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New portal to the ¹⁵O(α,γ)¹⁹Ne resonance triggering CNO-cycle breakout

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The ${}^{15}O(\alpha,\gamma)^{19}Ne$ reaction is expected to trigger the initial path for break-out 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 alpha-particle branching ratio, Γ_{α}/Γ , of the 4.03 MeV state in ¹⁹Ne. 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 ¹⁹Ne state is populated in ²⁰Mg beta-delayed proton emission. This new channel has the potential to provide the necessary sensitivity to detect a finite value of Γ_{α}/Γ .

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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 (CNO) 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 ≈ 0.4 GK are reached, the rate of the ${}^{15}O(\alpha,\gamma){}^{19}Ne$ reaction $(Q = 3528.5 \pm 0.5 \text{ keV} [3])$ is expected to become high enough to trigger a nucleosynthesis break out path from the Hot CNO cycles to higher masses, initiating a chain of rapid proton captures and beta 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 break-out 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 $E_{\rm CM} = 505.8 \pm 1.0 \text{ keV} [3, 7, 9, 10]$ corresponding to a ¹⁹Ne 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 ¹⁵O ($T_{1/2} = 122$ 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 alpha particle branching ratio, Γ_{α}/Γ , using the following expression:

$$\omega\gamma = \frac{2\hbar}{\tau} \frac{\Gamma_{\alpha}}{\Gamma} \left(1 - \frac{\Gamma_{\alpha}}{\Gamma} \right) \approx \frac{2\hbar}{\tau} \frac{\Gamma_{\alpha}}{\Gamma}.$$
 (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 ¹⁹Ne state via nuclear beta decay. This new beta decay portal has the potential to provide more sensitive measurements than reaction-based methods.

Considering that ¹⁹Na is unbound to proton emission, causing it to decay on strong-interaction timescales, its

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beta decay cannot be used to populate the 4.03 MeV state of ¹⁹Ne. This may be the reason that beta 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 ¹⁹Ne is energetically accessible in the beta-delayed proton decay of $^{20}\mathrm{Mg}$ $(T_{1/2} = 91.4 \text{ ms} [16], Q_{\text{EC}} = 10.627 \text{ MeV} [3, 17, 18])$ through ²⁰Na and, therefore, it may be populated with significant intensity (Fig. 1) [19], but it has never been detected. The beta-delayed proton decay of ²⁰Mg 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, ²⁰Mg decay to the seventh excited state of ¹⁹Ne at 4.03 MeV would have to proceed through ²⁰Na states above 6223 keV excitation energy. While these ²⁰Na 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 ¹⁹Ne state is only 275 keV, so it should also be suppressed by the Coulomb barrier. Let us, therefore, consider the other ²⁰Na 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 $^{20}{\rm Mg}$ beta decay. The $^{20}{\rm Mg}$ beta decay feeding of T = 1 $^{20}{\rm Na}$ states above 6223 keV was recently measured to be $0.67 \pm 0.09\%$ using ²⁰Mg betadelayed proton decay [16]. If even a small fraction of this ²⁰Na feeding would undergo proton emission to populate the 4.03 MeV ¹⁹Ne 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 beta-delayed proton-gamma decay of ²⁰Mg.

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 beta decay experiments [22–26]. A fast radioactive ²⁰Mg beam was produced using projectile fragmentation of a 170 MeV/u, 60 pnA ²⁴Mg primary beam from the Coupled Cyclotron Facility. The beam impinged upon a 961 mg/cm² ⁹Be target, which transmitted the ²⁰Mg reaction products to the A1900 fragment separator. The A1900 separated ²⁰Mg 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 μ m-thick silicon detector located \approx 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 ²⁰Mg 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 % $^{20}{\rm Mg}$ with the contaminant isotones $^{18}{\rm Ne}$ $(T_{1/2} = 1.7 \text{ s}, 24 \%), {}^{17}\text{F} (T_{1/2} = 64 \text{ s}, 12 \%), {}^{16}\text{O} (\text{sta-}$ ble, 22 %), and 15 N (stable, 8 %) (these values have been refined since [21]). The ²⁰Mg 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 beta 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 8 detectors apiece and it was used to detect gamma rays. The NSCL digital data acquisition system was employed [29].

The SeGA spectra were gain-matched to produce cumulative spectra using the strong gamma-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 ²⁰⁸Tl decay) [31] as reference points, providing an *in-situ* first-order energy calibration. In order to reduce the room-background contribution to the gamma-ray spectra, a beta-coincident gamma-ray spectrum was produced by requiring coincidences with beta particle signals from the implantation scintillator (Figs. 2, 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 beta-delayed gamma (and alpha-gamma) decays of ²⁰Na (the daughter of ²⁰Mg beta 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 gamma-ray emission were applied throughout the calibration procedure.

