The first direct measurement of $^{17}O(\alpha,\gamma)^{21}Ne$ and its impact upon s-process abundances

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An experimental campaign to perform the first accurate measurement of the $^{17}O(\alpha,\gamma)^{21}Ne$ reaction rate was carried out during May and November 2009 at the DRAGON recoil separator in the TRIUMF laboratory, Vancouver, Canada. The goals were to differentiate between two previous conflicting theoretical predictions, and to establish the $(\alpha,\gamma)/(\alpha,n)$ reaction rate ratio.

Two distinct energy regions were scanned: a higher region, $E_{cm} \sim 1.5$ MeV, where the recoil cone was sufficiently confined and the cross section sufficiently large so that a statistically significant yield could be achieved, and a lower region, $E_{cm} \sim 0.7$ MeV, chosen to approach the astrophysical energies and reduce errors from extrapolation.

The experiment, performed in inverse kinematics, used the highest intensity beam ever delivered to DRAGON, 1×10^{12} pps of ^{17}O incident on a ^{4}He gas target. An array of 30 Bismuth Germanate (BGO) detectors [1] was used in conjunction with two microchannel plates (MCP) [2] for a local time-of-flight measurement, and ion chamber for coincident event detection.

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1. Introduction

Above the iron peak it becomes energetically unfavourable to produce more massive nuclei through the process of nuclear fusion [3][4]. Most of the heavy elements beyond iron that we observe in the solar system have been produced by the slow neutron capture process (or s process) and by the rapid neutron capture process (or r process) [5]. In massive stars, the so-called "weak" component of the s-process is responsible for the production of heavy isotopes up to the strontium-zirconium peak. In rotating models at low metallicity, the high neutron to seed ratio allows the production of isotopes beyond the Sr-Zr peak, up to barium depending on the neutron flux. One critical source of uncertainty for the abundance of these isotopes is the impact of parasitic light neutron absorbers.

In the specific case of massive rotating stars at low metallicity, ^{16}O is potentially a significant neutron poison [6]. Its impact as a neutron poison depends upon the $^{17}O(\alpha,\gamma)/^{17}O(\alpha,n)$ reaction rate ratio: the (α,n) reaction allows the neutrons to be recycled and be available to the s-process nucleosynthesis later on. The competition from the (α,γ) channel reduces the neutron abundance available for s-process nucleosynthesis.

Prior to this work, experimental data were sparse. Pre-existing unpublished data on the $^{17}O(\alpha,n)^{20}Ne$ reaction went as low as $E_{cm} \sim 0.5$ MeV. However, the strength of the competing $^{17}O(\alpha,\gamma)^{21}Ne$ channel is less well known, with no experimental data and conflicting predictions from the two existing theoretical models. Work by Descouvemont [7] predicts that the $^{17}O(\alpha,\gamma)^{21}Ne$ reaction should be 10^4 times weaker than the competing (α,n) reaction. On the other hand, an earlier prediction by Caughlan and Fowler [8] suggests only a factor of 10 should separate the channels, resulting in much lower s-process abundances between strontium and barium. The effect on the final s-process yields using the two different rates mentioned above for the $^{17}O(\alpha,\gamma)$ is shown in figure 1. The stellar model and the rest of the nuclear network are the same for the two cases [6].
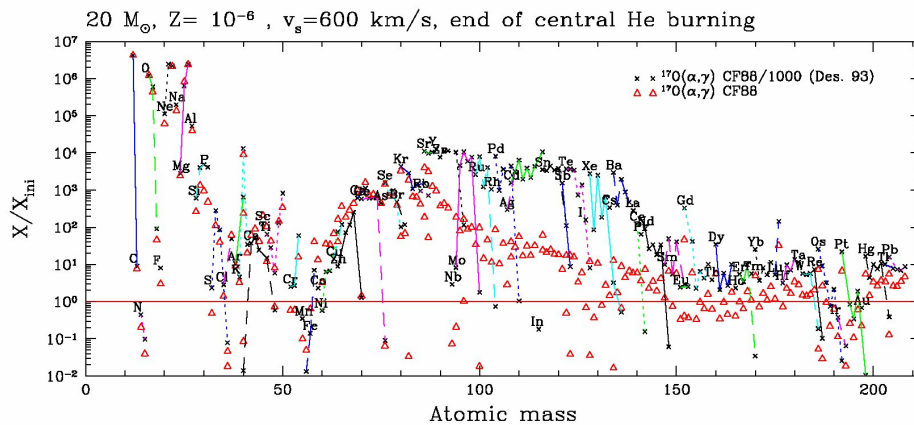
Figure 1: Comparison of the elemental abundances that result from Descouvemont and CF88 predictions taken from [6]

