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β delayed γ decay measurements to probe thermonuclear astrophysical explosions

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We describe a program of β delayed γ decay measurements to reduce and quantify several of the most important nuclear physics uncertainties associated with nucleosynthesis and energy generation in classical novae and type I x-ray bursts. These measurements employ beams of rare isotopes at the proton drip line produced by projectile fragmentation, and large arrays of high-purity germanium detectors. Using ^{26}P decay, we have observed the first evidence for the exit channel of the key ^{25}Al$(p,\gamma)^{26}$Si resonance in novae. This experiment has enabled an estimate of the nova contribution to the Milky Way's ^{26}Al abundance that is effectively free of nuclear-physics uncertainties. We recently collected a high-statistics data set on the β delayed γ decay of ^{31}Cl, which selectively populates $L = 0$ resonances in the ^{30}P$(p,\gamma)^{31}$S reaction, in order to identify these resonances with shell-model ones and calculate their strengths. This reaction is a bottleneck whose uncertain rate strongly influences nucleosynthesis in novae on white dwarfs near the Chandrasekhar mass and the identification of candidate presolar nova grains. In the near future, we plan to experimentally test the feasibility of a novel β-decay method to determine the unknown ^{15}O$(\alpha,\gamma)^{19}$Ne reaction rate, which is believed to initiate breakout from the hot CNO cycles in type I x-ray bursts.

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1. Introduction

Classical novae and type I x-ray bursts are luminous thermonuclear explosions occurring on the surfaces of dead compact stars that are accreting fresh hydrogen-rich fuel from close binary companions. In a classical nova, a white dwarf star is the accretor and peak temperatures of 0.4 GK can be reached driving nucleosynthesis that begins with seed nuclei of C, O, Ne, and Mg within the white dwarf along a path of proton captures and β decays up to masses as high as $A = 40$ [1], or higher [2]. Freshly synthesized nuclides are ejected from a nova and they can be observed in the form of characteristic photons or in the form of pre-solar grains in primitive meteorites. In a type I x-ray burst, a neutron star is the accretor and peak temperatures of 1-2 GK are reached, allowing for break-out from the CNO cycles via α particle captures, leading to the rapid proton-capture process, which may terminate around $A = 100$ [3]. In this case, the gravitational potential well is so deep that most of the explosive ashes are expected to fall back to the surface of the neutron star and the primary observable is the x-ray burst light curve [4].

Thermonuclear proton and α-particle capture reaction rates influence energy generation and nucleosynthesis in classical novae and type I x-ray bursts, affecting their observable properties. It is, therefore, important to constrain the most influential rates experimentally in order to make accurate comparisons between astrophysical models and observations. For example, the ^{25}Al$(p,\gamma)^{26}$Si reaction rate affects the classical-nova production of the radionuclide ^{26}Al [5], whose decay has been observed in the interstellar medium [6, 7]. Similarly, the ^{30}P$(p,\gamma)^{31}$S reaction affects the modeled silicon isotopic abundances in nova ejecta [8], which can be compared to those measured in candidate presolar nova grains to verify their origin. Finally, the ^{15}O$(\alpha,\gamma)^{19}$Ne reaction triggers nucleosynthetic break-out from the CNO cycles affecting energy generation and the shapes of type I x-ray burst light curves [9, 10, 11, 12]. We have initiated a program of experiments at Michigan State University's National Superconducting Cyclotron Laboratory (NSCL) to constrain these three reaction rates using the β delayed γ decays of ^{26}P, ^{31}Cl, and ^{20}Mg, respectively.

