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^{20}Ne(α,p)^{23}Na studied to constrain type Ia nucleosynthesis

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Abstract. The ^{20}Ne(α,p)^{23}Na reaction rate is important in determining the final abundances of various nuclei produced in type Ia supernovae. Previously, the ground state cross section was calculated from time reversal reaction experiments using detailed balance. The reaction rates extracted from these studies do not consider contributions from the population of excited states, and therefore, are only estimates. A resonance scan, populating both the ground and first excited states, was performed for the ^{20}Ne(α,p)^{23}Na reaction, measuring between 2.9 and 5 MeV center of mass energies at the Nuclear Science Lab at the University of Notre Dame. Data analysis is underway and preliminary results show substantial contribution from the excited state reaction.

1. Introduction

When a CO white dwarf in binary systems accretes enough mass from the companion star, thermonuclear supernova explosions can occur. This is considered a type Ia supernova. The type Ia supernova always reaches approximately the same brightness and is considered a standard candle for astronomers. However, there are still a number of open questions, and learning more about the nuclear physics taking place in these explosions could help give insight into type Ia supernovae and the universe.

Many reactions take place in type Ia supernovae and have an effect on the final abundances left over in the stellar environment. In 2013, Parikh et al. [1] used two different hydrodynamic Chadrasekhar-mass explosion models to examine 2305 nuclear reactions that can occur in type Ia supernovae. In the study, they individually varied the reaction rates of the reactions by factors of ten and determined which reaction rate variabilities had the largest contribution on the final predicted nuclei abundances. It was concluded that uncertainties in the reaction rates of five specific reactions had the greatest impact on the yields: ^{12}C(α,γ)^{16}O, ^{12}C + ^{12}C fusion, ^{20}Ne(α,p)^{23}Na, ^{20}Ne(α,γ)^{24}Mg, and ^{30}Si(p,γ)^{31}P. The study suggested that the ^{20}Ne(α,p)^{23}Na reaction, as well as some others, should be probed and the reaction rate determined for temperatures up to 5 GK, as uncertainties in this higher energy range (2.4 - 5.4 MeV Gamow window) have the most impact on the predicted yields. Knowing these rates with more certainty would guide the nuclear physics input for the nuclei abundance models [1].

The ^{20}Ne(α,p)^{23}Na reaction has previously been studied at a variety of energies, primarily indirectly and in inverse kinematics. In 1977, Bingham et al. studied the structure of ^{23}Na from the ^{20}Ne(α,p)^{23}Na reaction at an α energy of 39.5 MeV [2]. Additionally, in 1968, Spear et al. looked at the ^{20}Ne(α,pγ)^{23}Na reaction to provide spin and parity assignments from the angular distribution measurements for the levels of ^{24}Mg at excitation energies of 12.74, 12.81, and 12.98 MeV. Initially covering an α-particle energy range larger than the previously mentioned excitation energies, a detailed analysis was not attempted due to more a complex angular distribution at α-particle energies greater than 4.6 MeV [3]. At higher energies the ^{20}Ne(α,p$_1$)^{23}Na channel is open, and its contribution to the total reaction rate depends on the nuclear structure properties of ^{24}Mg.

The previous cross section measurements for the ^{20}Ne(α,p)^{23}Na reaction did not include contributions from both the ground and first excited states, and therefore, act only as estimates of the total cross section. Being particularly suited for direct reaction measurements involving noble gases and probing astrophysically relevant energies, an experiment was conducted at the Nuclear Science Lab at the University of Notre Dame studying both the ground and first excited state populations in the ^{20}Ne(α,p)^{23}Na reaction.

2. Experimental Setup

The ^{20}Ne(α,p)^{23}Na reaction experiment used the 5U accelerator and the Rhinoceros windowless gas target system [4]. The 5U accelerator produced a He 2+ beam with currents around 10-20 μA. A resonance scan was conducted across beam energies ranging from 3.5-6 MeV. This energy range was chosen as such to measure above and down into the T_9 = 5 GK Gamow window (2.4-5.4 MeV) as previously suggested by Parikh [1].

