Nova nucleosynthesis and production of the radioisotope $^{18}$F

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Abstract. Novae are cataclysmic stellar explosions driven by nuclear physics under extreme conditions. An important probe of nova conditions could come from the observation of long-lived radioisotopes such as $^{18}$F that are produced during the explosion process. To interpret such observations, however, the rates of reactions creating and destroying $^{18}$F need to be determined. A variety of direct and indirect studies have greatly reduced uncertainties in nova $^{18}$F production. Recent results are reviewed along with prospects for future progress.

1. Introduction

Nova explosions are brilliant astrophysical events resulting from the accretion of hydrogen-rich material onto a degenerate white dwarf from a binary companion [1]. Convection mixes underlying white dwarf material with this layer of hydrogen, and thermonuclear reactions are initiated as the temperatures and densities rise. These reactions produce radioactive proton-rich nuclei, which can undergo further proton-induced reactions before they decay [2]. The explosion dynamics and nucleosynthesis produced in novae are therefore strongly dependent upon the reaction rates and the properties of the proton-rich exotic nuclei produced.

A significant constraint on model predictions could come from the observation of decay $\gamma$ rays from long-lived radioisotopes that were produced in the explosion [3]. Possible candidates include $^{17}$N, $^{18}$F, $^{22}$Na, and $^{26}$Al – each of which may be the most important during a characteristic time window after the explosion. Model calculations indicate that during the first day after the explosion, the $\gamma$-ray emission is dominated by the decay of $^{18}$F [4]. Ideally, one would like to compare observations of $^{18}$F decay from novae with model predictions that are based upon experimentally determined nuclear reaction rates. In particular for $^{18}$F production, the rates of the $^{18}$F(p,$\alpha$)$^{15}$O and $^{17}$F(p,$\gamma$)$^{18}$Ne reactions are needed to determine the destruction and production rates of $^{18}$F, respectively. The $^{18}$F(p,$\alpha$)$^{15}$O reaction is faster than $^{18}$F $\beta$ decay at nova temperatures and is the primary destruction mechanism of $^{18}$F in the nova environment. The $^{17}$F(p,$\gamma$)$^{18}$Ne reaction creates $^{18}$Ne, which in turn decays to $^{18}$F, and is one of the primary production channels for $^{18}$F. An alternative production mechanism is through the $^{17}$O(p,$\gamma$)$^{18}$F reaction which is favoured in cooler scenarios. The $^{17}$O(p,$\gamma$)$^{18}$F reaction is fairly-well characterized since it can be measured directly with stable beams and targets. There remain, however, large uncertainties in the $^{18}$F(p,$\alpha$)$^{15}$O and $^{17}$F(p,$\gamma$)$^{18}$Ne astrophysical reaction rates since their direct measurements at nova energies would require very high intensities ($>10^8$ ion/s) of radioactive $^{17,18}$F beams, which are currently not available anywhere in the world.
Figure 1: Nuclear reactions in a nova explosion that can affect the production of $^{18}$F.

In this manuscript, recent efforts to experimentally constrain the astrophysical rate of the $^{18}$F(p,α)$^{15}$O reaction are reviewed. Direct measurements of the reaction cross sections have been possible at energies primarily above those of astrophysical interest [5-9]. However, the information at higher energies can be used to estimate and extrapolate the cross sections to lower energies. Further information has come from indirect structure studies of the nuclei involved via transfer [10-12] and elastic scattering [13,14] measurements. The studies are complemented with stable-beam measurements [15-17], which have been critical for a more complete understanding of the nuclear structure. It is only after a combination of the various methods using both radioactive and stable beams that we can arrive at an experimentally justified reaction rate. It is critical that advances in beam production, detector development, and target technology be pursued to create opportunities for new and better measurements with the uncertainties required to address the rapidly increasing database of astrophysical observations.

2. The $^{18}$F(p,α)$^{15}$O Reaction

The $^{18}$F(p,α)$^{15}$O reaction cross section is dominated by the influence of resonances arising from levels in $^{19}$Ne near and above the proton threshold at $E_x=6.411$ MeV [18]. Known levels in $^{19}$Ne near the proton threshold are shown in Figure 2 along with established mirror levels in $^{19}$F. At higher astrophysical temperatures ($T \geq 0.3$ GK), the reaction rate is dominated by a 3/2+ resonance at $E_{c.m.} = 665$ keV and a 3/2- resonance at 330 keV, respectively. The strengths of these resonances have been measured directly [5,6] using intense radioactive beams of $^{18}$F at the Holifield Radioactive Ion Beam Facility (HRIBF) [19] and were verified by later measurements [8] at the Tri-University Meson Facility (TRIUMF) where the cross section was measured at even lower energies. Measurements of the $^{18}$F(p,α)$^{15}$O cross section are shown in Figure 3. Since the cross sections decrease rapidly at lower energies, the uncertainties in the cross section data are too large to effectively constrain the extrapolation to energies of novae interest. Large variations are possible in the $^{18}$F(p,α)$^{15}$O cross section at these energies owing to the interference of near threshold levels with broad higher-lying resonances [8, 10, 20]. Additional uncertainties exist because, as can be seen in Figure 1, several levels are known in $^{19}$F for which mirrors have not been established in $^{19}$Ne. Further insights were made with the investigation of indirect studies of the reaction rate.
**Figure 2:** Known energy levels in $^{19}\text{Ne}$ above the $^{18}\text{F}+p$ threshold along with established mirror assignments. The energies for $^{19}\text{Ne}$ levels are taken from Ref. [15,18]. $^{19}\text{F}$ levels are from the compilation [29] with updates from Ref. [21].

