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

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The ^{21}Na$(p, \gamma)^{22}$Mg reaction is expected to play an important role in the nucleosynthesis of ^{22}Na in oxygen-neon novae. The decay of ^{22}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}Na beam, and discusses its astrophysical implications. The energy of the important state was measured to be $E_{\text{c.m.}} = 205.7 \pm 0.5$ keV with a resonance strength $\omega\gamma = 1.03 \pm 0.16_{\text{stat}} \pm 0.14_{\text{sys}}$ 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 [1–3]. 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}Ne.

Nucleosynthesis in the NeNa cycle during nova outbursts leads to the synthesis of the astronomically important, but unstable ^{22}Na nucleus. Its β decay ($t_{1/2} = 2.6$ yr) leads to the emission of a 1.275 MeV γ ray, following population of the first excited state of ^{22}Ne. In fact, this γ ray is an ideal observable for nova events as first suggested by Clayton and Hoyle [4]. Thus far, observational searches performed with NASA's COMPTEL on-board CGRO satellite of five ONe novae have not found this γ-ray signature [5]. Whereas the inferred upper limits are in agreement with recent results from ONe nova models [2,3], the reduction of the nuclear uncertainties associated with the main reactions involved in the synthesis of ^{22}Na is critically important in order to predict how much ^{22}Na can be produced in a typical nova event, and at what distance a nova explosion is expected to provide a detectable flux of γ rays.

Another aspect that stresses the astronomical interest of ^{22}Na relies on the identification of presolar grains likely condensed in the ejecta from nova outbursts. Traditionally, they have been identified by low ^{20}Ne/^{22}Ne ratios (where ^{22}Ne is attributed to *in situ* ^{22}Ne decay). A ^{22}Na/C ratio of 9×10^{-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}Na in novae would further assist in identifying presolar grains from novae and for tuning models accordingly.

Synthesis of ^{22}Na in novae takes place following two possible reaction paths (Fig. 1): in the first ("cold" NeNa cycle), ^{21}Na forms from the seed ^{20}Ne which then leads to ^{21}Na$(\beta^+)^{21}$Ne$(p, \gamma)^{22}$Na; in the second path, associated with higher temperatures ("hot" NeNa cycle), proton-capture on ^{21}Na dominates over its β decay, followed by ^{21}Na$(p, \gamma)^{22}$Mg$(\beta^+)^{22}$Na. There is little net mass flow from ^{22}Mg to ^{23}Al due to the low Q value for photo disintegration of ^{23}Al [7]. Current models of ONe novae indicate that the unknown rate of ^{21}Na(p, γ) is the main source of uncertainty associated with calculating the amount of ^{22}Na in nova outbursts [8,9]. The purpose of this Letter is to report on the first direct measurement of this rate.

Under nova conditions the capture reaction rate, $N_{\text{A}}\langle\sigma v\rangle$, is expected to be dominated by one or more narrow resonances. Each resonance contributes to the

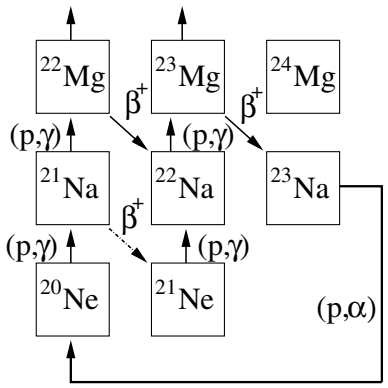

FIG. 1. The combined "cold" and "hot" NeNa reaction cycles. The isotope ^{21}Na will either β decay into ^{21}Ne (the "cold" NeNa cycle) or capture a proton leading to ^{22}Mg (the "hot" cycle) depending upon the temperature and the reaction rate.

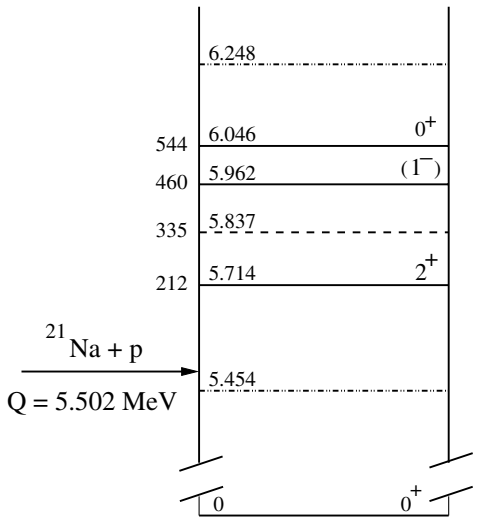

FIG. 2. The ^{22}Mg level scheme of those states of astrophysical interest for ONe nova, shown with solid lines [12,13]. The numbers on the far left denote center-of-mass energies (E_x-Q) in units of keV. The state at 5.837 MeV was observed once but not confirmed in other studies [12–14].

