Novae in a test-tube

Investigating the ^{21}Na(p,γ)^{22}Mg reaction at TRIUMF's ISAC facility

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The ^{21}Na(p,γ)^{22}Mg reaction is expected to play an important role in the synthesis of intermediate mass elements in Oxygen-Neon novae. The first direct measurement of the rate of this reaction was completed using the DRAGON recoil mass separator at TRIUMF's ISAC facility. The energy of one excited state important in the reaction was measured to be $E_{cm} = 728.1 \pm 1.2$ keV, and its resonance strength was determined to be $\omega\gamma = 254 \pm 16_{stat} \pm 44_{sys}$ meV.

I. INTRODUCTION

Without the elements, we would be nothing. Whether it be the oxygen we breathe, the carbon in our bones, or the gold in our precious jewelry, elements make up every part of our world. But where did these elements come from? When the universe began, only the lightest elements filled its spaces. Since the early universe was still fairly hot, some of this original hydrogen was able to fuse into small quantities of heavier atoms. Nonetheless, these processes do not account for the majority of elements we encounter in our day to day lives.

To discover where the rest of the elements came from, we must look to the heavens. Most of the heavy elements found on Earth were formed during explosive stellar events, when both stable and radioactive isotopes were able to participate in fusion reactions. In normal stellar conditions, unstable nuclei decay before they have an opportunity to react. In the hot temperatures and high densities of exploding stars, however, these decays can by bypassed by proton capture reactions. This changes the usual cycles for element creation, leading to synthesis of new elements.

One site where such reactions can take place are novae, explosions resulting from the accretion of matter onto a white dwarf star from a massive companion [1–3]. Depending on the type of nova and the temperatures reached, different elements will be formed during these explosions. Predominant in ONe novae, a type of nova involving accretion onto an oxygen and neon rich white dwarf, is the so-called NeNa cycle of nuclear reactions. Initiated by proton captures on the abundant seed nuclei ^{20}Ne, this cycle results in the creation of heavier elements such as sodium and magnesium.

Novae models predict that several key reactions at the beginning of an explosion can greatly influence its future path. Better knowledge of the rates of these crucial reactions will therefore lead to a more accurate understanding of stellar evolution and associated element synthesis. One reaction important in ONe novae is the ^{21}Na(p,γ)^{22}Mg reaction. This paper will report on the first direct measurement of the rate of this reaction using the DRAGON recoil mass separator at TRIUMF's ISAC facility.

II. THEORY

A. The NeNa Cycle

The NeNa cycle is a chain of nuclear reactions that take place in ONe novae. This cycle is of astronomical importance because it leads to the synthesis of the ^{22}Na nucleus, which emits an observable γ-ray ideal for testing models of novae [4]. Unstable, ^{22}Na β-decays to the first excited state of ^{22}Ne ($t_{1/2} = 2.6$ years) before emitting the characteristic 1.275 MeV γ-ray as it proceeds to its ground state.

Observations of five novae by NASA's COMPTEL onboard CGRO satellite have thus far failed to detect the γ signature [5]. The upper limits associated with this result are not in disagreement with recent results obtained from ONe models [1, 2]. However, reducing the uncertainties associated with the reactions leading to the production of ^{22}Na is crucial, as it leads to more accurate predictions of the different types elements produced in a nova.

Synthesis of ^{22}Na follows one of two possible pathways (Fig. 1): in the "cold" NeNa cycle, ^{21}Na is formed by a proton capture on the seed ^{20}Ne, which then β-decays to ^{21}Ne. A subsequent proton capture leads to the creation of ^{22}Na via the ^{21}Ne(p,γ)^{22}Na reaction. In the "hot" NeNa cycle, which is associated with higher nova temperatures, ^{21}Na is again formed by a proton capture on the seed ^{20}Ne. At these higher temperatures, however, proton-capture on ^{21}Na dominates over its β-decay, and ^{22}Na is created via the ^{21}Na(p,γ)^{22}Mg(β^+)^{22}Na chain of reactions. According to current nova models, the unknown rate of the ^{21}Na(p,γ)^{22}Mg is the main source of uncertainty in calculating the amount of ^{22}Na created in nova outbursts [6, 7].

