PROCEEDINGS OF SCIENCE

Destruction of ^{22}Na in Novae: Surprising Results from an Absolute Measurement of ^{22}Na(p,γ) Resonance Strengths

A. L. Sallaska*, **C. Wrede, A. García, D. W. Storm, T. A. D. Brown†, K. A. Snover**
Department of Physics, University of Washington, Seattle, WA 98195-1560, USA
E-mail: sallaska@u.washington.edu

C. Ruiz, D. F. Ottewell, L. Buchmann, C. Vockenhuber‡, D. A. Hutcheon, J. A. Caggiano§
TRIUMF, Vancouver, BC V6T 2A3, Canada

Hydrodynamic simulations of classical novae on ONe white dwarfs predict substantial production of ^{22}Na. Observation of ^{22}Na decay should be correlated with the corresponding nova because the half life of ^{22}Na is only 2.6 years. The 1275-keV gamma ray from the β decay of ^{22}Na is, therefore, an excellent diagnostic for the nova phenomenon and a long-sought target of gamma-ray telescopes. Nova simulations determine the maximum ^{22}Na-detection distance to be < 1 kpc for the INTEGRAL spectrometer SPI, consistent with its non-observation to date. However, model estimates are strongly dependent on the thermonuclear rate of the ^{22}Na$(p,\gamma)^{23}$Mg reaction, which destroys ^{22}Na in novae. The ^{22}Na$(p,\gamma)^{23}$Mg rate is expected to be dominated by narrow, isolated resonances with $E_p < 300$ keV. The currently employed rate is based two sets of direct measurements, only one of which was absolute. Recently, a new level has been found in ^{23}Mg, which would correspond to a resonance at $E_p = 198$ keV that might dominate the reaction rate at nova temperatures.

We have measured the ^{22}Na(p,γ) resonance strengths directly and absolutely. Proton beams were produced at the University of Washington and delivered to a specially designed beam line that included rastering and cold vacuum protection of the ^{22}Na-implanted targets (fabricated at TRIUMF-ISAC). Measurements were made on known ^{22}Na+p resonances and on the proposed new resonance at $E_p = 198$ keV. We measured the strengths of the known resonances to be inconsistent with previous measurements. Due to the resulting change in the ^{22}Na(p,γ) reaction rate, we expect the amount of ^{22}Na produced by novae to differ significantly from current estimates, revising the prospects for its observation. Analysis of our results is presented.

11th Symposium on Nuclei in the Cosmos, NIC XI
July 19-23, 2010
Heidelberg, Germany

*Speaker.
†Present address: Mary Bird Perkins Cancer Center, Baton Rouge, LA 70809
‡Present address: ETH Laboratory of Ion Beam Physics, Zurich, Switzerland CH-8093
§Present address: LLNL, Livermore, CA 94550

PoS(NIC XI)051

1. Introduction

A classical nova is a thermonuclear explosion in a binary system, caused by accretion of hydrogen-rich material onto the surface of a white-dwarf star from its companion. Because most of the relevant thermonuclear reaction rates are based on experimental information, novae are exemplary sites for the modeling of explosive nucleosynthesis [1, 2]. Particular isotopes produced in nova explosions, such as ^{22}Na [3], have the potential to be detected by orbiting gamma-ray telescopes via their characteristic decay lines. Novae are believed to be the primary source for Galactic ^{22}Na, and its detection could provide more detailed information on the underlying physical processes [4]. Its half life (2.6 yr) confines it to the location of its production site, yet it is long enough that it will exist beyond the violent opaque phase (and hence be detectable) [5], assuming it is not destroyed during the explosion. The main destructive mechanism for ^{22}Na is the ^{22}Na$(p,\gamma)^{23}$Mg reaction, in which narrow, isolated resonances dominate the reaction rate at peak nova temperatures ($0.1 < T < 0.4$ GK). Currently, the accepted rate is based on two previous sets of direct measurements that utilized radioactive ^{22}Na targets [6]. It has been suggested that a recently discovered state in ^{23}Mg could produce a resonance at E_p = 198 keV that could dominate the reaction rate [7].

