The $^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$ Reaction and Oxygen-Neon Novae

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The $^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$ reaction is expected to play an important role in the nucleosynthesis of $^{22}\text{Na}$ in Oxygen-Neon novae. The decay of $^{22}\text{Na}$ leads to the emission of a characteristic 1.275 MeV gamma-ray line. This report provides the first direct measurement of the rate of this reaction using a radioactive $^{21}\text{Na}$ beam, and discusses its astrophysical implications. The energy of the important state was measured to be $E_{c.m.} = 205.7 \pm 0.5$ keV with a resonance strength $\omega_\gamma = 1.03 \pm 0.16_{stat} \pm 0.14_{sys}$ meV.

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The synthesis of light and intermediate-mass elements can take place through radiative proton captures on unstable nuclei during explosive stellar events. One astrophysical site where such processes can occur involves classical novae, stellar explosions powered by thermonuclear runaways on accreting ONe or CO white dwarf stars 1, 2, 3. In this hydrogen burning process, nuclear activity involves different cycles, depending on the nova type and on the temperatures achieved during the explosion. A predominant nuclear activity in ONe novae takes place in the NeNa cycle, initiated by radiative proton captures on the abundant seed nuclei $^{20}\text{Ne}$.

Nucleosynthesis in the NeNa cycle during nova outbursts leads to the synthesis of the astronomically important, but unstable $^{22}\text{Na}$ nucleus. Its $\beta$-decay ($t_{1/2} = 2.6 \text{ yr}$) leads to the emission of a 1.275 MeV $\gamma$-ray, following population of the first excited state of $^{22}\text{Ne}$. In fact, this $\gamma$-ray is an ideal observable for nova events as first suggested by Clayton & Hoyle 4. Thus far, observational searches performed with NASA’s COMPTEL on-board CGRO satellite of five ONe novae have not found this $\gamma$-ray signature 5. Whereas the inferred upper limits are in agreement with recent results from ONe nova models 2, 5, the reduction of the nuclear uncertainties associated with the main reactions involved in the synthesis of $^{22}\text{Na}$ is critically important in order to predict how much $^{22}\text{Na}$ can be produced in a typical nova event, and at what distance a nova explosion is expected to provide a detectable flux of $\gamma$-rays.

Another aspect that stresses the astronomical interest of $^{22}\text{Na}$ relies on the identification of presolar grains likely condensed in the ejecta from nova outbursts. Traditionally, they have been identified by low $^{20}\text{Ne}/^{22}\text{Ne}$ ratios (where $^{22}\text{Ne}$ is attributed to in-situ $^{22}\text{Na}$ decay). A $^{22}\text{Na}/^{20}\text{Ne}$ ratio of $9 \times 10^{-6}$ 6 has been determined recently in the graphite grain KFB1a-161, in which other isotopic ratios resemble those found in the envelopes ejected by nova outbursts. Again, a more accurate knowledge of reactions in the synthesis of $^{22}\text{Na}$ in novae would further assist in identifying presolar grains from novae and for tuning models accordingly.

Synthesis of $^{22}\text{Na}$ in novae takes place following two possible reaction paths (Fig. 1): in the first (“cold” NeNa cycle), $^{21}\text{Na}$ forms from the seed $^{20}\text{Ne}$ which then leads to $^{21}\text{Na}(\beta^+)^{21}\text{Ne}(p,\gamma)^{22}\text{Na}$; in the second path, associated with higher temperatures (“hot” NeNa cycle), proton-capture on $^{21}\text{Na}$ dominates over its $\beta$-decay, followed by $^{21}\text{Na}(p,\gamma)^{22}\text{Mg}(\beta^+)^{22}\text{Na}$. There is little net mass flow from $^{22}\text{Mg}$ to $^{23}\text{Al}$ due to the low Q-value for photodisintegration of $^{23}\text{Al}$. Current models of ONe novae indicate that the unknown rate of $^{21}\text{Na}(p,\gamma)$ is the main source of uncertainty associated with calculating the amount of $^{22}\text{Na}$ in nova outbursts 8, 9. The purpose of this paper is to report on the first direct measurement.
of this rate. Under nova conditions the capture reaction rate, $N_A\langle\sigma v\rangle$, is expected to be dominated by one or more narrow resonances. Each resonance contributes to the reaction rate in direct proportion to its resonance strength, $\omega\gamma$, and depends exponentially on the resonance energy, $E_R$. In units of cm$^3$s$^{-1}$ mol$^{-1}$, it is given by,

$$N_A\langle\sigma v\rangle = 1.54 \times 10^{11} \left(\mu T_9\right)^{-3/2} \omega\gamma \exp \left[-11.605 \frac{E_R}{T_9}\right],$$

with $N_A$ Avogadro’s number, $\mu$ the reduced mass in u, $T_9$ the temperature in units of GK, $\langle\sigma v\rangle$ the thermally averaged nuclear cross section, and $\omega\gamma$ and $E_R$ in MeV [10]. The narrow resonance thick target yield, $Y$, at maximum is [11],

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

with $\lambda$ the centre-of-mass de Broglie wave length, $M$ the (heavy) projectile nucleus mass, $m$ the (light) target nucleus mass, and $\frac{dE}{dx}$ the energy loss per atom/cm$^2$(lab). Thus, measurement of the maximum thick target yield can determine the resonance strength, $\omega\gamma$.

