From the Sun to supernovae: experimental determinations of stellar reaction rates at TRIUMF

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Abstract. The ongoing goal of the TRIUMF astrophysics group is to measure resonance strengths and cross sections for reactions of astrophysical importance. This is done using accelerated radioactive and stable beams from ISAC I and II delivered to the DRAGON and TUDA facilities. The wide range of available beams at the energies provided by the ISAC I and II accelerators enable us to measure reaction rates of interest in many different astrophysical environments. Experiments in the past year have studied reactions important for understanding the production of solar neutrinos as well as nucleosynthesis in the Big Bang, Asymptotic Giant Branch (AGB) stars, novae, and supernovae. These experiments and the various techniques required for these measurements will be discussed.

1. Introduction
The past year has been a busy and successful year for the TRIUMF nuclear astrophysics group, resulting in the measurement of 8 reactions for the study of nucleosynthesis is a wide range of astrophysical environments. These experiments range from: $^3\text{He}(\alpha, \gamma)^7\text{Be}$ to study big bang nucleosynthesis and the production of solar neutrinos; to $^{16}\text{O}(\alpha, \gamma)^{20}\text{Ne}$ which is the end point of He-burning; to $^{21}\text{Ne}(p, \alpha)^{18}\text{F}$ to study the production of $^{19}\text{F}$ in Asymptotic Giant Branch (AGB) stars; to $^{17}\text{O}(p, \gamma)^{18}\text{F}$, $^{18}\text{F}(p, \gamma)^{19}\text{Ne}$, $^{33}\text{S}(p, \gamma)^{34}\text{Cl}$ and $^{26}_{\text{Mg}}\text{Al}(p, \gamma)^{27}\text{Si}$ to study the resulting abundances of the important isotopic observables $^{18}\text{F}$, $^{33}\text{S}$ and $^{26}_{\text{Mg}}\text{Al}$ from novae; to recent tests leading up to a $^{76}_{\text{Se}}\text{Se}(\alpha, \gamma)^{80}_{\text{Kr}}\text{Kr}$ experiment which will provide the first measurement of this rate needed to calculate the inverse reaction, which is a branching point of the p-process in late stage AGB stars and supernovae. These measurements were performed at the DRAGON and TUDA facilities using both radioactive and stable beams provided the ISAC accelerator facility at TRIUMF. While the majority of the data is still under analysis, the astrophysical motivations, preliminary results and potential implications of these reactions will be discussed.

2. Experimental Facilities
2.1. ISAC
The TRIUMF Isotope Separator and Accelerator (ISAC) is an ISOL facility with the ability to deliver a wide range of radioactive beams [1]. The radioactive isotopes are produced when up to 100 $\mu$A of 500 MeV protons impinge on a production target. These isotopes are ionized and sent through a mass separator before being delivered to either the ISAC low energy area or to the ISAC accelerator.
The ISAC-I accelerator consists of a radio-frequency quadrupole (RFQ) accelerator followed by a drift tube linac (DTL) and provides beams up to 1.9 MeV/u (dependant on the mass-to-charge ratio of the isotope being accelerated). This beam can be delivered to the ISAC-I experimental area, where the DRAGON facility is located, or it can be accelerated further, up to 11 MeV/u using the ISAC-II superconducting linear accelerator (SC-linac). The TUDA facility is currently located in the ISAC-II experimental area.

In addition to the ISOL source, an off-line ion source (OLIS) consisting of a microwave source and a Supernanogan ECR source provides stable beams as either pilot beams for tuning the accelerator, or for science goals when the radioactive beam is being delivered to the ISAC low energy area.

2.2. DRAGON
DRAGON (the Detector of Recoils And Gammas Of Nuclear reactions) is a recoil mass spectrometer designed to measure radiative capture reactions in inverse kinematics, and is located in the ISAC-I experimental hall. These reactions occur when the accelerated beam impinges on a windowless gas target filled with up to 8 Torr of H or He. Thirty BGO (bismuth germanate) gamma detectors, to detect the prompt gammas from the reaction, surround the target, covering 90% of the $4\pi$ solid angle. Two surface barrier Si detectors are located within the gas target. The elastic scattering rates measured on these detectors provide a means of monitoring the beam current in real time [2]. For narrow, isolated resonances the position of the reaction in the target can be determined from the position of the BGOs in which the $\gamma$s are detected. When combined with the stopping power of the target, this allows for a determination of the resonance energy of the reaction provided sufficient statistics are acquired [3].

An additional benefit to measuring in inverse kinematics is that the recoil from the reaction leaves the target along with the remaining unreacted beam. Measuring these recoils, however,
requires significant suppression of the unreacted beam as recoil product yields are low, typically $10^{-10} - 10^{-14}$ per incident beam nucleus. This beam suppression is achieved through two stages of mass separation, each consisting of a pair of magnetic and electrostatic dipoles (Fig. 1) [4].

