum is identical to the lower spectrum in Fig. 2, but the binning is different. The error bars associated with the data points are statistical. The smooth line is a functional fit to the data comprised of a Gaussian function added to a linear background. (a): the points show the difference between the data and the linear background component of the fit shown in (b). The smooth line is the Gaussian function derived from the fit shown in (b).

The SeGA spectra were gain-matched to produce cumulative spectra using the strong γ-ray lines from room-background activity with transition energies of 1460.851 ± 0.006 keV (from ^{40}K decay) [30] and 2614.511 ± 0.010 keV (from ^{208}Tl decay) [31] as reference points, providing an *in situ* first-order energy calibration. In order to reduce the room-background contribution to the γ-ray spectra, a β-coincident γ-ray spectrum was produced by requiring coincidences with β-particle signals from the implantation scintillator (Figs. 2 and 3). Lines with well-known transition energies of 1633.602 ± 0.015, 3332.84 ± 0.20, 6129.89 ± 0.04, 8239 ± 4, and 8640 ± 3 keV [32,33] from the β-delayed γ (and α-γ) decays of ^{20}Na (the daughter of ^{20}Mg β decay) were observed with high statistics and used together with the two room-background lines for a more extensive energy calibration. Small corrections for the energy carried by daughter nuclei recoiling from γ-ray emission were applied throughout the calibration procedure.

The efficiency of the scintillator to detect β decays in coincidence with γ rays was investigated using the SeGA spectra. Comparing the integrals of known β-delayed γ decay lines in the cumulative singles spectrum to the integrals of the corresponding lines in coincidence with scintillator events yielded the efficiency. By considering several such data points, a uniform efficiency of $90 \pm 1\%$ was found for the β decays of ^{20}Mg to ^{20}Na, ^{20}Na to ^{20}Ne, and for the β-delayed proton decay of ^{20}Mg to ^{19}Ne.

The photopeak efficiency of the SeGA array was determined using measurements with a standard ^{154}Eu calibration source and GEANT4 Monte Carlo simulations. The source was placed on the front face of the scintillator at the center of the SeGA array. It provided absolute efficiency calibration points up to an energy of 1.6 MeV. The GEANT4 simulation included the gross features of the experimental geometry and was found to overestimate the absolute photopeak efficiencies by a constant scale factor of 1.03. The relative efficiencies from GEANT4 were found to be very accurate and were, therefore, used to interpolate and extrapolate the measured absolute efficiencies to other energies.

Discussion. Previously known ^{19}Ne γ rays from the β-delayed proton decay of ^{20}Mg [9,20] were observed at 238, 275, 1232, and 1298 keV. In addition, the known ^{19}Ne γ rays at 1261, 1269, and 1340 keV [9] were observed for the first time in ^{20}Mg β decay. All of these γ rays are from deexcitations of the five lowest energy excited states of ^{19}Ne at 238, 275, 1508, 1536, and 1616 keV. Several of the γ-ray peaks were conspicuously Doppler broadened [23,34] due to the recoil of ^{19}Ne following proton emission from ^{20}Na and, due to their complex shapes, we reserve a quantitative discussion of those peaks for a more detailed report. We did not observe the population of the sixth ^{19}Ne excited state at 2795 keV ($J^\pi = 9/2^+$), likely because the allowed β decays of ^{20}Mg ($J^\pi = 0^+$)

populate 0^+ and 1^+ states of ^{20}Na, which would need to emit $\ell \geqslant 4$ protons to feed the 2795 keV ^{19}Ne state; these proton emissions should be strongly suppressed by the centrifugal barrier.