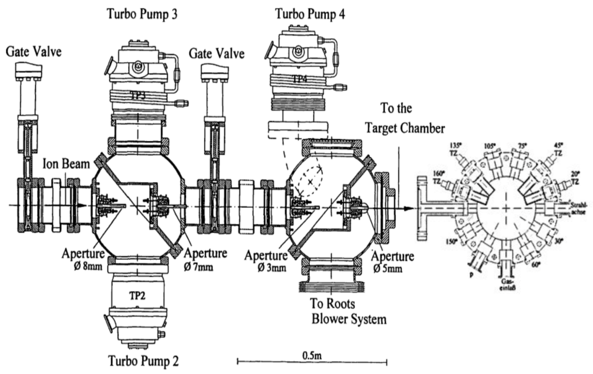

Figure 1. The Rhinoceros gas target system. It features differential pumping and the Octopus target chamber. In this experiment, it was operated with 10 Torr of Ne gas [5].

The Rhinoceros gas target system, also commonly referred to as Rhino, is an extended differentially pumped gas target system that allows for the detection of charged particles via the Octopus target chamber, see Fig. 1. It has a flat disk shape and six radially mounted detector ports for silicon detectors. For this experiment, the target chamber housed around 10 Torr of Ne gas and used collimated ruggedized silicon surface barrier detectors that viewed only the target chamber center for charge particle detection. The detectors were placed to give angular coverage at 45, 60, 90, 105, 120, and 135 degrees. This made it ideal for obtaining angular distribution information for the cross section measurement.

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3. Experimental Data

The experimental data consists of spectra for each of the six detectors at 140 different energy steps. Each spectrum showed usually six distinct peaks that correspond to various reactions taking place within the target chamber. These have been identified as: ^{22}Ne(α,α)^{22}Ne, ^{20}Ne(α,α)^{20}Ne, ^{22}Ne(α,α_1)^{22}Ne, ^{20}Ne(α,p$_0$)^{23}Na, ^{20}Ne(α,α_1)^{20}Ne, and ^{20}Ne(α,p$_1$)^{23}Na. Using kinematics calculations for these reactions at the various detector angles, each peak in the spectra can be identified, as shown in example Fig. 2. Specifically, the ^{20}Ne(α,p$_0$)^{23}Na and ^{20}Ne(α,p$_1$)^{23}Na reactions can be distinguished. The ^{20}Ne(α,p$_1$)^{23}Na peak is always present and prominent. However, at some detector angles the ^{20}Ne(α,p$_0$)^{23}Na overlaps with the ^{20}Ne(α,α_1)^{20}Ne peak because it lies at a similar energy.

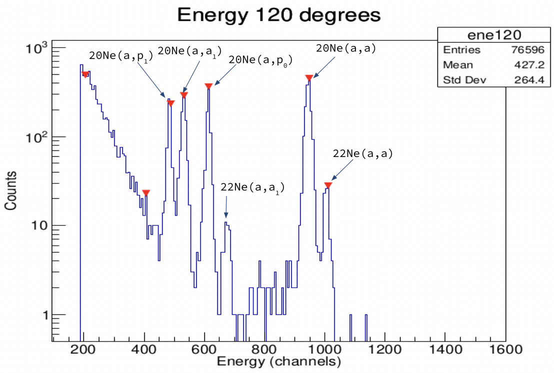

Figure 2. Representative spectrum for the 120 degree detector in the setup. Each detector produced a similar spectrum at each energy and will be used in the analysis of the total ^{20}Ne(α,p)^{23}Na reaction yield.

Because the beam disperses and ionizes as it travels through the gas, the beam current measured on the beam stop was not a reliable measurement of the integrated beam current. Therefore, to determine the beam intensity on target, two minute charge integration runs were taken before and after each energy change without gas in the target chamber. Between the average of these two minute charge integration runs and a comparison between the amount of elastic α scattering during two minutes of a data-taking run, the amount of beam on target can be determined from the integrated α scattering during the entire run. The uncertainty on the charge with this method has yet to be determined, however the largest contribution will likely come from the assumption that the beam current does not change between the time of the charge integration and the first few minutes of a data-taking run. This will likely lead to more than just statistical uncertainties, and any pre and post run normalizations differing by more than ten percent will either be thrown out or marked for further consideration.