If the beam suppression of the separator itself is not sufficient, applying additional software cuts on the data, such as a measurement of the local time-of-flight after the second stage of separation [5] and/or a coincidence requirement between detected γ's and heavy ions arriving at the end detector, can increase the background suppression by several orders of magnitude [4].

The DRAGON end detector can be either a double-sided silicon strip detector, which provides position and energy information [6], or an ionization chamber with a segmented anode, which allows for measurements of both energy loss and total energy deposited [7]. The choice of which end detector to use for a given experiment depends on the masses of the beam and recoil particles and their respective energies.

2.3. TUDA
TUDA (The TRIUMF UK Detector Array) is difficult to describe in the same detail as the DRAGON facility as it is extremely configurable. It consists of a 1.5 m long scattering chamber with infrastructure to mount solid targets (e.g. CH$_2$) or a gas cell (for $^4$He, $^3$He and H$_2$ with the option of liquid nitrogen cooling) and place a number of silicon strip detectors of various types both upstream and downstream of the target at variable distances. The existing detector electronics can accommodate up to 512 silicon detector channels, with the signals being fed into high resolution, high linearity analogue ADC and TDC modules. The data acquisition system is theoretically capable of sustaining rates of up to 10kHz. The specific configuration of the target and detectors depends on the kinematics of the reaction of interest and is therefore typically described along with each reaction.

TUDA is currently located in the ISAC-II experimental hall, but can be moved back to ISAC-I if the measurement of a reaction of interest is more appropriate at those energies.

3. Recent experiments
3.1. $^3$He($\alpha$, $\gamma$)$^7$Be
The $^3$He($\alpha$, $\gamma$)$^7$Be reaction is of interest for two reasons. Firstly, it is responsible for producing most of the primordial $^7$Li (from the decay of $^7$Be) that is currently observed in the universe. While the uncertainty in this reaction rate is unlikely to account for the discrepancy between the predicted $^7$Li and current observations, a more precise rate would limit the nuclear uncertainty component of this discrepancy. Secondly $^3$He($\alpha$, $\gamma$)$^7$Be plays a major role in determining the high energy component of the solar neutrino flux: it is the third most uncertain reaction in the pp-chain [8].

While there are past measurements of the $^3$He($\alpha$, $\gamma$)$^7$Be rate at Big Bang nucleosynthesis energies there are currently no experimental data at the even lower energies relevant for solar hydrogen burning ($E_{c.m.} = 24$ keV). The models have to rely on extrapolations from higher energy data and there is currently a large discrepancy between the two existing data sets above $E_{c.m.} = 1.3$ MeV [9, 10]. DRAGON has taken data at 3 energies over the energy range of the discrepant data ($E_{c.m.} = 1.516, 2.224$ and 2.822 MeV) to confirm or refute the existing datasets.

Acquiring statistics for this reaction was no challenge at all - in fact the first measurement alone more than doubled the total number of recoils measured in the history of DRAGON. There were some additional challenges to consider, however. This was the first time that $^3$He had been used as a target gas, and though the target gas is recirculated, this was the first time it had ever been recaptured at the end of the experiment. Also, as the reaction cross section is nearly constant across the energy range covered by the gas target, a measurement of the gas target profile was required. This was achieved by scanning a highly columnated BGO detector across the gas target region and plotting the measured 6.45 MeV $\gamma$-ray flux from the de-excitation of N
after a $^3$He($^{12}$C,p)$^{14}$N* reaction. Another consideration was that the expected recoil cone angle of the reaction was at the limit of the DRAGON acceptance. The separator transmission for this reaction was simulated at all 3 energies and is the subject of a recently defended Master’s thesis [11].

The last pieces of information needed to fully interpret the $^3$He($\alpha,\gamma$)$^7$Be data are measurements of the charge state distribution of the $^7$Be recoils as they leave the target. These measurements are being completed even as I write this proceedings. A publication detailing the final $^3$He($\alpha,\gamma$)$^7$Be results will therefore be submitted shortly.

3.2. $^{16}$O($\alpha,\gamma$)$^{20}$Ne
Due to its low reaction rate at the relevant temperatures, $^{16}$O($\alpha,\gamma$)$^{20}$Ne is the end-point of the He-burning sequence. However, there is currently no experimental data at the He-burning temperatures and the rate used in models is the result of extrapolations of the S factor of the two direct capture (DC) components. This DRAGON measurement is the first experiment to measure the total S factor as well as the two contributing DC components in a single experiment. A paper presenting this work in detail has already been published [12].