2. Galactic ^{26}Al: β decay of ^{26}P and the ^{25}Al$(p,\gamma)^{26}$Si reaction in novae

The ^{25}Al$(p,\gamma)^{26}$Si reaction is dominated by a $J^{\pi} = 3^{+}$ resonance at an excitation energy of 5.93 MeV in ^{26}Si corresponding to a center of mass resonance energy of 0.41 MeV [13]. Proton emission has previously been observed to be the dominant decay branch from this resonance [14]; the weaker and unmeasured γ-decay branch determines the resonance strength. Conveniently, ^{26}P β decay strongly populates the 3^{+} resonance of interest [13]. NSCL can produce over 100 ^{26}P ions per second and we designed an experiment at NSCL to measure the 1.74 MeV ^{26}P β delayed γ ray through this resonance for the first time [15]. We implanted a fast ^{26}P beam into a planar germanium double sided strip detector (GeDSSD) [16], which was surrounded by the SeGA array of Ge detectors [17]. We used the GeDSSD as a β particle detector to trigger SeGA's detection of β delayed γ rays. Figure 1 shows a portion of the β delayed γ ray spectrum acquired in the region of interest including the 1.74-MeV γ ray peak. The absence of a more intense 1.74-MeV peak in this experiment enabled the first estimate of the amount of ^{26}Al produced by classical novae that was effectively independent of nuclear physics uncertainties. More details about the experimental results and the astrophysical simulations can be found in Refs. [18, 19].

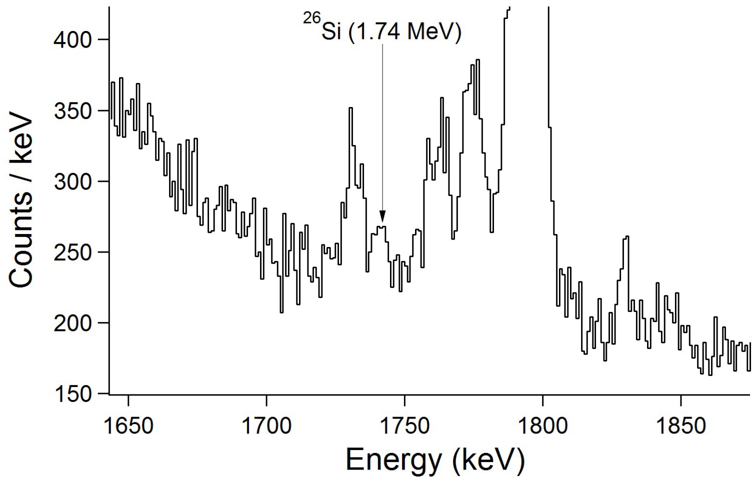

Figure 1: ^{26}P β delayed γ ray spectrum showing the peak corresponding to the 1.74-MeV transition of interest. A detailed fit identifying all of the features is shown in Refs. [18, 19].

3. Pre-solar grain ID: β decay of ^{31}Cl and the ^{30}P$(p,\gamma)^{31}$S reaction in novae

There are many known ^{31}S excited states that could potentially contribute to the ^{30}P$(p,\gamma)^{31}$S reaction rate as resonances at nova temperatures [20]. However, it is not yet clear which of these resonances are the most important ones because the detailed properties of the resonances are not yet known. Considering that the spin/parity of ^{30}P is 1^+, the $L = 0$ proton captures (which have no centrifugal barrier to suppress their strengths) populate 1/2$^+$ and 3/2$^+$ states in ^{31}S. Conveniently, the β decay of 3/2$^+$ ^{31}Cl proceeds via allowed transitions to ^{31}S states with spin/parities of 1/2$^+$, 3/2$^+$, and 5/2$^+$, providing a means to populate and identify some of the most important states [21]. Shell model calculations [22] predict that the allowed ^{31}Cl β decay transition intensities to ^{31}S levels in the region of interest are all above 0.01%.