B. Thermonuclear Reaction Rates

Under nova conditions, the ^{21}Na(p,γ)^{22}Mg reaction is expected to pass through one or more excited states of ^{22}Mg before emitting a γ-ray and proceeding to the ground state. The rate of this reaction, $N_A\langle\sigma v\rangle$, is dependent on both the capacity of the excited states for creating the product nucleus (also known as the "resonance strength" or $\omega\gamma$), and the energy of the states,

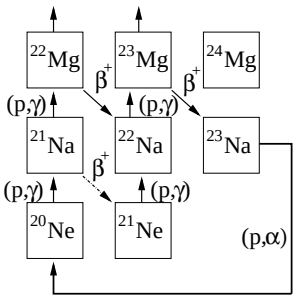

FIG. 1: Graphical representation of the NeNa reaction cycle. Depending on the temperature of the star, the isotope ^{21}Na will either β-decay into ^{21}Ne (the "cold" NeNa cycle), or capture a proton leading to ^{22}Mg (the "hot" NeNa cycle).

E_R. In units of cm^3 s^{-1} mol^{-1}, the reaction rate is given by,

$$N_A\langle\sigma v\rangle = 1.54\times10^{11}(\mu T_9)^{-3/2}\omega\gamma\ \exp\left[-11.605\frac{E_R}{T_9}\right], \quad (1)$$

where μ is the reduced mass in atomic mass units, T_9 is the temperature in GK, $\omega\gamma$ is the resonance strength in MeV, and E_R is the resonance energy in MeV [8].

The amount of ^{22}Mg created by any particular excited state, Y, is given by,

$$Y = \frac{\lambda^2}{2}\frac{M+m}{m}\omega\gamma\left(\frac{dE}{dx}\right)^{-1}, \quad (2)$$

where λ is the centre-of-mass de Broglie wavelength, M is the mass of the projectile nucleus, m is the mass of the target nucleus, and $\frac{dE}{dx}$ is the energy loss per atom/cm^2 during the reaction [9].

Figure 2 shows the excited states of ^{22}Mg important for ONe novae. Studies show that the 212 keV state will contribute most to the rate of the ^{21}Na(p,γ)^{22}Mg reaction at nova temperatures from 0.2 to 0.35 GK. At higher temperatures, however, higher resonant states will begin to dominate. The resonance strength has previously been determined for the 212 keV state [10]. The purpose of this paper is to report on a state of importance at higher nova temperatures - the state at 746 keV.

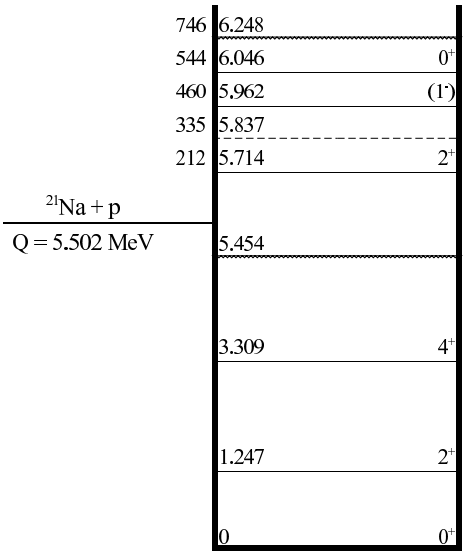

FIG. 2: The states of ^{22}Mg important in ONe novae [11–13]. The energy of the states and their parities are shown above each level, with energies given in MeV. The numbers to the far left denote the kinetic energy needed by ^{21}Na to achieve an excited state, in units of keV. The state at 5.837 MeV was observed once but has not been confirmed in other studies [11–14].

III. DATA

A. The DRAGON Facility

Data was collected using the DRAGON (Detector of Recoils And Gammas Of Nuclear reactions) facility at the TRIUMF-ISAC facility in Vancouver, British Columbia [15]. DRAGON consists of a windowless gas target surrounded by an array of gamma detectors, followed by a recoil mass separator (see Figure 3). It is capable of creating elements via proton or alpha capture reactions and then separating them based on mass.