**Figure 3:** $^{18}\text{F}(p,\alpha)^{15}\text{O}$ cross section measurements from Ref. [5-8] along with several calculated cross section extrapolations that are consistent with the measured data. Figure adopted from Ref. [8].
3. Studies of the $^{18}$F(d,p)$^{19}$F and $^{18}$F(d,n)$^{19}$Ne reactions

To gain further insight into the nature of the near threshold levels in $^{19}$Ne, single-nucleon transfer reactions were studied on the intense $^{18}$F beams available at the HRIBF [11,12] and at Louvain-la-Neuve [10]. Additional goals were to search for “missing” levels in $^{19}$Ne and to provide the first estimates of single-particle strength based upon experimental data. The presumption was that any levels with appreciable single-particle strength and thus astrophysical importance would be populated in such studies and “missing” levels that were not observed were probably of lower importance.

In studies of the $^{18}$F(d,p)$^{19}$F reaction [10,11], beams of $^{18}$F were used to bombard CD$_2$ targets and reaction protons were detected in arrays of silicon-strip detectors. Since $^{18}$F is an N=Z nucleus, transferring a neutron onto $^{18}$F should populate the mirrors to strong single-proton levels in $^{19}$Ne. Such a study, therefore, can provide experimental constraints on strengths and guide future measurements. The primary difference between the two studies was that one [10] was performed at 0.78 MeV/u while the other [11] was performed at 6 MeV/u. Despite these differences, both studies found significant single-particle strength was concentrated in the excitation energy region of $^{19}$F corresponding to mirror levels near the proton threshold in $^{19}$Ne. The angular distributions were consistent with the strength being concentrated in an s-wave resonance, and the conclusion was that interference between such a resonance and higher-lying 3/2$^+$ resonances (such as the known 665-keV resonance) could significantly alter estimates of the $^{18}$F(p,α)$^{15}$O reaction rate.

Motivated in part by these results, a proton-transfer study was initiated at the HRIBF to find where this single-particle proton strength actually exists in $^{19}$Ne and to measure the properties of the states in which the strength is manifested. The experiment consisted of a measurement of the $^{18}$F(d,n)$^{19}$Ne reaction using a 150-MeV $^{18}$F beam to bombard a CD$_2$ target [12]. Because the states of interest are well above the alpha threshold, the produced $^{19}$Ne nuclei immediately decay by α emission to $^{15}$O. The forward-going α and $^{15}$O ions were detected in coincidence in position-sensitive silicon telescopes. From the measured energies and angles of the decay products, the kinematics of the (d,n) reaction could be reconstructed. The excitation energy spectrum produced from such a reconstruction is shown in Figure 4. Analysis of the results showed that the mirror to the strong state observed in the $^{18}$F(d,p)$^{19}$F reaction studies was actually below the proton threshold in $^{19}$Ne. The state was observed at $E_x=6.29$ MeV in $^{19}$Ne which means it is actually a subthreshold resonance at $E_{c.m.}=-121$ keV in the $^{18}$F(p,α)$^{15}$O reaction [12]. The influence of this resonance was still uncertain however because the single-particle transfer reactions were only sensitive to the transferred angular momentum. The 6.29-MeV level was populated by an s-wave resulting in possible spin assignments of 1/2$^+$ or 3/2$^+$. Either spin assignment would result in interference with higher lying resonances, but the interference would be quite different depending upon the energies and widths of these resonances (i.e., interference with the $E_{c.m.}=665$ keV 3/2$^+$ resonance would produce a much larger effect that interference with possible 1/2$^+$ resonances which are expected above $E_{c.m.}=1$ MeV) [12,20]. Further constraints on the spin of the subthreshold resonance were needed to better understand the implications.