Using ^{22}Na targets implanted at the radioactive ion beam facility TRIUMF-ISAC, we have made direct, absolute measurements of key ^{22}Na$(p,\gamma)^{23}$Mg resonance strengths for $E_p < 610$ keV and searched for the proposed 198-keV resonance at the Center for Experimental Nuclear Physics and Astrophysics (CENPA) of the University of Washington. By scanning the beam uniformly over the target area, in contrast to Ref. [6], we bombarded *all* target atoms and integrated the excitation function for each resonance. Our method is not very sensitive to target stoichiometry and non-uniformity or an evolving target distribution due to extended bombardment. More details will be given in Ref. [8].

2. Experiment

Three 300-μCi targets of ^{22}Na were implanted at TRIUMF by rastering a 30-keV ion beam over a 5-mm diameter collimator and into an OFHC copper substrate. Two targets were coated with 20 nm of Cr using vacuum evaporation to prevent sputtering of ^{22}Na by the high-current proton beam during (p,γ) measurements [9]. Because the Cr-coated targets did not exhibit much degradation, they were used to obtain data for all resonances, except one at $E_p = 232$ keV. From an ion source at the terminal of a tandem Van de Graaff accelerator at CENPA, proton beams of $\approx$ 40 μA were produced and delivered to a beam line equipped with a target chamber including a dual cold-shroud system, a water-cooled target mount, and a magnetic raster. During data acquisition, this raster was used to uniformly irradiate the implanted target area.

Two detection systems, each consisting of a high-purity Ge (HPGe) crystal surrounded by Pb shielding and scintillators for cosmic-ray rejection, were positioned at $\pm$ 55° to the beam axis. The active shielding filtered out excess background by rejecting 80% of the beam-off signal above 5 MeV. To reduce the 511-keV γ-ray detection rate, Pb plates 26-mm thick were placed between the target and the HPGe detectors. The vertical and horizontal magnetic fields produced by the raster were recorded and used to deduce the beam position on the target for each event.

3. Data and Results

Known ^{22}Na$(p,\gamma)^{23}$Mg resonances [6], which we find at $E_p = 213, 288, 454$, and 610 keV, and proposed resonances at 198 [7] and 232 keV [10] were measured. Assuming the beam is uniformly rastered over the target's implanted area, the resonance strength, $\omega\gamma$, may be extracted using the equation,

$$\int Y\,dE = \frac{\lambda^2}{2}\frac{m+M}{M} N_T\,\rho_b\,\omega\gamma, \tag{3.1}$$

where Y is the gamma-ray yield at a beam energy E, $\int Y\,dE$ is the integral over the excitation function, λ is the de Broglie wavelength in the center of mass, m is the proton mass, M is the target mass, N_T is the number of target atoms, $\rho_b = \frac{dN_b}{dA}/(Q/e)$ is the beam density normalized to the total number of incident beam particles, and $\frac{dN_b}{dA}$ is the areal density of the beam.

Detector efficiencies were determined from both absolute and relative measurements, together with PENELOPE simulations [11]. For the absolute measurement at $E_\gamma = 1332$ keV, a ^{60}Co source calibrated to 1.7% (99% *C.L.*) was used, and, for the relative measurements, ^{24}Na$(\beta\gamma)$ decay branches and ^{27}Al(p,γ) reaction branches were used. The simulated photopeak detection efficiency is shown in the top panel of Fig. 1, and agreement with data is shown in the bottom panel. A systematic uncertainty of 6% was applied to all efficiencies, which includes an estimated 3% uncertainty arising from possible deviations from the assumed isotropic angular distribution.