Lastly, and most importantly in the context of the present work, we observed evidence for the population of the seventh ^{19}Ne excited state at 4.03 MeV in the form of a 4.03 MeV γ-ray peak corresponding to its deexcitation by a transition to the ^{19}Ne ground state (Figs. 2 and 3). The 4.03-MeV γ-ray transition is already known to have a $80 \pm 15\%$ branch deexciting the 4.03 MeV state [9]. To avoid assumptions about the magnitude of Doppler broadening of the peak, we used a simple Gaussian function to fit the peak with the width, centroid, and amplitude as free parameters. In the fit, the peak was summed with a linear background described by two free parameters over the range shown in Fig. 3. The χ-squared value per degree of freedom for the fit was $\chi^2/\nu = 67.4/47$. Including an additional parameter to describe the curvature of the background did not improve the fit, suggesting that there may be small fluctuations in the background beyond statistical ones. To account for the fluctuations, we inflated the statistical uncertainties of all quantities extracted from the fit by a factor of $\sqrt{\chi^2/\nu}$. We also performed a separate fit of the data that was unweighted by the statistical error bars of each bin. An unweighted fit is justified to a good approximation in this case because every bin carries roughly the same statistical weight. The unweighted fit intrinsically captures both statistical and systematic fluctuations of the background in the uncertainties of the fit parameters. The values and uncertainties from the unweighted fit were found to be almost identical to those from the weighted fit with inflated uncertainty. By adopting the results from the weighted fit with inflated uncertainties, the integral of the peak was found to be 2684 ± 503 counts: 5.3 standard deviations above the expected background level. The measured γ-ray energy of 4033.4 ± 1.7 keV in the laboratory reference frame corresponds to an excitation energy of 4033.8 ± 1.7 keV, which is in good agreement with the evaluated literature value of 4034.3 ± 0.9 keV [7,9,10] for the ^{19}Ne transition. Using the integral of the peak and applying the scintillator and SeGA efficiency calibrations anchored by the known intensity of the strong 984 keV ^{20}Na line [16,20] yields an intensity of $0.0125 \pm 0.0020\%$ for the 4.03 MeV γ ray in ^{20}Mg β decay. This value corresponds to a β-delayed proton feeding of $0.0156 \pm 0.0038\%$ for the 4.03 MeV level of ^{19}Ne after the 20% γ-decay branch of this level to excited states [9] is taken into account. Our experiment was not sensitive to the weaker branches via β-γ or β-γ-γ coincidences. The measured intensities are compatible with the 0.67% ^{20}Mg β decay feeding of isospin $T = 1$ ^{20}Na levels that are energetically allowed to feed the 4.03 MeV ^{19}Ne state [16]. In particular, the measurements suggest that approximately 2% of the proton emissions from these levels feed the 4.03 MeV ^{19}Ne state rather than lower lying ^{19}Ne states, which is consistent with expectations based on a simple barrier penetration model.

This is the first detection of the population of the 4.03 MeV ^{19}Ne state via β decay and it opens a potentially sensitive new channel that can now be exploited to measure Γ_α/Γ. Each event will involve a β-p-α decay sequence in which the proton carries ≈0.5–1.0 MeV of kinetic energy and the α particle shares ≈0.5 MeV with the ^{15}O recoil. By taking advantage of coincidences between the proton and the α particle (and potentially, but not necessarily, the ^{15}O recoil), background events can be strongly suppressed. This measurement could be realized by thermalizing ^{20}Mg in a time-projection chamber (TPC), for example, and identifying the individual decay products inside using their characteristic Bragg curves. Alternatively, ^{20}Mg could be trapped in vacuum using electromagnetic fields and the decay products could be observed with surrounding detectors. Either of these methods could yield an efficiency approaching 100% for the detection of the events of interest.

Considering a ^{20}Mg production rate of 4000 per second (already realized at NSCL, for example, in the present experiment) and the 0.0156% feeding of the 4.03 MeV ^{19}Ne level in ^{20}Mg β decay, this state will be populated 37 times per minute on average. Assuming $\Gamma_\alpha/\Gamma = 3 \times 10^{-4}$ [15], approximately 16 α-particle emissions from this level would occur every day. A week-long experiment would yield on the order of 100 events, corresponding to 10% statistical precision on the value of Γ_α/Γ assuming an efficient detection system with negligible background. If the model-dependent value of Γ_α from Ref. [35] is adopted instead, then the count-rate estimate is reduced by a factor of ≈3. Potential backgrounds will have to be assessed carefully for specific experimental configurations, but the unique signatures of the events of interest including the particle identities, their energies, and the coincidence condition should enable a strong suppression of background events. In the case of a TPC measurement, a special signature is available to identify the events of interest: a relatively dense energy deposition from the α-particle emission located at the base of the proton's Bragg curve. The present value for the feeding of the 4.03 MeV ^{19}Ne level will be necessary to normalize the value of Γ_α/Γ in future measurements if a sensitive γ-ray spectrometer is not employed. Next-generation rare-isotope-beam facilities currently under construction will yield orders of magnitude more ^{20}Mg enabling precision studies.