The reactions of interest take place in the first stage of DRAGON, the windowless gas target. This target (effective length 12.3 cm) can be filled with either hydrogen or helium gas, depending on the type of reaction being studied. The target is surrounded by an array of 30 BGO gamma detectors, which are able to detect the γ-rays emitted in the capture reactions. The coincidence between 'seeing' a γ-ray and detecting an event distinguishes the products of a nuclear reaction from any original beam particles that may have leaked through the system.

To produce the desired ions, a beam of radioactive particles generated by the ISAC facility is passed through the gas cell. To allow the beam to pass unobstructed through the target, openings are located on either side of the gas cell (the "enter" and "exit", respectively). As it is necessary to keep the beamline as close as possible to a perfect vacuum, a set of pumps removes any gas that may leak out of the target.

Once created, the products (or "recoils") of a nuclear reaction are separated from the more intense beam by the second stage of DRAGON, a mass separator (21 m in length from target centre to end detector). This stage has two components that work together to separate the ions - the magnetic dipoles (MDs) and the electric dipoles (EDs).

The magnetic dipoles separate the ions by their charge state, since particles with different charges are bent by a different amount in a magnetic field (Eq. 3).

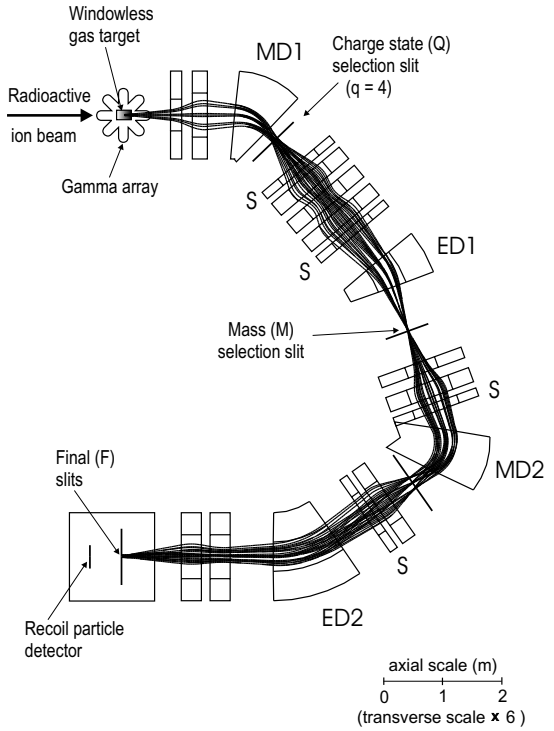

FIG. 3: Schematic representation of the DRAGON facility. Typical ion trajectories are shown passing through the recoil mass separator, which consists of a pair of magnetic dipoles (MD1 and MD2), four magnetic sextupoles (S), and a pair of electric dipoles (ED1 and ED2).

$$r = \frac{mv}{Bq} \tag{3}$$

These dipoles are set so that the charge state of interest (usually the state the recoils are most likely to be found in) will pass unobstructed through the dipole, and all other charge states are stopped by a slit placed in the dipole.

After passing through the magnetic dipole, the remaining ions pass through an electric dipole, where they are separated by mass. Physically, electric dipoles separate particles based on their kinetic energies. Since the beam and recoil ions leave the gas target with the same momentum, their differing masses cause them to differ in kinetic energy. As with the magnetic dipoles, the electric dipoles are set to an appropriate voltage so that the recoils pass through the separator while the beam particles are stopped. To further reduce the chances of detecting the wrong ion, beam particles then pass through a second stage of magnetic and electric dipoles.

Several end detectors are available at the end of the mass separator. Each measures a different quantity, and can be used alone or in combination depending on the type of data needed. For the purposes of the current experiment, a DSSSD (Double Sided Silicon Strip Detector) was used to detect the ^{22}Mg recoils. Heavy ions passed through the separator produce pulses on this detector, which then registers their position and energy.