Based on the shell-model calculations, we designed a ^{31}Cl β delayed γ decay experiment at NSCL to be sensitive to all of the $1/2^+$, $3/2^+$, and $5/2^+$ ^{31}S levels in the region of astrophysical interest. In principle, the experimental setup was similar to that of the ^{26}P-decay experiment, except the detectors were all different. Due to ^{31}Cl beam rates in excess of 10^4 ions per second, we implanted the ^{31}Cl beam into a plastic scintillator to act as the β decay trigger. The scintillator was surrounded by an array of 9 Ge "clover" detectors that was used to detect β delayed γ rays. Thanks to the intense beam provided by NSCL and the high γ-ray efficiency provided by the clovers, we obtained a very high statistics data set of ^{31}Cl β delayed γ rays including γ-γ coincidences. The data are currently under analysis; Figure 2 shows a portion of the ^{31}Cl β delayed γ-ray spectrum containing roughly 4% of the statistics acquired. Of particular note is the new 6.39 MeV transition, which may help to shed light on the number of levels in the 6.39 to 6.40 MeV region [20].

4. CNO break out: β decay of ^{20}Mg and the ^{15}O$(\alpha,\gamma)^{19}$Ne reaction in x-ray bursts

The ^{15}O$(\alpha,\gamma)^{19}$Ne reaction is dominated by a resonance at 4.03 MeV in ^{19}Ne at the temperatures of CNO-cycle break-out in type I x-ray bursts [23]. While the resonance energy is known, it

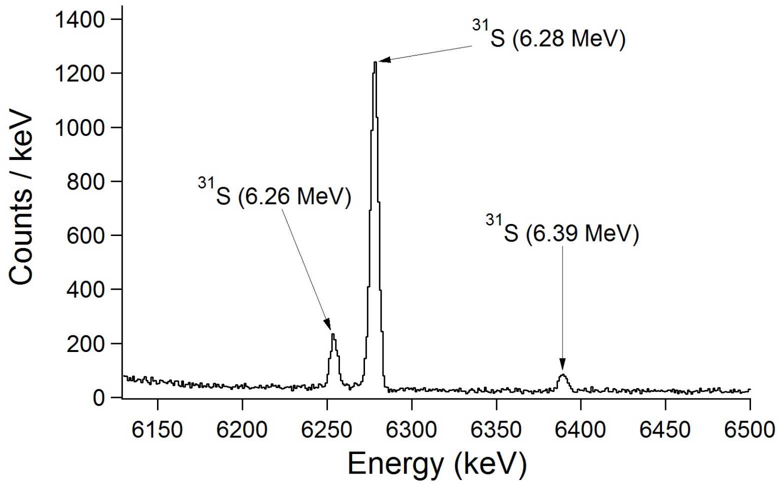

Figure 2: Preliminary ^{31}Cl β delayed γ ray spectrum showing approximately 4% of the total statistics acquired.

has not been possible to measure the resonance strength because the Coulomb barrier suppresses the width of the α-particle entrance channel. There are no facilities in the world that are able to produce a sufficiently intense ^{15}O beam to measure this resonance strength directly. However, since the lifetime of the ^{19}Ne resonance has been measured [24, 25], one only needs to determine the $\approx 10^{-4}$ α-particle emission branch in order to determine the resonance strength. Several efforts have been made to measure this branch by populating the 4.03 MeV level using nuclear reactions but these have effectively only led to upper limits [26, 27, 28, 23].

As shown in Figure 3, it is also energetically possible to populate the ^{19}Ne resonance of interest using the β delayed proton decay of ^{20}Mg. This feeding has not yet been observed, but it is already known that $T = 1$ ^{20}Na levels above the ^{19}Ne(4033 keV)+p energy threshold are populated with an intensity greater than 0.5% in ^{20}Mg β decay [29]. These levels must have at least a small decay branch to the 4.03 MeV level of interest. We have prepared a proposal that was accepted by the NSCL PAC to measure ^{20}Mg β delayed γ decay with the goal of detecting the 4.03 MeV γ ray, which would quantify the population of the ^{19}Ne level of interest. If population of the 4.03 MeV level is detected, then it will facilitate the planning of future ^{20}Mg($\beta p\alpha$)^{19}Ne decay experiments to measure the α particle emission branch from the 4.03 MeV ^{19}Ne level and determine the ^{15}O(α,γ)^{19}Ne reaction rate experimentally. For example, this could be measured using a time projection chamber.