Conclusions. We have reported the first experimental evidence for the population of the 4.03 MeV state of ^{19}Ne via ^{20}Mg β-delayed proton emission. We find that the 4.03 MeV state is populated in 0.0156% of ^{20}Mg β decays, providing a new portal for sensitive measurements of the α-decay branching ratio, which determines the conditions for breakout from the hot CNO cycles during type I x-ray bursts on accreting neutron stars.

Acknowledgments. We gratefully acknowledge the NSCL staff for working on the data acquisition system and providing the ^{20}Mg beam. This work was supported by the U.S. National Science Foundation under Grants No. PHY-1102511, No. PHY-1419765, and No. PHY-1404442, the U.S. Department of Energy, Office of Science, under Award No. DE-SC0016052, and the U.S. Department of Energy, National Nuclear Security Administration under Awards No. DE-NA0003221 and No. DE-NA0000979.

[1] W. H. G. Lewin, J. van Paradijs, and R. E. Taam, Space Sci. Rev. **62**, 223 (1993).
[2] M. Wiescher, J. Görres, and H. Schatz, J. Phys. G **25**, R133 (1999).
[3] M. Wang, G. Audi, A. H. Wapstra, F. G. Kondev, M. MacCormick, X. Xu, and B. Pfeiffer, Chin. Phys. C **36**, 1603 (2012).
[4] R. K. Wallace and S. E. Woosley, Astrophys. J. Suppl. Ser. **45**, 389 (1981).
[5] J. L. Fisker, J. Görres, M. Wiescher, and B. Davids, Astrophys. J. **650**, 332 (2006).
[6] J. L. Fisker, W. Tan, J. Görres, M. Wiescher, and R. L. Cooper, Astrophys. J. **665**, 637 (2007).
[7] B. Davids, R. H. Cyburt, J. José, and S. Mythili, Astrophys. J. **735**, 40 (2011).
[8] R. H. Cyburt, A. M. Amthor, A. Heger, E. Johnson, L. Keek, Z. Meisel, H. Schatz, and K. Smith, Astrophys. J. **830**, 55 (2016).
[9] D. R. Tilley, H. R. Weller, C. M. Cheves, and R. M. Chasteler, Nucl. Phys. **A595**, 1 (1995).
[10] W. P. Tan, J. Görres, J. Daly, M. Couder, A. Couture, H. Y. Lee, E. Stech, E. Strandberg, C. Ugalde, and M. Wiescher, Phys. Rev. C **72**, 041302 (2005).
[11] R. Kanungo, T. K. Alexander, A. N. Andreyev, G. C. Ball, R. S. Chakrawarthy, M. Chicoine, R. Churchman, B. Davids, J. S. Forster, S. Gujrathi, G. Hackman, D. Howell, J. R. Leslie, A. C. Morton, S. Mythili, C. J. Pearson, J. J. Ressler, C. Ruiz, H. Savajols, M. A. Schumaker, I. Tanihata, P. Walden, and S. Yen, Phys. Rev. C **74**, 045803 (2006).
[12] S. Mythili, B. Davids, T. K. Alexander, G. C. Ball, M. Chicoine, R. S. Chakrawarthy, R. Churchman, J. S. Forster, S. Gujrathi, G. Hackman, D. Howell, R. Kanungo, J. R. Leslie, E. Padilla, C. J. Pearson, C. Ruiz, G. Ruprecht, M. A. Schumaker, I. Tanihata, C. Vockenhuber, P. Walden, and S. Yen, Phys. Rev. C **77**, 035803 (2008).
