Nuclear Astrophysics with DRAGON at ISAC: The $^{21}Na(p,\gamma)^{22}Mg$ reaction

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Abstract

The DRAGON facility at the new intense radioactive beams facility, ISAC, is now operational. It was built to perform studies of radiative alpha and proton capture reactions involving radioactive reactants, and of interest to nuclear astrophysics.The rate of the $^{21}Na(p,\gamma)^{22}Mg$ reaction has been measured using inverse kinematics. Resonance strengths have been measured for states of importance for novae explosions. This report will summarize aspects of this study and its impact.

1 Introduction

DRAGON (Detector of Recoils And Gamma-rays Of Nuclear reactions) is TRIUMF's new facility for measuring radiative capture cross sections of astrophysical interest. DRAGON uses the accelerated radioactive beams produced at the ISAC (Isotope Separator and ACcelerator) facility to measure cross sections in inverse-reaction kinematics. Summarized herein are features of DRAGON as well as results of commissioning measurements with stable beams. Results of the first astrophysics experiment utilizing a ^{21}Na radioactive beam on a hydrogen target, of importance for understanding novae explosions, will be presented.

1.1 ISAC

ISAC is a high intensity radioactive beams facility of the ISOL type. Intense beams ($\leq 100\mu$A) of 500 MeV protons intercept a thick target. Using a heated surface ion source, beams of alkali elements are extracted and mass analysed. For these studies accelerated (0.2 - 1.5 MeV/u) beams of ^{21}Na with intensities up to 10^9 are available. Consult the web page, (http://www.triumf.ca/isac/) for more information.

1.2 DRAGON

DRAGON was built to measure the rate of radiative proton and alpha capture reactions involving radioactive reactants, using inverse kinematics. It consists of a windowless gas (for hydrogen or helium) target surrounded by a 30 unit, BGO gamma array to detect the reaction prompt gamma ray and followed by a 20 m long recoil mass separator(RMS). Reaction products are separated from the more intense beam using electric and magnetic dipoles in two separate sections, taking advantage of the small energy ($\approx$ 2%) difference . One charge state is delivered to the focal plane detector, which in these studies was a DSSSD (double sided, silicon strip detector). Beam suppression of about 10^{10} was measured for the RMS system, and this increased three orders of magnitude using coincidences with the prompt reaction gamma ray and by measuring the energy and time of flight of the recoils in the DSSSD. A full description can be found elsewhere, namely [1] and on the web (http://www.triumf.ca/dragon/).

2 The $^{21}Na(p,\gamma)^{22}Mg$ Reaction

2.1 Rationale

Synthesis of the light and intermediate-mass elements can proceed by way of radiative proton captures, through narrow resonances, on unstable nuclei during explosive stellar events. A thermonuclear runaway on a white dwarf star, resulting in a nova explosion, is an astrophysical site where this explosive hydrogen burning is expected to occur [2, 3, 4]. During the thermonuclear runaway on a ONe white dwarf, a predominant burning cycle involves radiative proton captures on the seed ^{20}Ne leading to the production of ^{21}Na.

As Fig. 1 shows, two reaction paths are available for ^{21}Na: β-decay to ^{21}Ne or proton-capture to ^{22}Mg. Feeding to ^{22}Na, whose decay is astronomically observable, proceeds in the early stages (the "cold" NeNa cycle) by way of proton capture on ^{21}Ne. As the temperature increases (leading into the "hot" cycle) ^{22}Na synthesis proceeds through proton captures on ^{21}Na leading to ^{22}Mg ($t_{1/2}$ = 3.86 s), that decays into ^{22}Na. Build-up of ^{22}Mg ensues owing to the low Q-value for photodisintegration of ^{23}Al [5]. Current models of ONe novae indicate that the unknown rate of the ^{21}Na$(p,\gamma)^{22}$Mg reaction creates a large uncertainty in predicting how much ^{22}Na can be produced in a typical nova event [6, 7].