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

$$N_A\langle\sigma v\rangle = 1.54 \times 10^{11}(\mu T_9)^{-3/2}\omega\gamma \exp\left[-11.605\frac{E_R}{T_9}\right], \quad (1)$$

with N_A Avogadro's number, μ 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],

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

with λ the center-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 μA 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 center 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 5×10^8 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; a "start" timing signal was required from the γ 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. 3(a) were considered to be valid capture events. Their recoil energy distribution is presented in Fig. 3(b). Figure 3(c) 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. 3(d)] shows that the resonance was near the center 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-dispersed focus. Using the design bending radius of the dipole (1 m), it was possible to calculate beam energy in

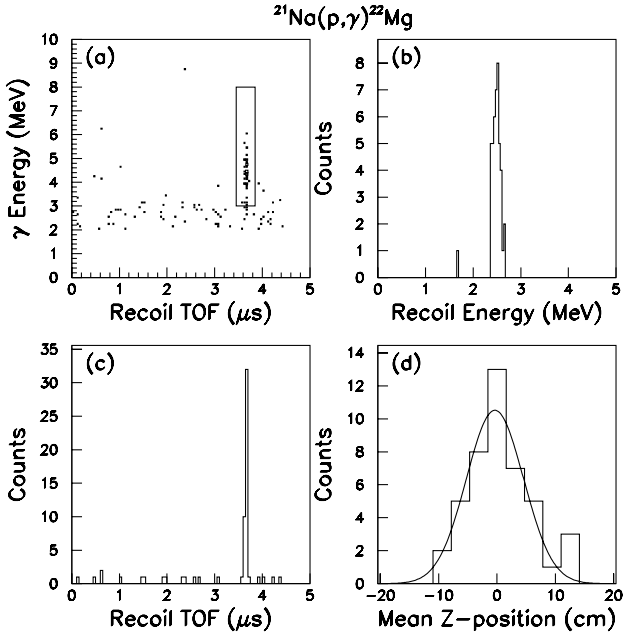

FIG. 3. Resonant-capture spectra for a ^{21}Na beam energy of 220 keV/u. (a) Valid events enclosed by a two-dimensional-cut box above a background of random-coincidence events; (b) the recoil-energy distribution of the events in the DSSSD, selected by the box in (a); (c) the recoil time of flight distribution for events above the γ-ray threshold energy; (d) distribution of box-selected γ-ray events observed in the BGO array along the target length, with a Gaussian fit.

terms of the dipole field. The expected relationship was confirmed by measuring a number of known resonances with stable beams. Figure 4 shows the yield curve for one of these studies, the ^{24}Mg(p, γ)^{25}Al reaction, demonstrating our agreement (inflection point of 214.4 ± 0.5 keV) with the literature resonance energy of 214.0 ± 0.1 keV [20]. As shown in the upper panel, we find the energy for the ^{21}Na(p, γ)^{22}Mg resonance to be 205.7 ± 0.5, and not 212 keV (see Fig. 2), the difference between the Q value and the level excitation energy, 5713.9 ± 1.2 keV [21]. Given that the latter value is based upon a direct gamma deexcitation measurement of the 5713.9 keV level, this disagreement could be explained by a modified mass excess for ^{22}Mg; our data imply a value of −403.2 ± 1.3 keV rather than −396.8 keV [22].

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 γ-ray energy and resonance position in the target was calculated using the GEANT program [23,24]. 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%) [19] and DSSSD detection efficiency (99%) [25] were determined separately, and the fraction of the charge state selected (44%) was

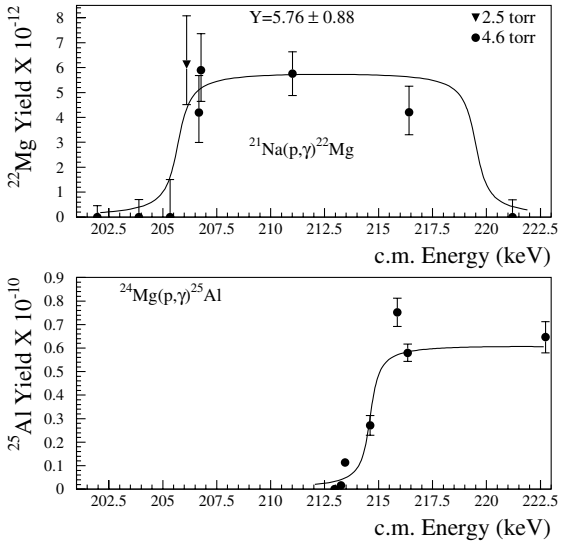

FIG. 4. The upper panel displays the thick target yield data for the ^{21}Na(p, γ)^{22}Mg reaction, with the solid line showing the nominal target thickness for 4.6 Torr. Yield of the ^{24}Mg(p, γ)^{25}Al reaction for the resonance at $E_{\text{c.m.}}$ = 214 keV, used for beam energy calibration, is displayed in the lower panel. Statistical errors only are displayed in both.

measured with a ^{24}Mg beam of 220 keV/u. At 4.6 Torr, charge state equilibrium in H^2 gas was measured to be attained within 2 mm [17]. 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 [26].