[13] K. E. Rehm, A. H. Wuosmaa, C. L. Jiang, J. Caggiano, J. P. Greene, A. Heinz, D. Henderson, R. V. F. Janssens, E. F. Moore, G. Mukherjee, R. C. Pardo, T. Pennington, J. P. Schiffer, R. H. Siemssen, M. Paul, L. Jisonna, and R. E. Segel, Phys. Rev. C **67**, 065809 (2003).
[14] B. Davids, A. M. van den Berg, P. Dendooven, F. Fleurot, M. Hunyadi, M. A. de Huu, R. H. Siemssen, H. W. Wilschut, H. J. Wörtche, M. Hernanz, J. José, K. E. Rehm, A. H. Wuosmaa, and R. E. Segel, Phys. Rev. C **67**, 065808 (2003).
[15] W. P. Tan, J. L. Fisker, J. Görres, M. Couder, and M. Wiescher, Phys. Rev. Lett. **98**, 242503 (2007).
[16] IDS Collaboration, M. V. Lund, A. Andreyev, M. J. G. Borge, J. Cederkäll, H. De Witte, L. M. Fraile, H. O. U. Fynbo, P. T. Greenlees, L. J. Harkness-Brennan, A. M. Howard, M. Huyse, B. Jonson, D. S. Judson, O. S. Kirsebom, J. Konki, J. Kurcewicz, I. Lazarus, R. Lica, S. Lindberg, M. Madurga, N. Marginean, R. Marginean, I. Marroquin, C. Mihai, M. Munch, E. Nacher, A. Negret, T. Nilsson, R. D. Page, S. Pascu, A. Perea, V. Pucknell, P. Rahkila, E. Rapisarda, K. Riisager, F. Rotaru, C. Sotty, M. Stanoiu, O. Tengblad, A. Turturica, P. Van Duppen, V. Vedia, R. Wadsworth, and N. Warr, Eur. Phys. J. A **52**, 304 (2016).
[17] C. Wrede, J. A. Clark, C. M. Deibel, T. Faestermann, R. Hertenberger, A. Parikh, H.-F. Wirth, S. Bishop, A. A. Chen, K. Eppinger, A. García, R. Krücken, O. Lepyoshkina, G. Rugel, and K. Setoodehnia, Phys. Rev. C **81**, 055503 (2010).
[18] A. T. Gallant, M. Brodeur, C. Andreoiu, A. Bader, A. Chaudhuri, U. Chowdhury, A. Grossheim, R. Klawitter, A. A. Kwiatkowski, K. G. Leach, A. Lennarz, T. D. Macdonald, B. E. Schultz, J. Lassen, H. Heggen, S. Raeder, A. Teigelhöfer, B. A. Brown, A. Magilligan, J. D. Holt, J. Menéndez, J. Simonis, A. Schwenk, and J. Dilling, Phys. Rev. Lett. **113**, 082501 (2014).
[19] C. Wrede, PoS **NIC XIII**, 039 (2014).
[20] A. Piechaczek, M. F. Mohar, R. Anne, V. Borrel, B. A. Brown, J. M. Corre, D. Guillemaud-Mueller, R. Hue, H. Keller, S. Kubono, V. Kunze, M. Lewitowicz, P. Magnus, A. C. Mueller, T. Nakamura, M. Pfützner, E. Roeckl, K. Rykaczewski, M. G. Saint-Laurent, W.-D. Schmidt-Ott, and O. Sorlin, Nucl. Phys. A **584**, 509 (1995).
[21] B. E. Glassman, D. Pérez-Loureiro, C. Wrede, J. Allen, D. W. Bardayan, M. B. Bennett, B. A. Brown, K. A. Chipps, M. Febbraro, C. Fry, M. R. Hall, O. Hall, S. N. Liddick, P. O'Malley, W. Ong, S. D. Pain, S. B. Schwartz, P. Shidling, H. Sims, P. Thompson, and H. Zhang, Phys. Rev. C **92**, 042501 (2015).