3.3. $^{17}$O($p,\gamma$)$^{18}$F
One of the goals of satellite based $\gamma$ astronomy is to observe the $\gamma$ radiation from classical novae. $^{18}$F is an important isotope as the 511 keV and continuum $\gamma$-rays from its $\beta^+$ decay are expected to dominate the $\gamma$ emission spectrum at timescales shortly after the nova ejecta becomes transparent to $\gamma$ rays ($t_{1/2} = 110$ min). Comparing the observed abundances to calculated abundances will provide a means of testing the current nova models, provided the nuclear physics inputs are sufficiently constrained.

The amount of $^{18}$F produced in novae depends on ratio of $^{17}$O($p,\gamma$)$^{18}$F and $^{17}$O($p,\alpha$) rates. At astrophysically relevant temperatures both resonances and direct capture (DC) contribute to the total reaction rate. The existing data give conflicting information about the DC rates and so direct measurements of the S factor for centre-of-mass energies between 250 and 500 keV have been performed at DRAGON. The results of this first phase of the experiment have been published [13], with a second phase including measurements of the 183 keV resonance planned for the fall.

3.4. $^{18}$F($p,\gamma$)$^{19}$Ne
The measurement of $^{18}$F($p,\gamma$)$^{19}$Ne has a similar motivation as the $^{17}$O($p,\gamma$)$^{18}$F reaction discussed above. In this case, however, we are studying of the destruction of $^{18}$F in novae which occurs via $^{18}$F($p,\alpha$)$^{15}$O and $^{18}$F($p,\gamma$)$^{19}$Ne.

There has been a lot of work in the past few years studying the $^{18}$F($p,\alpha$)$^{15}$O reaction [14, 15, 16, 17, 18], but the measurement at DRAGON is the first to study $^{18}$F($p,\gamma$)$^{19}$N directly at nova temperatures. The first phase of this experiment ran in the fall of 2011 and studied the 665 keV resonance. This lead to a surprising result as the measurement resulted in a much smaller resonance strength then predicted - we were expecting to see a few tens of recoil events over the course of the run and detected only two. Analysis to determine the resonance strength is ongoing, but we can already say that the influence of the 665 keV resonance at nova temperatures will be significantly reduced.

3.5. $^{21}$Ne($p,\alpha$)$^{18}$F: a time reversed measurement of $^{18}$F($\alpha,p$)$^{21}$Ne
A recent study by A. Recio-Blanco et al. [19] has shown that AGB stars are likely to be the main contributor to the observed flourine in the galaxy. Current models however don’t produce enough flourine to match the observations. In AGB stars the $^{18}$F($\alpha,p$)$^{21}$Ne reaction competes with $^{18}$F
Figure 2. Schematic representation of the TUDA scattering chamber and detector setup for the $^{21}\text{Ne}(p,\alpha)^{18}\text{F}$ experiment.

$\beta$ decay to $^{18}\text{O}$. An increase in the $^{18}\text{F}(\alpha,p)^{21}\text{Ne}$ rate reduces the $^{18}\text{O}$ available but increases the $p$ in the environment; the result is an increase in the production of $^{19}\text{F}$ via $^{18}\text{O}(p,\alpha)^{15}\text{N}(\alpha,\gamma)^{19}\text{F}$.

The $^{18}\text{F}(\alpha,p)^{21}\text{Ne}$ reaction also directly affects the amount of $^{21}\text{Ne}$ produced. The ratio of $^{21}\text{Ne}$ to $^{22}\text{Ne}$ resulting from this nucleosynthesis is also important as the $^{21}\text{Ne}/^{22}\text{Ne}$ isotopic ratios measured in SiC pre-solar grains of AGB star origin is significantly larger than expected from current nucleosynthesis calculations [20, 21, 22]. If the $^{18}\text{F}(\alpha,p)^{21}\text{Ne}$ rate is measured and found to be within the higher range of the current experimental uncertainty, it could explain this discrepancy.

The current upper limit on the $^{18}\text{F}(\alpha,p)^{21}\text{Ne}$ rate comes from recent work by H. Y. Lee et al. [23], who studied the time reversed reaction using the activation technique. While their work has extended the range of current data, their analysis concludes that further experimental work at and below $E_{\text{c.m.}} = 2.3$ MeV are needed to reduce the upper limit in the temperature range of AGB stars.

The recent measurement of the $^{21}\text{Ne}(p,\alpha)^{18}\text{F}$, performed in inverse kinematics at the TUDA facility covered energies ranging from 0.6 – 1.4 MeV in the centre-of-mass system. This experiment is unique among TUDA experiments as instead of using a solid- or enclosed gas-target, the whole scattering chamber was filled with $\text{H}_2$ target gas. The setup for this experiment can be seen in Fig. 2. Both the $^{18}\text{F}$ and $\alpha$ particle were detected to allow for kinematic reconstruction of the events.