The efficiency of the scintillator to detect beta decays in coincidence with gamma rays was investigated using the SeGA spectra. Comparing the integrals of known beta-delayed gamma 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 beta decays of 20 Mg to 20 Na, 20 Na to 20 Ne, and for the beta delayed proton decay of 20 Mg to 19 Ne.

The photopeak efficiency of the SeGA array was determined using measurements with a standard ¹⁵⁴Eu 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 ef-



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

ficiencies to other energies.

Discussion Previously known $^{19}\mathrm{Ne}$ gamma rays from the beta-delayed proton decay of ^{20}Mg [9, 20] were observed at 238, 275, 1232, and 1298 keV. In addition, the known 19 Ne gamma rays at 1261, 1269, and 1340 keV [9] were observed for the first time in ²⁰Mg beta decay. All of these gamma rays are from de-excitations of the five lowest-energy excited states of ¹⁹Ne at 238, 275, 1508, 1536, and 1616 keV. Several of the gamma-ray peaks were conspicuously Doppler broadened [23, 34] due to the recoil of ¹⁹Ne following proton emission from ²⁰Na 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 ¹⁹Ne excited state at 2795 keV $(J^{\pi} = 9/2^+)$, likely because the allowed beta decays of $^{20}{\rm Mg}~(J^{\pi}=0^+)$ populate 0^+ and 1^+ states of ²⁰Na, which would need to emit $\ell \geq 4$ protons to feed the 2795-keV $^{19}\mathrm{Ne}$ 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 ¹⁹Ne 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 ¹⁹Ne ground state (Figs. 2, 3). The 4.03-MeV gamma-ray transition is already known to have a 80 ± 15 % branch de-exciting 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, cen-

troid, 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 chi-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 gamma-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 ¹⁹Ne transition. Using the integral of the peak and applying the scintil-



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 beta decays. This spectrum includes prompt gamma rays from nuclear reactions and beta-delayed gamma rays. The lower spectrum selects events in coincidence with events depositing less than 10 MeV in the scintillator. This spectrum includes beta-delayed gamma rays and excludes prompt gamma rays. Gamma-ray photopeaks are labeled by the nuclide in which the gamma-ray transition occurs. First and second 511-keV gamma-ray escape peaks are labeled by one and two asterisks, respectively.

lator 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 ± 0.0020 % for the 4.03 MeV gamma ray in ²⁰Mg beta decay. This value corresponds to a beta-delayed proton feeding of 0.0156 ± 0.0038 % for the 4.03 MeV level of $^{19}\mathrm{Ne}$ after the 20 % gamma-decay branch of this level to excited states [9] is taken into account. Our experiment was not sensitive to the weaker branches via beta-gamma or beta-gamma-gamma coincidences. The measured intensities are compatible with the $0.67\%^{20}$ Mg beta decay feeding of isospin $T = 1^{20}$ Na levels that are energetically allowed to feed the 4.03 MeV ¹⁹Ne state [16]. In particular, the measurements suggest that approximately 2% of the proton emissions from these levels feed the 4.03 MeV ¹⁹Ne state rather than lower-lying ¹⁹Ne 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 ¹⁹Ne state via beta decay and it opens a potentially sensitive new channel that can now be exploited to measure Γ_{α}/Γ . Each event will involve a $\beta - p - \alpha$ decay sequence in which the proton carries ≈ 0.5 to 1.0 MeV of kinetic energy and the alpha particle shares ≈ 0.5 MeV with the ¹⁵O recoil. By taking advantage of coincidences between the proton and the alpha particle (and potentially, but not necessarily, the ¹⁵O recoil), back-



FIG. 3. Panel (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 betadelayed gamma rays and excludes prompt gamma rays. The spectrum is identical to the lower spectrum in Figure 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. Panel (a): the points show the difference between the data and the linear background component of the fit shown in Panel (b). The smooth line is the Gaussian function derived from the fit shown in Panel (b).

ground 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 ²⁰Mg 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 ¹⁹Ne level in ²⁰Mg beta decay, this state will be populated 37 times per minute on average. Assuming $\Gamma_{\alpha}/\Gamma = 3 \times 10^{-4}$ [15], approximately 16 alpha-particle emissions from this level would occur every day. A week-long experiment would yield on the order of one hundred 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 \approx 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 alpha-particle emission located at the base of the proton's Bragg curve. The present value for the feeding of the 4.03-MeV ¹⁹Ne level will be necessary to normalize the value of Γ_{α}/Γ in future measurements if a sensitive γ -ray spectrometer is not employed. Nextgeneration rare-isotope beam facilities currently under construction will yield orders of magnitude more ²⁰Mg enabling precision studies.

Conclusions We have reported the first experimental

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evidence for the population of the 4.03 MeV state of ¹⁹Ne via ²⁰Mg beta-delayed proton emission. We find that the 4.03 MeV state is populated in 0.0156 % of ²⁰Mg beta decays, providing a new portal for sensitive measurements of the alpha-decay branching ratio, which determines the conditions for break-out from the Hot CNO cycles during type I x-ray bursts on accreting neutron stars.

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