4. Study of the $^{20}$Ne(p,d)$^{19}$Ne reaction

These further constraints would come from studies of the $^{20}$Ne(p,d)$^{19}$Ne reaction. States with spins of 1/2$^+$ and 3/2$^+$ would be populated with L = 0 and 2 angular momentum transfers, respectively. The angular distributions of outgoing deuterons would be very different for the two cases, and thus the spin of the subthreshold state could be determined.
Figure 4: The reconstructed energy spectrum produced from the $^{18}\text{F}(d,n)^{19}\text{Ne}*(\alpha)^{15}\text{O}$ reaction. Figure adopted from Adekola et al. [12].

A first attempt at measuring the $^{20}\text{Ne}(p,d)^{19}\text{Ne}$ reaction was attempted in 2011 using a 30-MeV proton beam at the HRIBF [22,23]. Data from such a study had never been previously published owing in part to the difficulty in making a sufficiently dense and localized $^{20}\text{Ne}$ target. Implanted targets [24] containing ~1-3 μg/cm² of $^{20}\text{Ne}$ in a 40 μg/cm² carbon foil were used. Outgoing deuterons were detected in the SIDAR Silicon Detector array [25] covering laboratory angles between 30-70 degrees. The detectors were configured in telescope mode so that deuterons could be distinguished from other reaction products. Clean separation was possible [22], but (p,d) reactions on the host carbon atoms proved to be too intense to distinguish deuterons from the $^{20}\text{Ne}(p,d)^{19}\text{Ne}$ reaction.

A better quality $^{20}\text{Ne}$ target was needed, and fortunately the Jet Experiments in Nuclear Structure and Astrophysics (JENSA) [26] target was under construction. The target operates via the injection of target gas at ~30 atm of pressure through a Laval nozzle resulting in a jet focus several mm away. The unreacted gas then exits the target chamber though conical receivers to be recompressed by several pumping stages and an industrial compressor in preparation for recirculation and reinjection back into the chamber. The target chamber is also differentially pumped through apertures ranging in diameter from 3-28 mm through which the beam is tuned. The interaction point of the beam with the gas jet is surrounded by arrays of silicon detectors such as SIDAR, ORRUBA [27], and SuperORRUBA [28].

For the $^{20}\text{Ne}(p,d)^{19}\text{Ne}$ measurement, JENSA was operated at 300 psig inlet pressure resulting in a $^{20}\text{Ne}$ target of areal density ~4×10¹⁸ Ne atoms/cm² over the 4 mm-wide jet. The deuteron energy spectrum produced at 29 degrees after bombardment with 3 nA protons beams for 15 hours is shown in Figure 5. The spectrum produced corresponds well with known $^{19}\text{Ne}$ levels, and the only peaks that could not be accounted for were due to $^{22}\text{Ne}(p,d)^{21}\text{Ne}$ reactions from the natural abundance of $^{22}\text{Ne}$.
Figure 5: (Top panel) The deuteron energy spectrum produced from the $^{20}$Ne(p,d)$^{19}$Ne reaction. (Bottom panel) The energies expected from the known $^{19}$Ne states. The very clean correspondence between the two indicates the target was relatively pure Ne. The peaks labeled with asterisks were used for the internal energy calibration, and the labelled excitation energies are from Ref. [29].

The state providing the subthreshold resonance was clearly observed resulting in a peak at $E_x=6.282(3)$ MeV, which agrees well with the compilation value of 6.288(7) MeV [29]. The angular distribution of the state was compared with finite range distorted-wave Born approximation (DWBA) calculations using the code TWOFNR7 [30]. The results indicate that the subthreshold state was populated with an $L=0$ angular momentum transfer, and therefore has spin and parity of $1/2^+$ [31].

Figure 6: Calculated astrophysical S factors for the $^{18}$F(p,α)$^{15}$O reaction consistent with directly measured cross sections. The solid lines show the possibilities for a $1/2^-$ subthreshold resonance while the dashed lines arise from a $3/2^-$ assignment and are now excluded.
5. Conclusions

The R-Matrix code AZURE2 [32] was used to explore the implications of the measurement. The astrophysical S factor was calculated using the resonance parameters from Adekola [12]. The largest uncertainties were due to the unknown signs of the interference between resonances of the same spin. The results are plotted in Figure 6. The solid lines show the results for a subthreshold 1/2+ resonance interfering with a high-lying 1/2+ resonance observed by Mountford et al. [9]. The dashed lines show the previous possibilities of interference between a subthreshold 3/2+ resonance, a 3/2+ resonance at 38 keV, and the well-measured 3/2+ resonance at 665 keV. The calculations shown by dashed lines are now excluded. The lower limit on the rate band has been increased by a factor of 1.5-4 of the temperature range 0.05-0.25 GK, which is in the prime temperature range for nova nucleosynthesis [31].

The largest remaining uncertainty arises from the still unknown properties of the existing resonances near threshold. Only an upper limit [12] is known for the strength of the possible 3/2+ resonance at 38 keV, and whether the state is actually a multiplet with different spins has been questioned [17]. A further study of this excitation energy region possibly by measuring γ decays from these states could be illuminating.

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