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RIB studies for explosive scenarios and future opportunities at FRIB

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C. Wrede

Department of Physics and Astronomy and National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA

E-mail: `wrede@nscl.msu.edu`

Abstract. An accreting compact star in a binary system can generate periodic thermonuclear runaways on its surface. In the case of a white dwarf star, the result is a classical nova, which enriches the interstellar medium with newly synthesized nuclides. In the case of a neutron star, a detectable burst of X-rays is emitted. Nucleosynthesis and energy generation in these events depends on resonant thermonuclear reaction rates, which are especially challenging to measure directly in the laboratory when they involve radioactive reactants. Fortunately, the resonances can be discovered and their relevant properties can be constructed using nuclear structure experiments. We will describe a program of beta decay experiments the National Superconducting Cyclotron Laboratory to this end. In particular, the Gaseous Detector with Germanium Tagging (GADGET) system, developed to measure very weak low-energy beta delayed proton emission branches and gamma rays, is now operational. Recent results and future opportunities at the Facility for Rare Isotope Beams will be discussed.
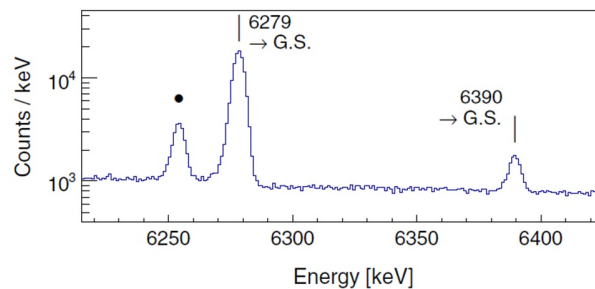
1. Introduction
Classical novae and Type I X-ray bursts are recurrent thermonuclear explosions on the surfaces of accreting white dwarf stars and neutron stars, respectively. Both types of events are observed frequently in the Milky Way galaxy. Novae have been observed in all major wavelength bands of the electromagnetic spectrum and eject material into the interstellar medium. Some of this material condenses as dust grains and isotopic signatures of such grains found in meteoritic material can be used to identify their pre-solar source. In the case of X-ray bursts, it is more difficult to expel material due the depth of the neutron star's gravitational potential well and, therefore, the primary observable is the X-ray light curve. Understanding both types of events requires thermonuclear rates of proton- and alpha-particle-induced reactions on the proton-rich side of the valley of beta stability. Many of these reactions involve radioactive reactants and are, therefore, difficult to measure directly. However, if the reactions are dominated by a small number of resonances then it is possible to construct each resonance strength by measuring the lifetime and branching ratios for particle and gamma-ray emission.

2. The ^{30}P(p,γ)^{31}S reaction in classical novae
The path of nova nucleosynthesis extends to masses as high as $A \approx 40$ for the highest temperature novae up to 0.4 GK occurring on oxygen-neon white dwarfs [1]. A potential bottleneck that may constrain the transfer of material to the $A > 30$ region is the ^{30}P(p,γ)^{31}S reaction, which influences the predicted elemental and isotopic yields from novae. For example, this reaction
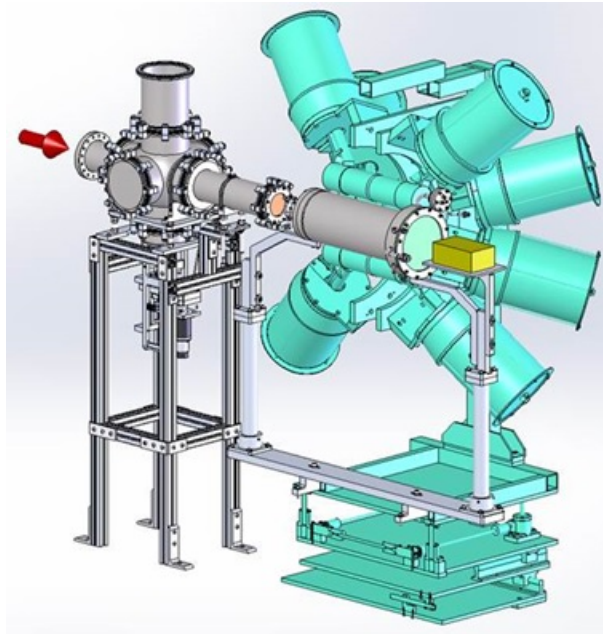
Figure 1. Portion of the cumulative spectrum of ^{31}Cl beta delayed gamma rays from the Clovershare array showing a peak corresponding to one of the transitions from the 6390-keV ^{31}S state [6]. The other peaks correspond to previously-known transitions.