Figure 2 shows the $^{22}$Mg level scheme [12, 13]. Calculation of the Gamow window indicates that the 212 keV, $\ell = 0$ resonance will be the dominant contributor (as compared to other higher resonances and direct capture) to the $^{21}$Na$(p,\gamma)^{22}$Mg reaction at all nova temperatures from 0.2 to 0.35 GK. We report here a measurement of the strength, $\omega\gamma$, and a revised energy, $E_R$, for this resonance in the $^{21}$Na$(p,\gamma)^{22}$Mg reaction.

The experiment was carried out at the TRIUMF-ISAC radioactive beams facility located in Vancouver, Canada. Fifteen $\mu$A of 500 MeV protons bombarded a thick target of SiC resulting in an intense ($\sim 10^9$ s$^{-1}$), pure ($\sim 100\%$) $^{21}$Na beam extracted from a surface ion source and a high resolution mass analyzer [15]. It was accelerated using the new ISAC linear accelerator, resulting in beams with energies variable from 0.15 to 1.5 MeV/u [16]. The study was performed using inverse kinematics with the DRAGON (Detector of Recoils And Gammas Of Nuclear reactions) facility. DRAGON consists of a windowless gas target (effective length of 12.3 cm) surrounded by a gamma array (30 units of BGO), and followed by a two-stage, recoil mass separator, 21 m in length (from target centre to focal plane). Separation of the rare recoil from more intense beam is achieved using magnetic and electric dipoles. Following an initial selection of a single (optimal) charge state [17] in the first magnetic dipole, energy dispersion in the electric dipole allows mass separation, and the process is repeated in the second stage. A DSSSD (Double Sided Silicon Strip Detector) was used at the focal plane of DRAGON to detect the $^{22}$Mg recoils. A more complete description of DRAGON can be found elsewhere [18, 19].

A radioactive beam of $^{21}$Na (q=5$^+$) at typical intensities up to $5 \times 10^8$ s$^{-1}$ was delivered to the DRAGON hydrogen gas target (4.6 Torr). The gas target received a total of $\sim 10^{13}$ $^{21}$Na atoms for this study. Data taking was done in both singles and coincidence modes; the coincidence mode required a “start” timing signal from the $\gamma$-array in coincidence with a “stop” timing signal from the DSSSD. Figure 3 shows resonant-capture spectra for a beam energy of 220 keV/u. Counts within the box in Fig. 3a were considered to be valid capture events. Their recoil energy distribution is presented in Fig. 3a. Fig. 3b is the recoil time-of-flight spectrum for events satisfying the cut on gamma-ray energy. The distribution of the hit BGO detector position along the beam axis (Fig. 3c) shows that the resonance was near the centre of the gas target at beam energy 220 keV/u ($E_{c.m.} = 211$ keV).

The beam energies were measured by adjusting the field of the first magnetic dipole in the separator so as to position the beam on the ion-optical axis at an energy-
our data imply a value of -403.2 ± could be explained by a modified mass excess for measurement of the 5713.9 keV level, this disagreement latter value is based upon a direct gamma de-excitation resonance to be 205.7 ± 0.5, and not 212 keV (see Fig. 2), given that the latter value is based upon a direct gamma de-excitation measurement of the 5713.9 keV level, this disagreement could be explained by a modified mass excess for 22Mg; our data imply a value of -403.2 ± 1.3 keV rather than -396.8 keV.

Figure 4 (upper panel) shows the thick target yield curve corrected/scaled for various factors listed in Table I. The efficiency of the BGO array as a function of gamma-ray energy and resonance position in the target was calculated using the GEANT program. The variation of resonance position with beam energy resulted in the following calculated efficiencies: 45% for 202 keV ≤ E ≤ 207 keV, 48% at 211 keV, and 46% above 216 keV. The systematic error was deduced from values of the array efficiency measured with stable beam reactions. The separator transmission (98%) and DSSSD detection efficiency (99%) were determined separately, and the fraction of the charge state selected (44%) was measured with a 24Mg beam of 220 keV/u.

At 4.6 Torr, charge state equilibrium in H2 gas was measured to be attained within 2 mm. The energy loss in the target (4.6 Torr) was measured to be 14.4 keV/u (lab) or 8.18 × 10^{-14}eV/(atom/cm^2), in agreement with SRIM.

The data of Fig. 4 (upper panel) were obtained by maximum likelihood combination of several runs at each energy. The error bars on the zero counts seen at off-resonance energies are 68% confidence limits. Table I presents a summary of systematic errors. Using Eq. 2 and only the mid-target data point (211 keV), a yield of (5.76 ± 0.88) × 10^{-12} per incident 21Na, results in a resonance strength of ωγ = 1.03 ± 0.16(stat) ± 0.14(sys) meV.

The effect of these results on the calculated stellar reaction rate is shown in Fig. 3. The rate is reduced over that determined by shell model calculations of ωγ as reported in [12], and enhanced over that found in [8]. An analysis of the impact of the new measurements on the...
a firmer basis for predictions of the expected gamma-ray signature at 1.275 MeV associated with $^{22}$Na decay in ONe novae, and confirm the previous determination of 1 kiloparsec for a typical ONe nova observed with ESA’s (European Space Agency) INTEGRAL spectrometer, SPI. Furthermore, the smaller uncertainty in the rate also indicates that the predicted $^{22}$Na yields are not in conflict with the upper limits derived from several observational searches.

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