The β decay of ^{22}Na ($t_{1/2}$ = 2.6 a) leads to the emission of a 1.275 MeV γ-ray following population of the first excited state of ^{22}Ne. This γ-ray is

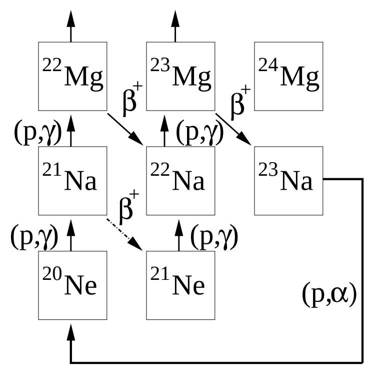

Figure 1: The combined "cold" and "hot" NeNa reaction cycles. The isotope ^{21}Na will beta decay into ^{21}Ne(the "cold" NeNa cycle) or capture a proton leading to ^{22}Mg (the "hot" cycle) when the temperature is high enough, as determined by the rate.

an ideal observable for nova events but thus far, observational data taken by NASA's COMPTEL on-board CGRO satellite of five ONe nova candidates have not displayed this γ-ray line [8]. While the deduced upper limits are in agreement with recent ONe novae models [3, 4], reducing the uncertainties in the ^{21}Na(p, γ)^{22}Mg reaction rate by direct measurement of the astrophysically relevant resonance strengths is clearly important for predicting how much ^{22}Na can be produced in a typical nova event, and how distant a nova explosion may be to provide a detectable flux in gamma rays.

2.2 The Experiment

Fig. 2 shows the ^{22}Mg level scheme [9, 10]. Calculations of the Gamow window for the ^{21}Na(p, γ)^{22}Mg reaction at estimated ONe nova temperatures from 0.2 to 0.35 GK at peak temperature [6], suggest that throughout the duration of the outburst the 212 keV, $l = 0$ resonance will be dominant in the nucleosynthesis of ^{22}Na (as compared to other resonances and direct capture). The goal of the study is to measure the resonance strength of this key state.

The experiment was carried out at the TRIUMF-ISAC radioactive beams facility located in Vancouver, Canada using DRAGON. A radioactive beam of ^{21}Na (q=5$^+$) at typical intensities up to 1×10^9 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

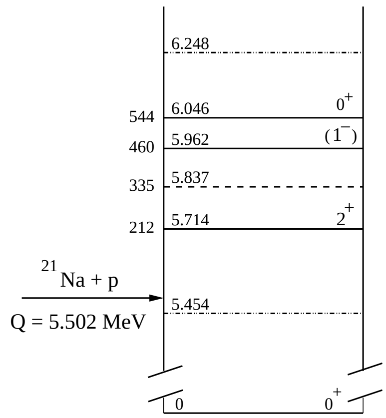

Figure 2: The ^{22}Mg level scheme of those states of astrophysical interest for ONe nova, shown with solid lines [9, 10]. The numbers on the far left denote center-of-mass energies (E_x- Q), in units of keV. The state at 5.837 MeV was observed once and not confirmed in other studies [9, 10, 11].

the γ-array in coincidence with a "stop" timing signal in the final focus of the DSSSD. Figure 3 shows resonant-capture data spectra for a beam energy of 220 keV/u (maximum yield). Valid recoil TOF(time-of-flight)-γ-ray energy coincidence events above background are enclosed within the box (Fig. 3a). Distributions of real coincidence events (TOF and energy) in the recoil detector above thresholds are displayed in Fig. 3b,c while Fig. 3d displays the position of coincident γ-ray events, observed in the BGO array, at a beam energy of 220 keV/u. A total of 103 ^{22}Mg fusion events was extracted from coincidence data at all energies, and these events produce the yield curve in Fig. 4.

2.3 Results and Discussion

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 terms of the dipole field. The expected relationship was confirmed by measuring a number of known resonances with stable beams. The lower panel of Figure 4 shows the yield curve for one of these studies, the ^{24}Mg$(\mathrm{p}, \gamma)^{25}$Al reaction, demonstrating our agreement (inflection point-214.4 $\pm$0.5 keV) with the literature resonance energy of 214.0$\pm$0.1 keV [12]. As shown in the upper panel, we find the resonance energy (inflection