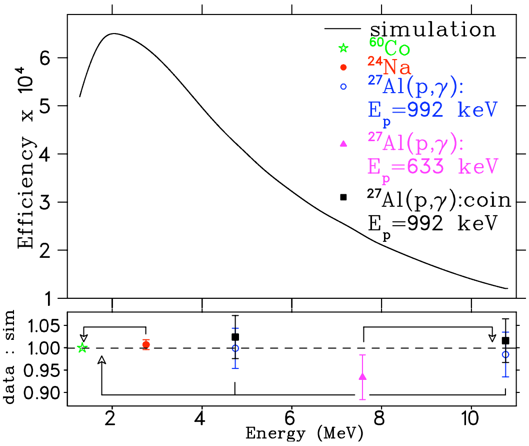

Figure 1: Photopeak efficiency. Top panel is the efficiency from PENELOPE simulations. Bottom panel shows the ratio of efficiencies from measurement to simulation, and arrows connect the gamma-ray energy used in the relative efficiency analysis.

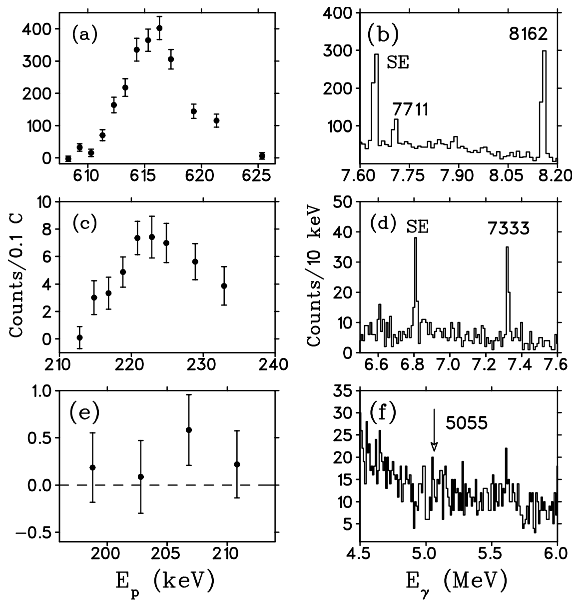

Figure 2: Excitation functions (left column) and corresponding summed γ-ray spectra (right column). Panels (a) and (b), (c) and (d), and (e) and (f) are for $E_p = 610$, 213, and 198 keV, respectively. Single-escape peaks are denoted by SE.

An *in-situ* measurement of target activity from the 1275-keV line was used to determine the initial value of N_T for each ^{22}Na target. However, ^{22}Na loss is possible due to sputtering during

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E_p (keV)	Previous $\omega\gamma$ (meV)	Present $\omega\gamma$ (meV)	R
198	$\leq 4.0^a$	≤ 0.51	0.1
213	1.8 ± 0.7^b	$5.7^{+1.6}_{-0.9}$	3.2
232	2.2 ± 1.0^c	≤ 0.67	0.3
288	15.8 ± 3.4^b	39 ± 8	2.5
454	68 ± 20^b	166 ± 22	2.4
610	235 ± 33^b	591^{+103}_{-74}	2.5

Table 1: Resonance strengths for the ^{22}Na$(p,\gamma)^{23}$Mg reaction in the present work, compared to previous values. Present uncertainties and limits are at the 68% *C.L.* Finite strengths are the sum of partial strengths from measured branches, reported in detail in Ref. [8]. R is the ratio of the present to the previous strength.

^{a}Indirect estimate from Ref. [7].
^{b}Direct measurement from Ref. [6].
^{c}Indirect estimate from Ref. [10].

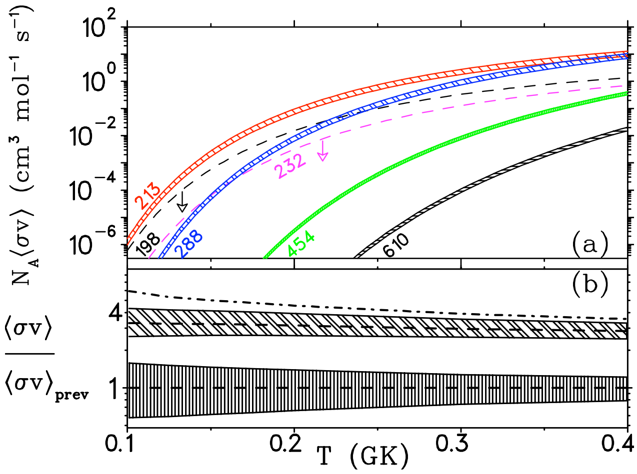

Figure 3: Panel (a) shows the contributions of individual resonances to the present thermonuclear ^{22}Na$(p,\gamma)^{23}$Mg reaction rate, with upper limits indicated by dashed lines with arrows. Panel (b) shows the ratios of reaction rates and their 1σ uncertainties to the central values of the rate deduced from Ref. [6]. Dashed lines in the vertical- and diagonal-hatched regions represent the rates from Ref. [6] and the present work, respectively. The dot-dashed line includes the upper limit for the 198-keV resonance.