2. Experimental Method

An experimental campaign to study the $^{17}O(\alpha,\gamma)^{21}Ne$ reaction in inverse kinematics was carried out in May and November 2009. The experiment used an ^{17}O beam accelerated to selected energies over the range, $E_{cm} \sim 0.621$-1.597 MeV. The lower of these energies approaches the region of astrophysical interest of $E_{cm} \sim 0.3$-0.5 MeV. The experiment was carried out at TRIUMF in Vancouver, Canada, using the DRAGON recoil separator [9] in the ISAC I experimental hall.

An $^{17}O^{3+}$ beam was delivered from the Offline Ion Source (OLIS) and accelerated to the desired energy. The resulting maximum beam intensity of 1×10^{12} pps was the most intense beam ever delivered to DRAGON. The beam intensity was recorded through hourly Faraday cup readings at several points along the separator, and was continually monitored by elastic scattering within the DRAGON gas target by two surface barrier detectors, positioned at 30° and 57°.

The beam was delivered to the DRAGON windowless gas target filled with ^4He with different pressures used in order to vary the target thickness, although the standard setting was 4 Torr. The windowless gas target uses a differential pumping system to maintain a sharp density profile despite the lack of entrance or exit windows, thus minimising the effect of beam straggling.

Several methods of particle identification were utilised for the experiment. The end recoil detector, an ion chamber (IC) [10] comprising 4 anodes, provided ΔE-E information. Correlating the arrival time of an ion in the IC with a corresponding γ ray detected with the BGO array results in additional beam suppresion. In addition, two MCP detectors, located 60 cm apart, provided a local time-of-flight (ToF) measurement which could be combined with the IC information. The resulting IC energy Vs MCP ToF spectra became those primarily used in the following analysis. The different length anodes of the IC allowed for a ΔE-E method to be used when the separation in the ICsum (total energy deposited in the IC) Versus MCP ToF spectrum was not sufficient. Using different combinations of anodes, various ΔE thicknesses could be used to obtain the optimum separation. The relative timing signals of γ and ion signals for coincident events were also used for particle identification.

An example of the IC energy versus MCP time of flight particle ID analysis is shown in figure 2. The ^{21}Ne nuclei can clearly be separated from those beam particles that have not been removed by the DRAGON separator.

3. Results and Discussion

While the results presented in this work are preliminary, the experimental analysis is nearing completion. Calculation of the raw yields is complete, from these the absolute cross sections and astrophysical S-factors can then be derived. The S-factor is useful in that it removes the dependency on the non-nuclear component, allowing for a more accurate extrapolation down to the lower energies, whereas the cross section tails off exponentially with decreasing energy, making extrapolation unreliable.