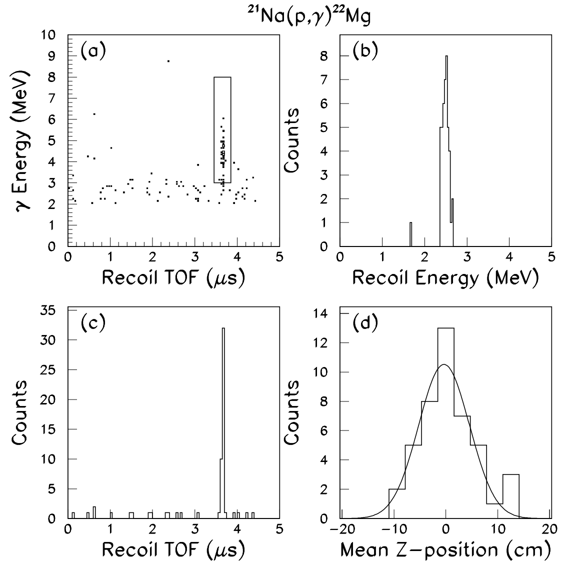

Figure 3: Resonant-capture data spectra for a ^{21}Na beam energy of 220 keV/u. See text for details.

point) 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 [13]. 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 ^{22}Mg; our data implies a value of -403.2±1.3 keV rather than -396.8 keV [14].

Fig. 4 (upper panel) shows the thick target yield curve corrected/scaled for various factors, namely the BGO array efficiency, charge state fraction, separator transmission, DSSSD detection efficiency and integrated beam intensity. Table 1 presents a summary of related systematic errors. Using only the mid-target data point, an obtained yield of $(5.45 \pm 0.83) \times 10^{-12}$ per incident ^{21}Na, results in a resonance strength (preliminary) $\omega\gamma = 0.98 {\pm} 0.15_{stat} {\pm} 0.21_{sys}$ meV. Further details can be found elsewhere [15].

The effect of these results on the stellar reaction rate is shown in Fig. 5. The result is a rate reduced over what was determined by shell model calculations of $\omega\gamma$ as reported in [9] and [7] and enhanced over that found in [6]. A preliminary analysis was performed of the impact of the new measurements on the synthesis of ^{22}Na in novae. A new model of a nova outburst, hosting an ONe white dwarf of 1.25 solar mass, has been computed from the onset

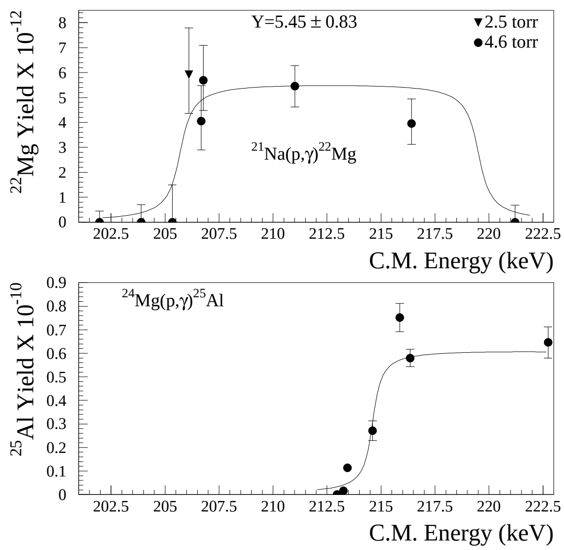

Figure 4: The upper panel displays the thick target yield data for the ^{21}Na(p, γ)^{22}Mg reaction, with the solid line showing the nominal target thickness for 4.6 Torr. Yield of the ^{24}Mg(p,γ)^{25}Al reaction for the resonance at E$_{cm}$=214 keV, used for beam energy calibration, is displayed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

of accretion up to the explosion and ejection stages, by means of a spherically symmetric, implicit, hydrodynamic code, in Lagrangian formulation (see [4] for details). Results have been compared with a model evolved with the previous prescription of the ^{21}Na(p,γ)^{22}Mg rate [6]: as a result of the higher contribution of the 212 keV level (Fig. 5), a slightly lower amount of ^{22}Na (a mean mass fraction of 2.8×10^{-4}, compared with the previous 3.5×10^{-4} estimate) is found. The small decrease in the ^{22}Na yield results from the fact that, increasing the proton capture rate on ^{21}Na favours the synthesis path through ^{21}Na(p,γ)^{22}Mg(β^+)^{22}Na. With 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 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.