[22] M. B. Bennett, C. Wrede, K. A. Chipps, J. José, S. N. Liddick, M. Santia, A. Bowe, A. A. Chen, N. Cooper, D. Irvine, E. McNeice, F. Montes, F. Naqvi, R. Ortez, S. D. Pain, J. Pereira, C. Prokop, J. Quaglia, S. J. Quinn, S. B. Schwartz, S. Shanab, A. Simon, A. Spyrou, and E. Thiagalingam, Phys. Rev. Lett. **111**, 232503 (2013).
[23] S. B. Schwartz, C. Wrede, M. B. Bennett, S. N. Liddick, D. Pérez-Loureiro, A. Bowe, A. A. Chen, K. A. Chipps, N. Cooper, D. Irvine, E. McNeice, F. Montes, F. Naqvi, R. Ortez, S. D. Pain, J. Pereira, C. Prokop, J. Quaglia, S. J. Quinn, J. Sakstrup, M. Santia, S. Shanab, A. Simon, A. Spyrou, and E. Thiagalingam, Phys. Rev. C **92**, 031302 (2015).
[24] D. Pérez-Loureiro, C. Wrede, M. B. Bennett, S. N. Liddick, A. Bowe, B. A. Brown, A. A. Chen, K. A. Chipps, N. Cooper, D. Irvine, E. McNeice, F. Montes, F. Naqvi, R. Ortez, S. D. Pain, J. Pereira, C. J. Prokop, J. Quaglia, S. J. Quinn, J. Sakstrup, M. Santia, S. B. Schwartz, S. Shanab, A. Simon, A. Spyrou, and E. Thiagalingam, Phys. Rev. C **93**, 064320 (2016).
[25] M. B. Bennett, C. Wrede, B. A. Brown, S. N. Liddick, D. Pérez-Loureiro, D. W. Bardayan, A. A. Chen, K. A. Chipps, C. Fry, B. E. Glassman, C. Langer, N. R. Larson, E. I. McNeice, Z. Meisel, W. Ong, P. D. O'Malley, S. D. Pain, C. J. Prokop, H. Schatz, S. B. Schwartz, S. Suchyta, P. Thompson, M. Walters, and X. Xu, Phys. Rev. Lett. **116**, 102502 (2016).
[26] M. B. Bennett, C. Wrede, B. A. Brown, S. N. Liddick, D. Pérez-Loureiro, D. W. Bardayan, A. A. Chen, K. A. Chipps, C. Fry, B. E. Glassman, C. Langer, N. R. Larson, E. I. McNeice, Z. Meisel, W. Ong, P. D. O'Malley, S. D. Pain, C. J. Prokop, S. B. Schwartz, S. Suchyta, P. Thompson, M. Walters, and X. Xu, Phys. Rev. C **93**, 064310 (2016).
[27] D. J. Morrissey, B. M. Sherrill, M. Steiner, A. Stolz, and I. Wiedenhoever, Nucl. Instrum. Methods Phys. Res., Sect. B **204**, 90 (2003).
[28] W. F. Mueller, J. A. Church, T. Glasmacher, D. Gutknecht, G. Hackman, P. G. Hansen, Z. Hu, K. L. Miller, and P. Quirin, Nucl. Instrum. Methods Phys. Res., Sect. A **466**, 492 (2001).
[29] C. J. Prokop, S. N. Liddick, N. R. Larson, S. Suchyta, and J. R. Tompkins, Nucl. Instrum. Methods Phys. Res., Sect. A **792**, 81 (2015).

[30] J. A. Cameron and B. Singh, Nucl. Data Sheets **102**, 293 (2004).
[31] M. J. Martin, Nucl. Data Sheets **108**, 1583 (2007).
[32] D. R. Tilley, C. M. Cheves, J. H. Kelley, S. Raman, and H. R. Weller, Nucl. Phys. **A636**, 249 (1998).
[33] D. R. Tilley, H. R. Weller, and C. M. Cheves, Nucl. Phys. **A564**, 1 (1993).
[34] H. O. U. Fynbo, Nucl. Instrum. Methods Phys. Res., Sect. B **207**, 275 (2003).
[35] Z. Q. Mao, H. T. Fortune, and A. G. Lacaze, Phys. Rev. Lett. **74**, 3760 (1995).