3.6. $^{26}\text{mAl}(p,\gamma)^{27}\text{Si}$

The $\gamma$-ray emitting isotope $^{26}\text{Al}$ has been a popular target for space based $\gamma$-ray telescopes. However the nucleosynthetic origin of this $^{26}\text{Al}$ is still a matter of some discussion. While the majority is expected to be produced in Wolf-Rayet stars, contributions from novae and supernovae are also expected. The nucleosynthesis of $^{26}\text{Al}$ in these objects is complicated by the existence of an isomeric state 228 keV above the $^{26}\text{Al}$ ground state. Because of the large difference in spin between the two states ($\Delta J = 5$), at temperatures below 0.4 GK they can be treated as independent radioactive nuclei [24]. Above 0.4 GK however these two states can reach a thermal equilibrium via transitions to higher-lying states [24]. Therefore, to determine an accurate abundance of $^{26}\text{Al}$ from ONe novae and supernovae the rate of $^{26}\text{mAl}(p,\gamma)^{27}\text{Si}$ needs to be measured.

While the motivation and preparation for this DRAGON experiment were discussed at NN2012, the experiment didn’t run until June. We are happy to report, however, that the experiment was completed successfully and the data analysis is already underway. To our
knowledge, this is the only resonance strength ever measured using an isomeric beam.

The term ‘isomeric beam’ is, perhaps, a slight misnomer as the $^{26m}$Al is in fact only a small fraction ($1/5000 - 1/10000^{1\text{th}}$) of the total $^{26}$Al beam on target. We determined the $^{26m}$Al beam intensity by monitoring the rate of $\beta^+$ decay of the beam deposited on the mass slits (where the beam is dumped when the separator is tuned for recoils) using two NaI counters. To monitor the even lower level of $^{26}$Na contamination, a HPGe detector was used to identify the characteristic $\gamma$s of the $^{26}$Na deposited on the mass slits.

3.7. $^{33}$S($p, \gamma$)$^{34}$Cl

The isotope $^{33}$S could be an important isotope for classifying pre-solar grains as is expected to be overproduced in ONe novae by a factor of 150 above solar [25]. There is, however, a large uncertainty on this value due to the uncertainty in the $^{33}$S($p, \gamma$)$^{34}$Cl reaction rate at the relevant temperatures (0.2 - 0.4 GK); this rate could be up to 3 times larger or 100 times smaller. The primary reason for this uncertainty are 7 resonances which have been identified at energies corresponding to the Gamow window in ONe novae, but whose resonance strengths are not yet known [26].

These 7 resonances, plus two with previously measured resonance strengths have been studied using the DRAGON facility. We were able to determine a resonance strength for two, and set upper limits on 5 of the previously unmeasured resonances. While the results are still preliminary, it appears that none of these reactions will contribute significantly above 0.3 GK and the known $E_r = 431$ keV resonance will continue to dominate the rate. This is good news for the prospect of using $^{33}$S to classify novae grains as this preserves the significant $^{33}$S overabundance.

3.8. $^{76}$Se($\alpha, \gamma$)$^{80}$Kr

This reaction is of particular interest as its inverse reaction $^{80}$Kr($\gamma, \alpha$)$^{76}$Se has been identified as an important branching point in the photo-disintegration based $p$ process [27]. The rate of this reaction, in comparison with the rates of the $^{80}$Kr($\gamma, p$) and $^{80}$Kr($\gamma, n$) reactions, will determine the abundance of $p$-nuclide $^{78}$Kr. None of these reactions have any experimental information to date.

While this experiment has not yet run, there have been several test runs in preparation. $^{76}$Se will be the highest mass beam ever measured at DRAGON, which was designed in anticipation of beams up to $A = 30$. A test run looking at $^{58}$Ni($p, \gamma$)$^{59}$Cu was performed and was able to demonstrate sufficient beam suppression to perform a measurement. This is actually a lower $\Delta m/m$ than for the $^{76}$Se($\alpha, \gamma$)$^{80}$Kr reaction. Tests have also been performed with a beam of $^{84}$Kr impinging on $^4$He gas. While no $^{88}$Sr recoils were expected over the timescale of this test, when the separator was tuned for recoils the ‘leaky’ beam rate was no higher than has been seen in previous, successful experiments.

We are very excited by these recent tests: not only does this demonstrate our ability to measure the $^{76}$Se($\alpha, \gamma$)$^{80}$Kr reaction, it opens up a whole new range of the chart of the nuclides whose radiative capture reactions can now be studied with DRAGON.

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