influences the abundance ratio of ^{30}Si to ^{28}Si, which is used to identify pre-solar grains from classical novae [2]. Unfortunately, the nuclear physics uncertainties associated with this reaction rate are currently too large for this ratio to be useful [3].
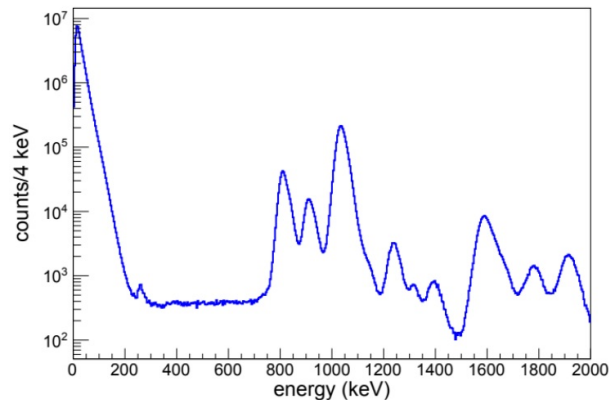
Building upon our earlier measurements of ^{26}P decay at the National Superconducting Cyclotron Laboratory (NSCL) on the campus of Michigan State University to probe resonances in the ^{25}Al(p,γ)^{26}Si reaction and the production of the radionuclide ^{26}Al in novae [4, 5], we have been using the beta decay of ^{31}Cl to search for ^{31}S resonances and measure their energies and branching ratios. A fast, fragmented beam of ^{31}Cl with an intensity of up to 10,000 particles per second and purity of $\approx$ 95 % is available at NSCL using a primary beam of ^{36}Ar from the Coupled Cyclotron Facility, a ^{9}Be target, the A1900 magnetic fragment separator, and the radiofrequency fragment separator.

Our first ^{31}Cl experiment focused on beta delayed gamma ray emission [6, 7]. The ^{31}Cl beam was continuously implanted into a plastic scintillator, which was used to detect beta particles. The Clovershare Array of 9 high-purity germanium clover-type detectors was used to detect gamma rays with high resolution in coincidence with the beta particles. A resonance in ^{31}S was observed at an excitation energy of 6390-keV, which is 259 keV above the proton emission threshold, in the middle of the ^{30}P(p,γ)^{31}S Gamow window at nova temperatures. Isospin mixing between this resonance and the isobaric analog state was evident from a comparison of the beta-decay feeding and the gamma decay branches with shell model calculations, indicating that the spin and parity must be $3/2^+$. Such a spin corresponds to an $\ell = 0$ resonance for proton capture on $J^\pi = 1^+$ ^{30}P that is not hindered by an angular momentum barrier. This resonance could potentially dominate the ^{30}P(p,γ)^{31}S reaction rate, but the resonance strength needs to be experimentally determined.

To this end, we have been pursuing experiments to measure the proton branching ratio. The total intensity of the ^{31}Cl beta delayed gamma rays through the 6390-keV state is known from our previous measurement to be 0.034, so in order to determine the branching ratio we must measure the intensity of the protons. Doing so is challenging because we estimate the intensity of the protons to be $\approx 10^{-5}$ and the beta-particle background can easily obscure the signal at such low energies. In order to mitigate these problems we have developed the Gaseous Detector with Germanium Tagging (GADGET) [8], which consists of a central Proton Detector surrounded by the Segmented Germanium Array (SeGA) of high-purity germanium detectors (Figure 2). The ^{31}Cl beam is deposited and thermalized in a volume of P10 gas in the cylindrical Proton Detector, which is co-axial with the beam line. Protons ionize the gas and electrons are drifted in a uniform electric field to a Micromegas readout on the downstream cap to produce an energy spectrum. The roughly atmospheric pressure P10 gas is enough to stop the low-energy protons

