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The $^{26g}Al(p,\gamma)^{27}Si$ Reaction in Novae

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The 184 keV resonance strength in the $^{26g}Al(p,\gamma)^{27}Si$ reaction was measured in inverse kinematics using the DRAGON facility at TRIUMF-ISAC. We obtain a value of $\omega\gamma$=35±7 μeV for the strength and E_R=184±1 keV for the resonance energy. These values are consistent with p-wave capture into the 7652(3) keV state in ^{27}Si. We discuss the implications of these results for ^{26g}Al nucleosynthesis in a typical O-Ne white dwarf nova.

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1. Introduction

^{26}Al [$t_{1/2}$=(7.2±0.2)×10^{5}yr] was the first radioisotope to be discovered in the Galaxy via its characteristic γ ray at 1809 keV in the early nineteen-eighties and since then, has been studied extensively with orbiting γ-ray telescopes such as RHESSI, COMPTEL and INTEGRAL [1,2,3]. The current paradigm for the formation of ^{26}Al is that it is made primarily in massive stars, this model being supported by features in the COMPTEL all-sky map. Although it is now thought that most of the 2.8±0.8 solar masses [4] of ^{26}Al present in the Galaxy is synthesized in core-collapse supernovae (CCSN) [5], there has been much debate in the past on the contributions from other sources such as novae, Wolf-Rayet phases of massive stars, and AGB stars [6].

It has been shown in the past [7] that up to 0.4 solar masses of ^{26}Al could come from classical novae. Although this is a small fraction of the total observed amount, it is still significant and is interesting to consider, because already we have a means to constrain our nova models; an overproduction of ^{26}Al in the models indicates that the model is incorrect in terms of the astrophysical conditions or the cross-sections in the nuclear reaction network. By reducing the nuclear physics uncertainties using experimentally measured cross-sections, we narrow down this potential uncertainty until the abundance of ^{26}Al produced in our models really does serve as a model diagnostic based on experiment and observation. Of the reactions which influence the production of ^{26}Al in novae, the direct destruction by the radiative capture of hydrogen, ^{26g}Al(p,γ)^{27}Si, is one of the most important.

An investigation of low-energy resonances in the ^{26g}Al(p,γ)^{27}Si reaction [8] showed that a single resonance at $E_{c.m.}$=188 keV should dominate the reaction rate at nova temperatures. A measurement of the resonance strength was performed [9], finding a value of $\omega\gamma = 55 \pm 9\ \mu$eV, but was never published.

Owing to the importance of this low energy resonance, a direct measurement was performed in inverse kinematics at the DRAGON recoil separator facility at TRIUMF-ISAC.

2. Experimental Method

At the ISAC facility, 70 μA of 500 MeV protons from TRIUMF's sector-focussing cyclotron bombarded a high-power SiC target [10] producing the radioactive ^{26g}Al which then diffused into a rhenium surface-ionization tube. This ionization was enhanced by the addition of an on-line laser system [11]. The products at A=26 were then separated using a high-resolution mass separator.

The beam was initially accelerated up to 150 A keV using a radio-frequency quadrupole (RFQ) accelerator before being stripped into a higher charge state and injected into a drift-tube linear accelerator (DTL), allowing acceleration between 150-1800 A keV [12]. The qualities of the beam at 200 A keV were typically a 1% FWHM spread in energy and < 2 ns FWHM spread in time, delivered in bunches with a period of 86 ns.

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The DRAGON facility [13,14] is based around a windowless hydrogen re-circulating gas target with an effective length of just over 12 cm, surrounded by an efficient array of BGO detectors. Recoil products from radiative capture reactions occurring in the gas target are focused and separated from beam ions in a two-stage electromagnetic separator, each stage including one magnetic dipole and one electric dipole. The separated products are detected 65 cm beyond the final m/q focus using a pixilated silicon detector, providing a measurement of particle position and energy. Normalisation of the incident beam current was provided via the measurement of elastically scattered protons within the gas target using a silicon surface barrier detector.

The separator was set to transmit charge-state 4^+ silicon recoils from the $^{26g}Al(p,\gamma)^{27}Si$ reaction which were then detected in the pixilated silicon detector in coincidence with prompt γ rays in the BGO array. Un-reacted beam particles are rejected via a set of slits at the first m/q focus, just after the first electric dipole, where the majority are stopped. A small fraction of beam (10^{-9}) makes it to the end of the separator, but results in coincidences with the BGO events which are uncorrelated in time, as opposed to the silicon recoils which are tightly bunched in time. These 'leaky' beam particles are also detected at slightly higher average energies than the silicon recoils. These two conditions allow true events to be extracted by means of an energy cut and a time-of-flight cut with background subtraction (see figure 1).