The data of Fig. 4 (upper panel) were obtained by maximum likelihood combination of several runs at each energy [27]. 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 midtarget data point (211 keV), a yield of (5.76 ± 0.88) × 10^{-12} per incident ^{21}Na, results in a resonance strength of $\omega\gamma = 1.03 \pm 0.16_{\text{stat}} \pm 0.14_{\text{sys}}$ meV.

The effect of these results on the calculated stellar reaction rate is shown in Fig. 5. The rate is reduced over that determined by shell model calculations of $\omega\gamma$ as reported in [12], and enhanced over that found in [8]. An analysis of the impact of the new measurements on the synthesis of ^{22}Na in novae was performed. A new model of a nova outburst, using an ONe white dwarf of 1.25 solar

TABLE I. Summary of systematic errors.

Factors	Value	Syst. error (%)
BGO array efficiency (@211 keV)	0.48	12
Separator transmission	0.98	2
DSSSD efficiency	0.99	1
Charge state fraction	0.44	3
Integrated beam (@211 keV)	3.62×10^{13}	4
dE/dx [eV/(atom/cm^2)]$_{\text{lab}}$	8.18×10^{-14}	5

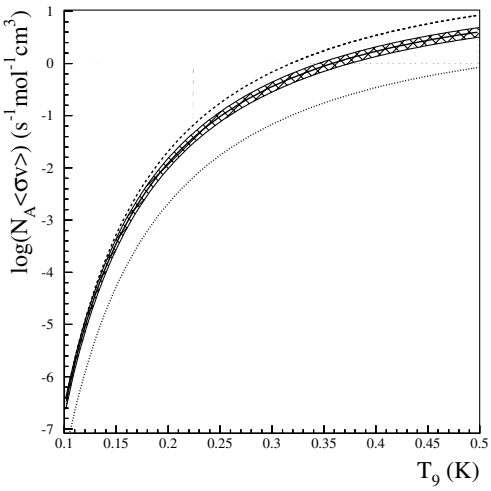

FIG. 5. The stellar rate for the ^{21}Na(p, γ)^{22}Mg reaction using Eq. (2) with typical novae temperatures and our measured values for $\omega\gamma$ and E_R= 0.206 MeV (solid line with hatched area reflecting errors), in comparison with other works; upper curve [12] and lower curve [8].

mass, has been computed from the onset of accretion up to the explosion and ejection stages, by means of a spherically symmetric, implicit, hydrodynamic code, in Lagrangian formulation (see [3] for details). Results have been compared with a model evolved with the previous prescription of the ^{21}Na(p, γ)^{22}Mg rate [8]. As a result of the higher contribution of the 5.714 MeV level (Fig. 5), a slightly lower amount of ^{22}Na (a mean mass fraction of 2.8×10^{-4}, compared with the previous estimate of 3.5×10^{-4}) is found. The small decrease in the ^{22}Na yield results from the fact that increasing the proton-capture rate on ^{21}Na favors the synthesis path through ^{21}Na(p, γ)^{22}Mg(β^+)^{22}Na, hence reducing the role of the alternative ^{21}Na(β^+)^{21}Ne(p, γ)^{22}Na path. In these newly derived conditions of increased proton-capture on ^{21}Na, ^{22}Na production takes place earlier in the outburst, at a time when the envelope has not yet significantly expanded and cooled down [contrary to the case when a lower ^{21}Na(p, γ) rate is adopted], and hence the temperature in the envelope is still high enough to allow proton captures on ^{22}Na, that reduce its final content in the ejecta.

Up to now, γ-ray flux determinations were limited by a large uncertainty in the ^{21}Na(p, γ) and ^{22}Na(p, γ) rates, which translated into an overall uncertainty in the ^{22}Na yields of a factor of $\sim$3. The maximum detectability distance was, accordingly, uncertain by a factor of $\sim$2. Such uncertainty, mainly due to the previously unknown reaction rate, has been largely reduced with the present experimental determination of $\omega\gamma = 1.03 \pm 0.16_{\text{stat}} \pm 0.14_{\text{sys}}$ meV. These results provide 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 kpc for a typical ONe nova [28,29] 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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