5. Conclusions

In conclusion, a program is underway at the NSCL to constrain some of the most important nuclear physics uncertainties associated with models of classical novae and type I x-ray bursts. A measurement of the β decay of ^{26}P to constrain the ^{25}Al(p,γ)^{26}Si reaction rate has been completed, removing the last nuclear-physics uncertainty associated with the amount of radioactive ^{26}Al in the Milky Way from classical novae. A high-statistics data set has been acquired on the β decay of

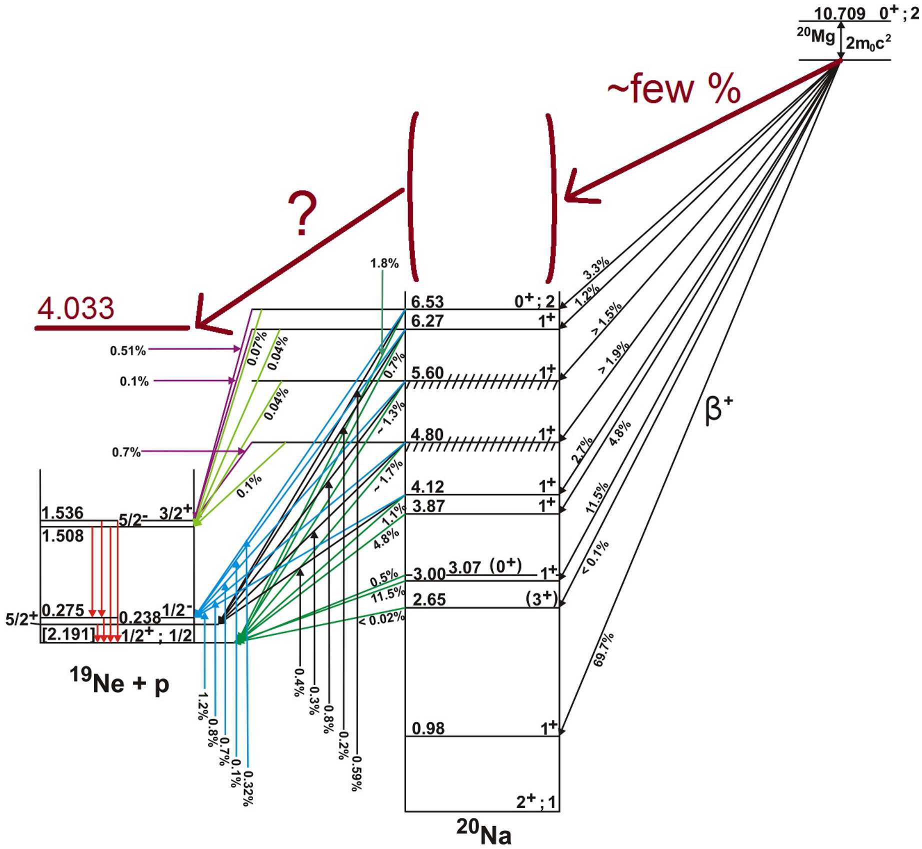

Figure 3: ^{20}Mg β decay scheme adapted from the TUNL evaluation [30] to include the measured feeding of ^{20}Na states above the $T = 2$ isobaric analog state followed by potential transitions to the 4033 keV state in ^{19}Ne.

^{31}Cl in order to constrain the ^{30}P$(p,\gamma)^{31}$S reaction rate in novae and facilitate the identification of pre-solar nova grains. We have also introduced a new method based on ^{20}Mg β decay to determine the elusive rate of the ^{15}O$(\alpha,\gamma)^{19}$Ne reaction, which is expected to trigger CNO cycle break out in type I x-ray bursts.

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