4. Analysis and Preliminary Results

While the experiment covered an energy range from 3.5-6 MeV, data analysis is still underway and has only been performed between 5.6-5.9 MeV. The preliminary results discussed below only refer to this subset of the data.

Figure 3 shows the preliminary yield curves for the ^{20}Ne(α,p$_0$)^{23}Na and the ^{20}Ne(α,p$_1$)^{23}Na reactions. It is seen that there is significant structure amongst the p$_1$ yield curves for each detector, further justifying that p$_1$ is an important contributor to the total ^{20}Ne(α,p)^{23}Na cross section calculation. Count data could not be obtained for the p$_0$ state from the 90 degree detector as the ^{20}Ne(α,p$_0$)^{23}Na peak often overlapped with the peak for the ^{20}Ne(α,α_1)^{20}Ne

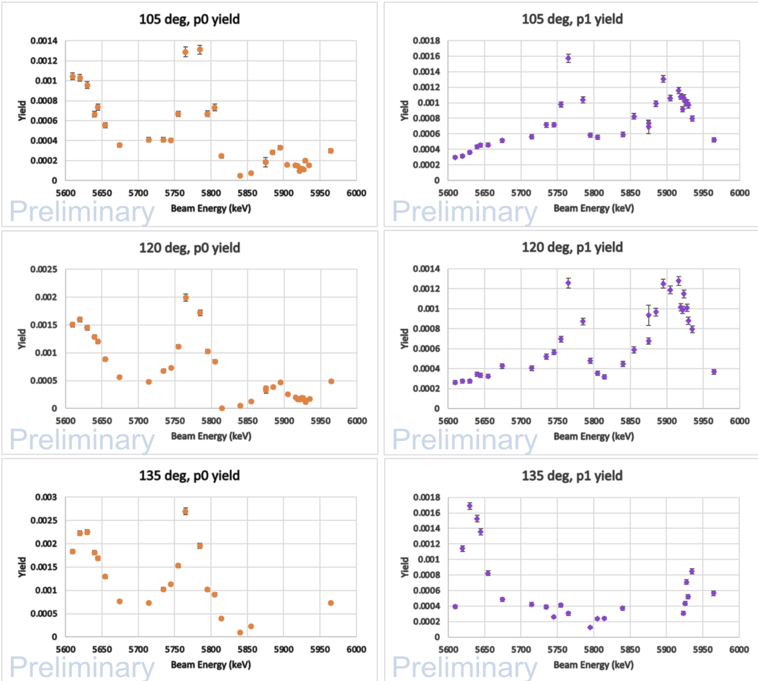

Figure 3. Representative preliminary yield curves for the p_0 and p_1 populations of the ^{20}Ne(α,p)^{23}Na reaction for three of the six silicon detectors.

reaction. However, at lower energies these reactions happen at distinguishable energy locations and counts will be able to be extracted to give a more complete idea of the cross section at 90 degrees. Similarly, this overlapping of the ^{20}Ne(α,p_0)^{23}Na peak happened at the higher energies for the 135 degree detector, but the peaks separated enough for counts to be extracted at lower energies.

5. Conclusions and Future Work

The ^{20}Ne(α,p)^{23}Na reaction is important for type Ia supernova nucleosynthesis. We have made the first measurement of both the ^{20}Ne(α,p_0)^{23}Na and ^{20}Ne(α,p_1)^{23}Na channels throughout the Gamow window. The preliminary results show significant contribution to the total ^{20}Ne(α,p)^{23}Na cross sections from both the ground and first excited states. Upon completion of the yields for both the ^{20}Ne(α,p_0)^{23}Na and ^{20}Ne(α,p_1)^{23}Na reactions at all angles, a thorough error analysis will be performed and the cross section will be calculated. These cross section calculations will undergo an R-Matrix analysis and the reaction rates will be obtained.

Acknowledgments

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