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Measuring the ^{15}O(α, γ)^{19}Ne reaction in Type I X-ray bursts using the GADGET II TPC: Hardware

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Abstract. Sensitivity studies have shown that the ^{15}O(α, γ)^{19}Ne reaction is the most important reaction rate uncertainty affecting the shape of light curves from Type I X-ray bursts. This reaction is dominated by the 4.03 MeV resonance in ^{19}Ne. Previous measurements by our group have shown that this state is populated in the decay sequence of ^{20}Mg. A single ^{20}Mg(βpα)^{15}O event through the key ^{15}O(α, γ)^{19}Ne resonance yields a characteristic signature: the emission of a proton and alpha particle. To achieve the granularity necessary for the identification of this signature, we have upgraded the Proton Detector of the Gaseous Detector with Germanium Tagging (GADGET) into a time projection chamber to form the GADGET II detection system. GADGET II has been fully constructed, and is entering the testing phase.

1 Astrophysical Motivation

When a neutron star is orbited by a low-mass population II star it will accrete hydrogen-rich material from this binary companion via a process called Roche lobe overflow. The temperatures and densities on the surface of the neutron star are such that the accreted hydrogen is continuously fused into helium. Eventually the helium is ignited and a thermonuclear runaway proceeds. This can lead to the synthesis of proton-rich nuclides up to mass number 100, and extremely powerful X-ray bursts [1]. These X-ray bursts are measured using space based telescopes, and the shape of the resulting light curves can in principle reveal interesting properties of the neutron star itself (mass, radius, crust elemental abundance). However, there are nuclear reaction rate uncertainties that significantly affect the shapes of simulated light curves [2]. Sensitivity studies have shown that for breakout temperatures of ~0.5 GK, the $^{15}O(\alpha, \gamma)^{19}Ne$ reaction is the most important reaction rate uncertainty that needs to be determined to properly constrain the modelling of Type I X-ray burst light curves [3].

2 Measuring the Reaction

Ideally, we would measure the $^{15}O(\alpha, \gamma)^{19}Ne$ reaction directly, but given that ^{15}O is radioactive ($t_{1/2} \sim 122$ s), beams of sufficient intensity are not currently available. However, the resonance strength, and by extension the reaction rate, can be determined indirectly from the spin, lifetime, and alpha particle branching ratio (Γ_α/Γ). The spin and lifetime are well known, so only Γ_α/Γ needs to be measured [4]. Thankfully, only one dominant resonance determines the $^{15}O(\alpha, \gamma)^{19}Ne$ reaction rate, which corresponds to the 4.03 MeV state in ^{19}Ne. We need only feed this one state to determine Γ_α/Γ [4]. There have been attempts to measure Γ_α/Γ using direct reactions to populate the 4.03 MeV state, but such attempts have only produced a strong upper limit of $(2.9 \pm 2.1) \times 10^{-4}$ [5]. We have proposed a different method for populating the state that will allow us to measure a finite value for Γ_α/Γ. Previous measurements by our group have shown that this state is populated in the $^{20}Mg(\beta p\alpha)$ decay sequence. Additionally, a single $^{20}Mg(\beta p\alpha)^{15}O$ event through the key $^{15}O(\alpha, \gamma)^{19}Ne$ resonance yields a characteristic signature—the simultaneous emission of a proton and alpha particle [6]. This signature is a unique 3D topology that will allow for a finite measurement of Γ_α/Γ and, hence, the thermonuclear rate of the reaction.

To produce the requisite amount of ^{20}Mg for this experiment we will be running at the Facility for Rare Isotope Beams (FRIB). FRIB is the new nuclear facility being built at Michigan State University that will be operational in 2022. Our PAC approved FRIB experiment will use a ^{36}Ar primary beam that will impinge on a ^{12}C target to create a fast beam of ^{20}Mg that will feed the 4.03 MeV ^{19}Ne resonance.

3 GADGET II

To achieve the granularity necessary for the identification of the events of interest, we have upgraded the Proton Detector of the Gaseous Detector with Germanium Tagging (GADGET) into a time projection chamber to form the GADGET II detection system. GADGET II has three distinct elements: a beam-pipe cross with a beam energy degrader and a silicon detector for beam particle identification, the Segmented Germanium Array (SeGA) for γ detection, and the TPC that fits inside SeGA (see figure 1, left panel) [7].

The TPC will allow us to reconstruct 3D images of the decay events inside our detector. Conventional cuts complemented by image reconstruction will enable a background-free measurement of the proton-alpha coincidence events of interest. Our TPC has a compact cylindrical geometry and will be filled with a gas such as P10 (90% Argon, 10% Methane) that acts both as a beam stop for the fast ^{20}Mg beam and the detection medium via ionization electrons. A homogeneous electric field causes the electrons to drift until the charge cluster is collected on a resistive Micromegas. The Micromegas was constructed by the European Organization for Nuclear Research (CERN) and is comprised of over one thousand 2.2 x 2.2 mm^2 pads that will provide the necessary position resolution in 2D, and the difference in drift time for the arriving electrons will provide the third dimension. Once 3D images of decay events are constructed we will use a machine learning algorithm, (a convolutional neural network), to identify the events of interest based on their unique topology.

To accommodate the high density of signals from our TPC we have implemented a new data acquisition system. This new system is the GET System, which stands for Generic Electronics for TPC's, and is a scalable and generic electronics system that was originally designed for gas-filled detector applications in nuclear physics including TPCs [8]. To attach the corresponding front-end electronics to our detector we designed what we call the AsAd box (see figure 1). The AsAd box houses these components in a copper box that acts as a Faraday Cage to prevent EM radiation from inducing noise.

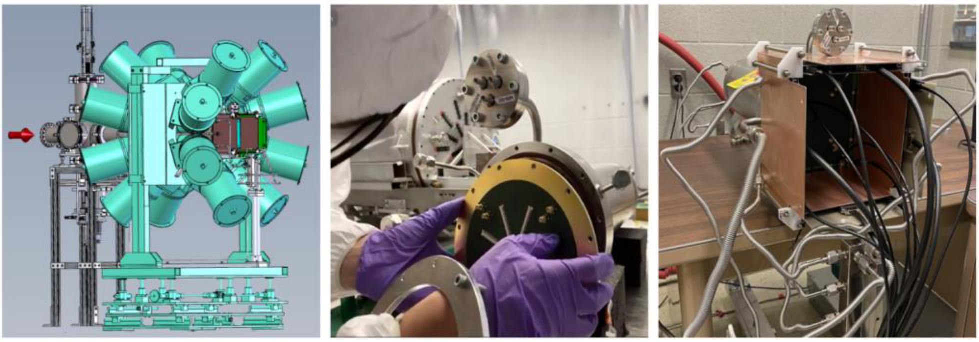

Fig. 1. Left Panel: CAD drawing of the full GADGET II setup, including the beam-cross, SeGA array, and TPC. Middle Panel: Micromegas being installed on GADGET II TPC. Right Panel: Assembled AsAd box attached to the TPC.

GADGET II has been fully constructed and has entered the bench-top testing phase. A radioactive alpha source (^{228}Th) was installed in the GADGET II gas handling system, which allows us to bleed ^{220}Rn into the detector. The alpha signals from the ^{220}Rn alphas have been successfully detected, demonstrating the system's functionality. We are now in the process of comparing detector events to detailed simulations for calibration purposes. GADGET II will be ready to run the ^{15}O(α, γ)^{19}Ne experiment in early 2022.

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