We have observed a new, strong resonant structure in the $^{17}O + \alpha$ system at $E_{cm} \sim 0.8$ MeV, this can be seen in figure 3. This structure is under analysis; it should be noted that in the (α,n) data [11], there are two states in this region, which do not correspond to known states in ^{21}Ne. The data suggests that the relative strengths of the (α,n) and (α,γ) channels are comparable. This is
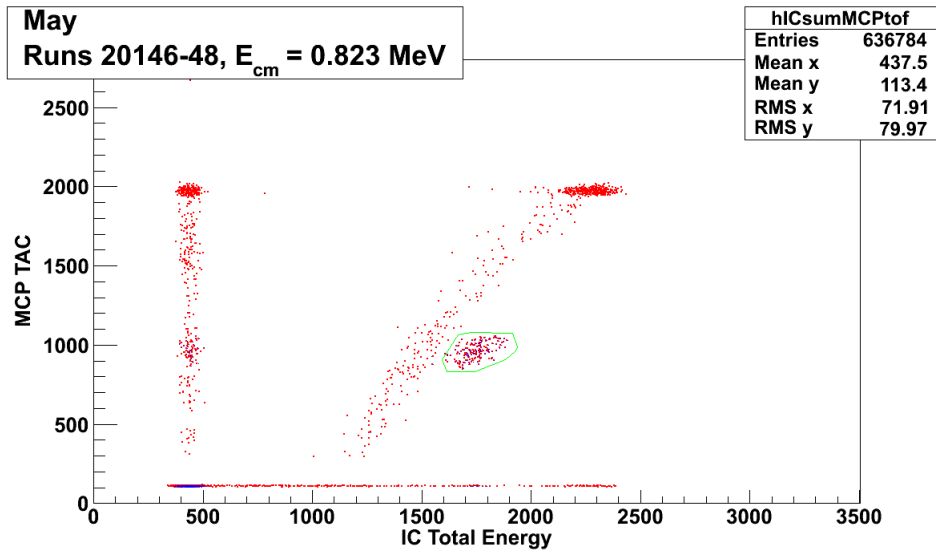
Figure 2: Particle ID example for runs 20146-48, $E_{cm} \sim 0.823$ MeV. Blue events show gamma-ray co-incidences, red depicts single IC hits and the green polygon is the cut applied should further analysis be required.
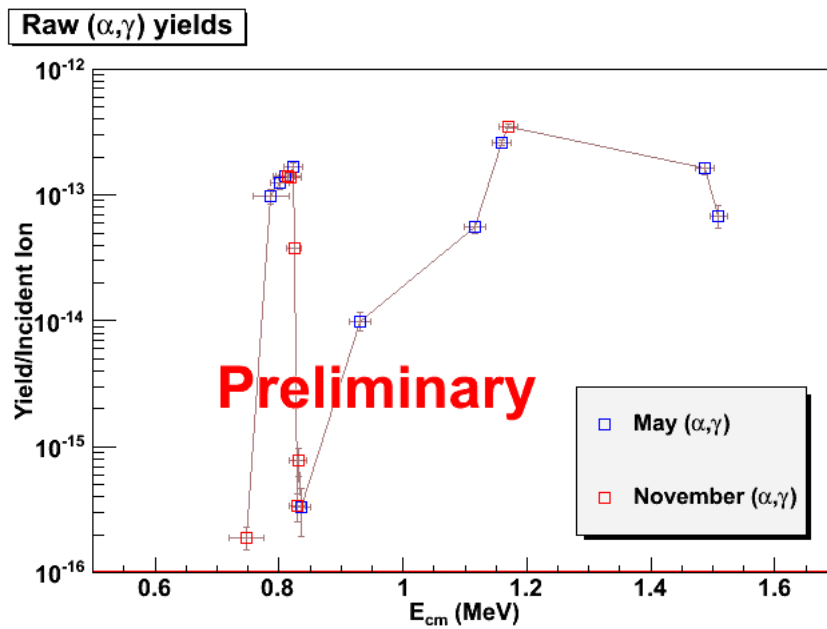
Figure 3: Plot of raw yields from the experiments performed in May and November 2009. It should be noted that the line is a guide to the eye and not in fact a fit of the data points.

surprising given that the ratio of the (α,γ) to (α,n) channels at the higher energies suggested that the (α,γ) yield should be orders of magnitude lower than observed. This structure was observed on two separate occasions, in both the May and November experimental runs.

Establishing the S-factor at the relevant energies is not the end of the work. These S-factors can then be used with astrophysical reaction rate codes to see the effect that this new $(\alpha,\gamma)/(\alpha,n)$ ratio has on the later s-process abundances, specifically in the relevant region from Sr to Ba.

In order to do this the cross-sections will be required across the full temperature range of the star, which for the He-burning stage of stellar evolution means 0.1 GK and above. This corresponds to an energy of $E_{cm} \sim 0.247$ MeV, below present realistic detection limits. For comparison, the energy range measured during the experimental campaign, $E_{cm} \sim 0.621$ - 1.597 MeV, corresponds to stellar temperatures of 0.40 - 1.65 GK respectively. As a result some extrapolation will be required in order to establish cross sections at these very low, astrophysically relevant energies.

4. Acknowledgements

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