Table 1: Summary of systematic errors.

Factors	Value	Syst.Error(%)
Charge state fraction	0.44	3
Separator transmission	0.98	2
DSSSD efficiency	0.99	1
BGO array efficiency (@211 keV)	0.51	20
Integrated beam (@211 keV)	3.62×10^{13}	4
dE/dx (eV/(atom/cm^2)$_{lab}$	8.18×10^{-14}	5

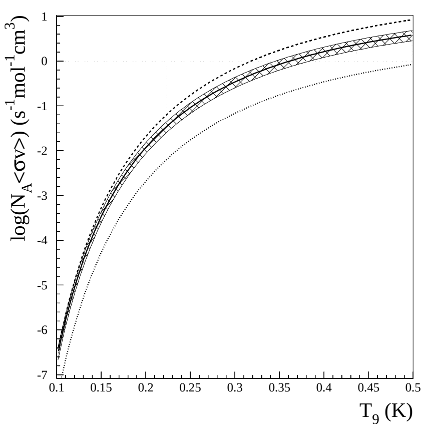

Figure 5: The stellar rate for the ^{21}Na$(p,\gamma)^{22}$Mg reaction using Eq. 2 with typical novae temperatures and our measured values for $\omega\gamma$ and E_{R}= 0.206 MeV (solid line with hatched area reflecting errors), in comparison with other works; upper curve [9] and lower curve [6].

3 Conclusion

The new DRAGON facility is now operational and combined with the wide range of intense radioactive beams at ISAC will now allow the possibility of performing a number of direct measurements of the rates of radiative proton and alpha capture reactions important for an understanding of explosive stellar scenarios.

The new results on the rate of the ^{21}Na(p,γ)^{22}Mg reaction provide a firmer basis for predictions of the expected γ-ray signature at 1.275 MeV associated with ^{22}Na decay from nearby novae. The new measurements confirm the previous estimates for the maximum detectability distance of the 1.275 MeV line with ESA's INTEGRAL satellite, around 1 kiloparsec [16, 17], reducing the uncertainty bar associated with it, and confirming that the predicted ^{22}Na yields are not in conflict with upper limits derived from several observational searches.

References

[1] D. Hutcheon, et. al. , Nucl. Inst. Meth., *The DRAGON facility for nuclear astrophysics at TRIUMF-ISAC: design, construction and operation*, (2003)in press.

[2] F. Kppeler, F.K. Thielemann, and M. Wiescher, Ann. Rev. Nucl. Part. Sci. **49**, (1998)175.

[3] S. Starrfield, et al., MNRAS **296**,502(1998).

[4] J. Jos and M. Hernanz, Astrophys. J. **494**,680 (1998).

[5] M. Wiescher, et al., Philos. Trans. Roy. Soc. London **356**,2105 (1998).

[6] J. Jos et al. Astrophys. J. **520**,347 (1999).

[7] N. A. Smirnova et al., Phys. Rev. C **62**,045803 (2000).

[8] A. F. Iyudin et al., Astron. Astrophys. **300**,422 (1995).

[9] N. Bateman et al., Phys. Rev. **63**, 035803(2001).

[10] S. Michimasa et al., Eur. Phys. J. A **14**, 275(2002).

[11] A. Chen et al., Phys. Rev. C**63**, 06507(2001).

[12] M. Uhrmacher et al., Nucl. Inst. Meth. B **9**, 234(1985).

[13] P.M. Endt, Nucl. Phys. A **521**, 1(1990).

[14] J. Hardy et al., (2002), similar observations; private communication.

[15] S. Bishop et al., Phys. Rev. Letts. *The* $^{21}Na(p,\gamma)^{22}Mg$ *Reaction and Oxygen-Neon Novae* (2003), in press.

[16] J. Gómez-Gomar et al., MNRAS **296**, 913 (1998).

[17] M. Hernanz et al., in **4th INTEGRAL Workshop Exploring the Gamma-Ray Universe**, ESA SP-459, ESA Publ. Division:ESTEC, Noordwijk, p. 65 (2001).