proton bombardment [9], and was therefore monitored by revisiting strong resonances throughout and by recording residual ^{22}Na activity in the beam line after the removal of each target. The amount of potential loss for each measurement varied but was always $\leq 12\%$ for Cr-coated targets. Using the yields from a ^{27}Al(p,γ) resonance measurement on a thick, extended ^{27}Al target, Y_s, and a 5-mm disk ^{27}Al target embedded in a copper substrate, Y_c, the quantity ρ_b was extracted via the equation, $\frac{Y_c}{Y_s} = \rho_b A_c$, where A_c is the area of the disk. The results from each resonance were in very good agreement, and the weighted average was chosen as the central value of ρ_b. To estimate a systematic uncertainty, this measurement was supplemented by tests in which the raster amplitudes and collimator diameters were varied and by using a Monte Carlo simulation that modeled the transport of the beam through the final components of the beam line.

For each gamma-ray branch at each proton energy, the yield was determined by integrating the photopeak and (in selected cases) the first-escape peak and summing over all measured branches (Fig. 2). The values of $\omega\gamma$ were extracted using Eq. 3.1 (Table 1). The last column of Table 1 shows the ratios of our strengths to the previous strengths, where ours are higher by a factor of $\sim$ 2.4 for resonances at $E_p = 288$, 454, and 610 keV. The 213-keV resonance is higher by a factor of 3.2. Our branches [8] are roughly in agreement with Ref. [6]. By searching for known branches, we set upper limits on the strengths of the proposed resonances at 198 [7] and 232 keV [10]. Our direct limit for the 198-keV resonance refines the indirect limit from Ref. [7] by a factor of 8, and our direct limit for the 232-keV resonance is lower than the finite value of 2.2 ± 1.0 meV reported previously [10], based on the β-delayed proton decay of ^{23}Al.

Using the presently measured resonance energies and strengths in Table 1, contributions to the thermonuclear ^{22}Na$(p,\gamma)^{23}$Mg reaction rate were calculated (Fig. 3 (a)). The 213-keV resonance dominates the rate at peak nova temperatures, shown by our strengths and our upper limit for the 198-keV resonance; however, near the highest nova temperature, the 288-keV resonance begins to make a significant contribution. Due to the higher strengths for the 213- and 288-keV resonances, the total reaction rate is significantly higher than the currently accepted rate [6] by roughly a factor of 3 (Fig. 3 (b)). We use the results of one-zone post-processing network calculations [1, 12] to test the effects of our rate on ^{22}Na production in nova models, since the ^{22}Na$(p,\gamma)^{23}$Mg reaction is not presumed to have a substantial effect on the total energy generation. We estimate that the amount of ^{22}Na produced is reduced by factors of 2 to 3 compared to the previous rate [6], depending on the nova model used and the mass and composition of the underlying white dwarf.

4. Conclusions

In conclusion, we have measured ^{22}Na$(p,\gamma)^{23}$Mg resonance strengths for E_p = 198, 213, 232, 288, 454, and 610 keV using radioactive ion-implanted ^{22}Na targets and a technique that is more reliable than those employed in previous measurements [6]. We find the strengths of key resonances that destroy ^{22}Na in novae to be higher than the previous measurements [6] by factors of 2.4 to 3.2. The contributions of proposed resonances at 198 and 232 keV are found to be small, or negligible, at peak nova temperatures. In summary, our measurements show that ^{22}Na will be destroyed much more efficiently in novae than previously thought, significantly reducing prospects for the observation of ^{22}Na during the currently-deployed INTEGRAL mission [13].

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