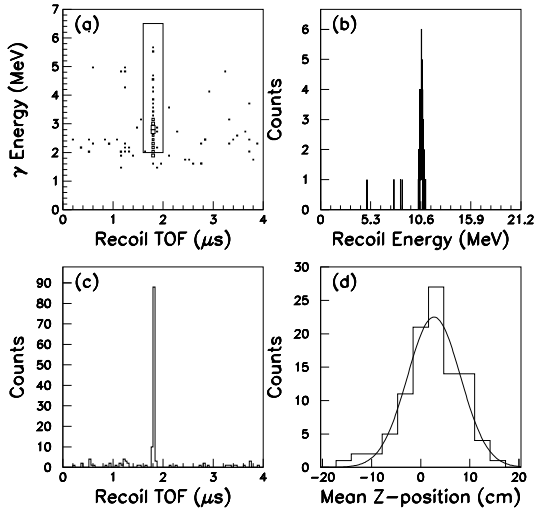

FIG. 4: Resonance data for a ^{21}Na beam of energy 775 keV/u. (a) Valid events restricted in time of flight and γ-ray energy above a background of random coincidence events. (b) Energy distribution for the ^{22}Mg recoils selected by the box in (a). (c) Time of flight of the recoils above the γ-ray threshold energy. (d) Distribution of the valid γ-ray events along the target length, with a Gaussian fit.

B. The ^{21}Na(p,γ)^{22}Mg Reaction

For the study of the ^{21}Na(p,γ)^{22}Mg reaction, a radioactive beam of ^{21}Na (charge state 5^+) was delivered to the DRAGON gas target (pressure 7.8 torr) at typical intensities of 2×10^8 s^{-1}. A total of $\sim 10^{12}$ ^{21}Na atoms were received for the study of the 746 keV resonance. Data taking was done in both singles and coincidence modes; the coincidence mode required a "start" signal from the γ-array in coincidence with a "stop" signal from the DSSSD after an appropriate time interval. (The expected time of flight of a recoil can be calculated by dividing the length of the separator by the velocity of the particle, determined by conservation of momentum considerations.)

Figure 4 shows resonant-capture data for a beam of energy 775 keV/u (E_{cm} = 745 keV in the centre of mass reference frame). Counts within the box in Fig. 4a were considered valid capture events, as they satisfy the time of flight restriction, and are associated with γ-rays above the 2 MeV hardware threshold. The energy distribution of these events is shown in Fig. 4b, and the time of flight for those events satisfying the cut in γ energy is shown in Fig. 4c. The distribution of valid γ-ray events along the target length (Fig. 4d) shows that the resonance occurred slightly downstream of the target centre.

The beam energy was measured in terms of the dipole field required to center the beam at the charge state se-

TABLE I: Summary of systematic errors at 775 keV/u.

Factors	Value	Syst. Error (%)
Charge state fraction (CSF)	0.43	10
Live time (LT)	0.99	0
Integrated beam	1.63×10^{12}	14
dE/dx (eV/(atom/cm^2))$_{lab}$	8.57×10^{-14}	4

lection slit. Knowing the bending radius of the dipole (1 m), a particle's centripetal acceleration can be equated to the acceleration it experiences in a magnetic field to give the following relation:

$$v = \frac{Bqr}{m}. \tag{4}$$

Hence,

$$E = \frac{1}{2}mv^2 = \frac{r^2}{2}\frac{B^2q^2}{m}. \tag{5}$$

The expected relation was confirmed by measuring a number of known resonances with stable beams [16].

IV. RESULTS

A. Resonance Strength ($\omega\gamma$)

To obtain the true yield of ^{22}Mg, non-coincident recoil events were corrected for the various factors listed in Table I.

$$Y = \frac{\#\text{ of non-coincident recoils}}{\text{CSF} \times \text{LT} \times \#\text{ of beam ions}} \tag{6}$$

The fraction of the charge state selected (43%) was interpolated from data taken with a ^{24}Mg beam at 800 keV/u [17], and the live time of the hardware (99%) was determined by comparing the heavy ions acquired to those originally presented.