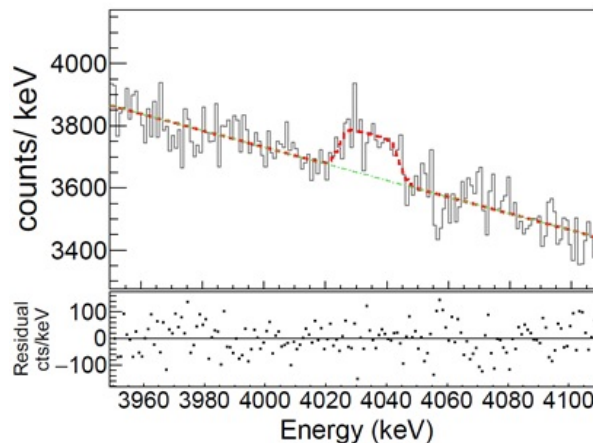**Figure 2.** Computer-aided design drawing of the GADGET system [8].

Figure 3. Preliminary spectrum of ^{31}Cl beta delayed protons from a single pad of GADGET's Proton Detector micromegas, vetoed by all other pads. Figure courtesy of Tamas Budner.

of interest, but is nearly transparent to the beta particles pushing the corresponding background below 200 keV. SeGA can be used to check if low-energy proton emissions are to excited final states or to the ground state of astrophysical interest using proton-γ coincidences. Figure 3 shows a preliminary proton spectrum including a peak with an energy and intensity that appear to be consistent with the expected properties of the 259-keV resonance. Analysis is ongoing to extract the proton branching ratio.

3. The ^{15}O(α,γ)^{19}O reaction in X-ray bursts
While novae primarily rely on Ne seeds in the underlying white dwarf to initiate the synthesis of heavier nuclides, X-ray busts can reach temperatures up to 2 GK enabling material to break-out from the CNO cycles into the rapid-proton capture process [9]. As temperatures are increasing
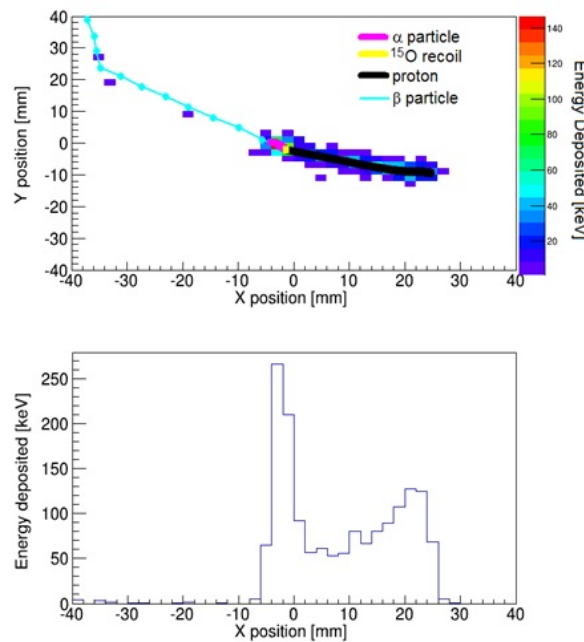
Figure 4. Portion of the cumulative spectrum of ^{20}Mg beta delayed gamma rays from SeGA showing the 4.03 MeV ^{19}Ne peak [6]. The fit incorporates Doppler broadening caused by proton emission [14].

during the thermonuclear runaway, the ^{15}O(α,γ)^{19}Ne(p,γ)^{20}Na reaction sequence is expected be be the first one to allow break-out to occur. Sensitivity studies have shown that the large uncertainties associated with the ^{15}O(α,γ)^{19}Ne reaction rate, in particular, have the greatest uncertainty of any reaction on the predicted shape of the X-ray burst slight curve [10]. It is known from previous work that a single resonance at an excitation energy of 4.03 MeV in ^{19}Ne dominates the reaction rate, but the resonance strength is unknown [11]. The lifetime of the state is well known, but measurements using various nuclear reactions to populate the 4.03 MeV state have only led to strong upper limits on the alpha-particle branching ratio. A finite experimental value for the small alpha-particle branching ratio is the last essential piece of data needed to determine the thermonuclear rate.

We used a similar method to our first ^{31}Cl beta decay experiment, employing SeGA instead, to measure the beta delayed gamma decay of ^{20}Mg. We detected a 4.03-keV gamma ray showing that the key 4.03 MeV ^{15}O(α,γ)^{19}Ne resonance is populated via ^{20}Mg beta delayed proton decay [12]. This presents an opportunity to measure the alpha-particle branching ratio in the future using ^{20}Mg decay. Using a Doppler broadening analysis technique [13], the energy of the proton transition populating the resonance was measured to be $\approx$ 1.2 MeV [14]. An additional astrophysical result of this experiment was a spin and parity constraint for the key resonance of the ^{19}Ne(p,γ)^{20}Na reaction, resolving a longstanding debate [15].

In order to measure the alpha particle branching ratio of the 4.03 MeV ^{19}Ne state using ^{20}Mg decay, one needs to detect the 1.2-MeV proton emission feeding the state and the 0.5 MeV alpha-particle emission. We are currently upgrading GADGET's Proton Detector into a time projection chamber (TPC) in order to perform this experiment at NSCL. The upgrade will increase the number of Micromegas pads from 13 to over 1000 and include high density GET electronics enabling a three-dimensional picture of the charged-particle energy loss as a function of position for each event. Figure 5 shows a simulation of the events of interest, which will have a unique signature to identify them: the proton Bragg curve with an alpha-particle spike at the base.
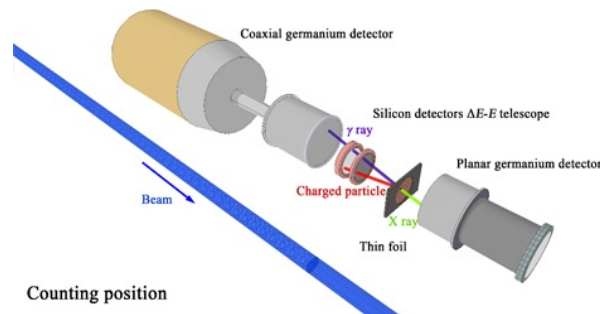
Figure 5. GADGET TPC simulation of a ^{20}Mg$(\beta$ p $\alpha)^{15}$O decay event proceeding through the ^{19}Ne state at 4.03 MeV. Figure courtesy of David Perez-Loureiro.

4. Future opportunities at FRIB

The Facility for Rare Isotope Beams (FRIB) is a world leading next-generation rare-isotope currently under construction at Michigan State University. It is funded by the U.S. Department of energy with contributions and cost share from Michigan State University. The key feature of FRIB is a 400 kW linear accelerator of heavy ions up to ^{238}U. The FRIB accelerator will essentially replace NSCL's cyclotrons providing orders of magnitude higher beam power, corresponding to orders of magnitude higher secondary rare-isotope beam intensities delivered to existing and new experimental areas and equipment. FRIB will be capable of rapidly developing a fast beam of any bound isotope, regardless of its chemical properties or half life, and delivering it to experimenters. These beams can also be thermalized and re-accelerated. Beneficial occupancy of the new FRIB building was achieved in March 2017 and technical construction and commissioning are currently progressing in parallel. First beams may become available to the user community of over 1400 researchers as early as 2022, with the initial primary beam power of ≈ 10 kW ramping up over time.

The FRIB Decay Station (FDS) has been proposed in order to take full advantage of FRIB beams. It is a modular system for the detection of all radiations associated with nuclear decays that can be moved between a fast-beam area or a thermalized beam area. For example, it will be capable of operating with various combinations of: a stack of Si detectors for charged-particle detection, a time projection chamber for charged-particle detection, a high-purity germanium array for high-resolution gamma-ray detection, a total absorption gamma-ray spectrometer for high-efficiency gamma-ray detection, a ^{3}He-n neutron moderator and counter, and a neutron spectrometer. For explosive astrophysical scenarios, the FDS will be capable of measuring important nuclear data such as half-lives, branching ratios, beta-decay strength functions, resonance properties, and statistical properties. GADGET's Proton Detector is part of the FDS Demonstrator, which will use existing equipment to perform experiments in the first few

Figure 6. Concept for a PXCT detection setup at FRIB. The thin foil is cycled between intercepting the low-energy beam path and the counting position. Figure courtesy of Lijie Sun.

years of FRIB operations before a suite of new detectors becomes available.