The number of beam ions presented at the target was determined from a known relationship between the counts in DRAGON's beta monitor and the beam current (Eq. 8) [18],

$$\#\text{ of beam ions} = (\text{Beam current})\frac{t}{Q_{beam} \times |e^-|} \tag{7}$$

$$= \left(\frac{\beta\text{ counts}}{t \times \text{CSF} \times R}\right)\frac{t}{Q_{beam} \times |e^-|}, \tag{8}$$

where t is amount of time data was collected, and R is a constant, 33.08 ± 3.33 epA^{-1}s^{-1}.

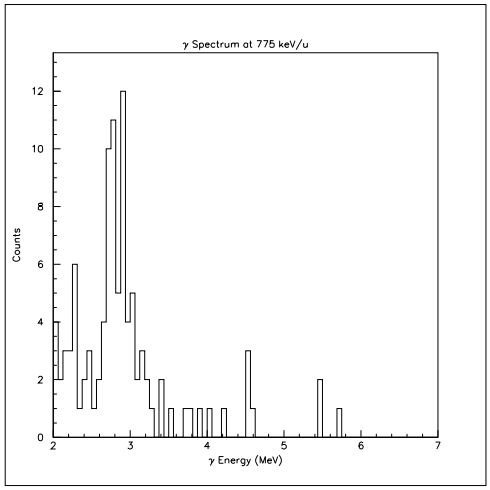

FIG. 5: Energy spectrum of all γ-rays coincident with a recoil event. Two peaks at $\sim$ 2.2 and 2.8 MeV are seen above a threshold of 2 MeV.

The energy loss in the target, dE/dx, was determined by taking the difference in the beam energy entering the target with that leaving the target. This was measured to be 24.1 keV/u at 7.45 torr, or 8.57×10^{-14} eV/(atom/cm^2). This agrees with calculations done by SRIM, a program which simulates the stopping range of ions in matter [19].

Using Eq. 6, corrected yields were calculated for six runs at 775 keV/u. Substituting these values into Eq. 2 gave an average resonance strength of $\overline{\omega\gamma} = 254 \pm 16_{stat} \pm 44_{sys}$ meV. The average,

$$\overline{\omega\gamma} = \frac{\sum \frac{\omega\gamma_i}{\Delta\omega\gamma_i}}{\sum \frac{1}{\Delta\omega\gamma_i}}, \tag{9}$$

took into account the statistical error, $\Delta\omega\gamma_i$, associated with each run.

As a check of the resonance strength, the yield was calculated a second time using a method independent of the first. Coincident recoil events (shown in Fig. 4b) were used after being corrected for the efficiency of the BGO γ-array.

$$Y = \frac{\#\text{ of coincident recoils}}{\text{BGO efficiency} \times \text{CSF} \times \text{LT} \times \#\text{ of beam ions}} \tag{10}$$

The efficiency of the BGO γ-array was calculated using the GEANT simulation program [20]. Upon examination of the coincident γ spectrum (Fig. 5), it was determined that the capture reaction resulted in a cascade of two γ-rays with energies 2.8 MeV and 2.2 MeV. For a cascade of these energies at a resonance position of Z = 2.7 cm (see Fig. 4d), the efficiency was found to be (61 $\pm$ 12)%. The systematic error was deduced from values of the array efficiency measured with stable beam reactions.