Besides further experiments using GADGET and the FDS, our group is pursuing an independent project to revitalize and expand upon the Particle X-ray Coincidence Technique (PXCT) [16] at FRIB. Electron-capture decays leave a vacancy in a low-lying atomic shell, which will quickly be filled by an electronic transition that emits an X-ray with an energy that is characteristic of the atomic number of the nucleus. If the electron capture populates a particle-unbound state then the particle emission (typically a proton or alpha particle) can have a similar timescale to the X-ray emission. If the X-ray is emitted first then its energy will be characteristic of the electron-capture daughter. If the proton is emitted first then the X-ray energy will be characteristic of the particle-emission daughter, which has different Z. By measuring the X-ray spectrum and integrating the two X-ray peaks, one can determine the lifetime of the proton emitting state since the atomic lifetimes are well known. In the past, this method has only been used to measure the average lifetimes as a function of excitation energy.

The goal of our PXCT setup (Figure 6) is to simultaneously measure both the lifetimes and branching ratios of individual resonances that are important for modeling explosive astrophysical scenarios. Doing so would yield the strengths of those resonances and an opportunity to set lower limits on the thermonuclear reaction rates. We are particularly interested in constraining the thermonuclear rates of the ^{59}Cu(p,α)^{56}Ni and ^{59}Cu(p,γ)^{60}Zn reactions using the beta decay of ^{60}Ga. Competition between these reactions affects the NiCu cycle in Type-I X-ray bursts, making them the 2nd- and 3rd-most important reactions to constrain in order to accurately model X-ray burst light curves [10]. Our new PXCT setup will also be capable of measuring the transmission coefficients needed for statistical model calculations of the thermonuclear photodisintegration rates affecting the nucleosynthesis yields of the γ-process in supernovae, which likely produces many of the p nuclides that can't be produced by neutron capture processes.

5. Conclusions

Explosive astrophysical scenarios typically require accurate data on nuclear reactions involving unstable reactants, which are difficult to measure directly. Beta decay can be used to populate resonances in those reactions and measure all of their relevant properties. Our group has been using high-purity germanium detectors to measure beta delayed gamma rays from resonances at NSCL. Recently, we have developed a new detection system, GADGET, to measure weak low-energy beta delayed protons. We are currently upgrading GADGET into a TPC in order to measure multiple charged-particle emissions. In a few years FRIB will become operational enabling much higher statistics to be obtained in beta decay experiments. The FDS is being developed for decay experiments that FRIB; GADGET will be part of the initial FDS

Demonstrator. FRIB will also enable us to revise and expand upon PXCT and apply the results to various explosive astrophysical scenarios.

References

[1] Jose J, Hernanz M, and Iliadis C 2006 *Nucl. Phys. A* **777** 550
[2] Jose J, Hernanz M, Amari S, Lodders K, and Zinner E 2004 *Astrophys. J.* **612** 414
[3] Wrede C 2014 *AIP Advances* **4** 041004
[4] Bennett M B *et al.* 2013 *Phys. Rev. Lett.* **111** 232503
[5] Perez-Loureiro D *et al.* 2016 *Phys. Rev. C* **93** 064320
[6] Bennett M B *et al.* 2016 *Phys. Rev. Lett.* **116** 102502
[7] Bennett M B *et al.* 2018 *Phys. Rev. C* **97** 065803
[8] Friedman M *et al.* 2019 *Nucl. Instrum. Methods Phys. Res., Sect. A* **940** 93
[9] Wallace R K and Woosley S E 1981 *Astrophys. J. Suppl. Ser.* **45** 389
[10] Cyburt R *et al.* 2016 *Astrophys. J.* **830** 55
[11] Davids B, Cyburt R H, Jose J, and Mythili S 2011 *Astrophys. J.* **735** 40
[12] Wrede C *et al.* 2017 *Phys. Rev. C* **96** 032801(R)
[13] Schwartz S B *et al.* 2015 *Phys. Rev. C* **92** 031302(R)
[14] Glassman B E *et al.* 2019 *Phys. Rev. C* **99** 065801
[15] Glassman B E *et al.* 2018 *Phys. Lett. B* **778** 397
[16] Hardy J C *et al.* 1976 *Phys. Rev. Lett.* **37** 33