Using Eq. 10, yields were again calculated for the six runs at 775 keV/u. Substituting these values into Eq. 2

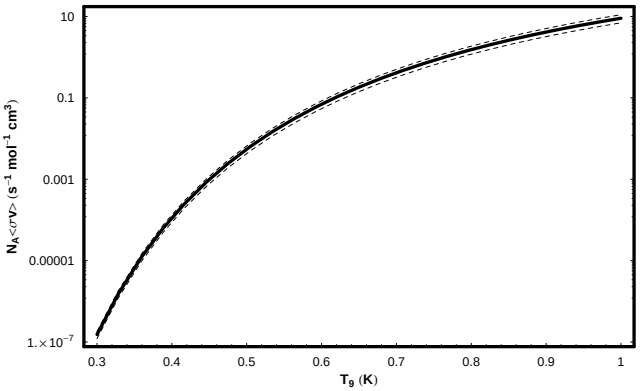

FIG. 6: The rate for the ^{21}Na(p,γ)^{22}Mg reaction at typical novae temperatures using Eq. 1 and our values for $\omega\gamma$ and E_R. The dashed lines represent the upper and lower limits on the rate.

gave an average resonance strength of $\overline{\omega\gamma} = 152 \pm 16_{stat} \pm 32_{sys}$ meV. This value is not in agreement with the value found when using the non-coincident recoils. The source of this discrepancy is currently unknown, although it is suspected to be related to the loss of data below the γ energy threshold.

B. Resonance Energy (E_R)

The energy of ^{21}Na(p,γ)^{22}Mg resonance was determined by examining the position of the resonance in the gas target. Knowing this position, one can determine the amount of energy lost by the beam before resonance is achieved. Subtracting this value from the original beam energy gives the desired resonance energy:

$$E_R = E_{in} - \left(\frac{1}{2} + \frac{Z_R}{\ell}\right)\Delta E \qquad (11)$$

Here, E_{in} is the energy of the beam entering the gas target, ΔE is the total energy lost in the gas target (see Table I), and ℓ, the effective target length, is 12.3 ± 0.4 cm [15]. The distance of the resonance from the centre of the target, Z_R, was determined by a Gaussian fit to the distribution of valid γ-ray events along the target length (see Fig. 4d).

Using Eq. 11, resonance energies were calculated for the six runs at 775 keV/u. Averaging these values gave a resonance energy of $E_{cm} = 728.1 \pm 1.2$ keV, and not 746 keV, as previously expected (see Fig. 2). Using the current value for the mass of ^{22}Mg, -396.8 keV, gives an excitation level of $E_x = 6.230$ MeV.

A new mass for ^{22}Mg of -403.2 ± 1.3 keV has recently been suggested by Bishop et. al. [10]. If this value is used, the Q-value becomes 5.508 MeV, and the excitation level, $E_x = 6.236 \pm 0.001_{stat} \pm 0.001_{sys}$ MeV. This is in closer agreement with the original level scheme for ^{22}Mg, which predicted an excitation energy of $E_x = 6.248$ MeV. Thus, these findings give support for a modified mass excess for ^{22}Mg.

V. DISCUSSION

The effect of these results on the calculated stellar reaction rate is shown in Fig. 6. The reaction rate was determined by substituting the derived values of $\omega\gamma$ and E_R into Eq. 1. Novae model calculations have not been performed at this resonance energy, so comparisons between theoretical and measured reaction rates are not yet available.

In addition to the reduction of uncertainties in the rate of the ^{21}Na(p,γ)^{22}Mg reaction, and the subsequent impact on the expected amount of ^{22}Na synthesized in ONe novae, the present work provides some insight into the properties of the 6.236 MeV excited state of ^{22}Mg. The energy spectrum of γ-rays emitted in this reaction (Fig. 5) peaks at $\sim$ 2.2 and 2.8 MeV. This suggests that the state cascades 100% to the 3.31 MeV state (parity 4^+), then onto the 1.25 MeV state (parity 2^+), before proceeding to the ground state (see Fig. 2). The initial transition to the 4^+ state suggests that the 6.236 MeV state also has a high parity. As reported in [21], this parity is most likely 4^+.

VI. CONCLUSIONS

The rate of the ^{21}Na(p,γ)^{22}Mg reaction was determined. The main conclusions are as follows:

- The energy of one excited state important for element synthesis in ONe novae is $E_{cm} = 728.1 \pm 1.2$ keV. This value supports a modified mass excess for ^{22}Mg.
- The resonance strength of this state is $\omega\gamma = 254 \pm 16_{stat} \pm 44_{sys}$ meV.

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