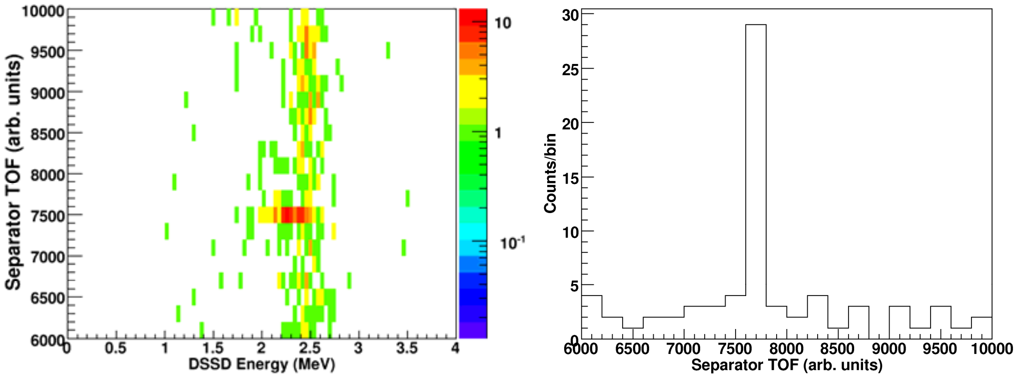

Figure 1: (left) Separator time-of-flight for coincident gamma-ray-heavy-ion events vs detected particle energy for the 5.122 MeV run. The true ^{27}Si recoils are bunched tightly in time, and are peaked at lower energy than the randomly coincident 'leaky' beam particles. (right) y-projection of the spectrum on the left, showing the underlying random-coincidence background, and the clear recoil peak.

Most of the γ-ray background in the experiment came from ^{26}Na contamination in the beam, being too close in mass to ^{26}Al to be distinguishable using the ISAC high-resolution separator. ^{26}Na in the beam 'halo', which stops on the entrance aperture to the gas target, decays with a 1 second half-life causing signals in the BGO array. By introducing a beam-halo-clipping iris upstream, we removed some of this activity to upstream near the BGO array, reducing the random coincidence rate. The amount of ^{26}Na in the beam was monitored via a high-purity germanium detector installed at the mass slits to detect the 1809 keV γ ray from its decay. By providing the ISAC operators with this signal and a monitor of total beam intensity, the fraction

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of ^{26}Na in the beam was able to be reduced substantially by tuning the ISAC separator, resulting in a ^{26}Na decay BGO rate equivalent to room background, enabling very clean identification of true recoil events.

During the run, the gas pressure was maintained at 6.0±0.1 Torr and the re-circulating hydrogen was cleaned using an LN_2 cooled zeolite trap. The temperature of the target was also monitored. An initial beam energy of 5.226 MeV ($E_{c.m.}$=0.195 MeV)* was used and 179 hours of data taken at this energy using an average intensity of 2.5×10^9 s^{-1}. Peak intensities of 5×10^9 s^{-1} were achieved. An additional 49 hours of data were taken at 5.122 MeV ($E_{c.m.}$=0.191 MeV), and an 'off-resonance' background run taken at 5.850 MeV ($E_{c.m.}$=0.218 MeV) for 30 hours.

Separately, a beam of ^{28}Si was produced using the ISAC off-line microwave ion source by extracting A=31 ($^{28}SiH_3^+$) molecules into the RFQ then accepting the post-stripped $^{28}Si^{5+}$ for acceleration in the DTL. This beam enabled the measurement of the charge-state fraction of 4^+ silicon recoils at an exit velocity equal to those of those from the reaction of interest.

3. Analysis and results

Using the cuts mentioned above, 119±14 recoils were identified for the 5.226 MeV run, 28±6 recoils for the 5.122 MeV run, and <3.72 recoils for the off-resonance run (at 90% confidence level). The reaction yield is given by the number of detected recoils, divided by the number of incident ions, over the product of the efficiencies involved in the experiment:

$$Y = N_{\text{det}} / (N_{inc}\eta_{bgo}\eta_{sep}\eta_{Si4+}\eta_{DSSD})$$

The BGO efficiency, η_{bgo}, was found by simulating the array using GEANT3, checked uing measurements with calibration sources, and simulating the reaction, including variation of the unknown cascade transitions from the resonant state, which was included in the error. The separator acceptance, η_{sep}, was found by using a GEANT3 simulation of the entire separator and the reaction kinematics. The charge state-fraction of 4^+ recoils was found using the ^{28}Si measurements mentioned above, and the pixilated silicon detector efficiency, η_{DSSD}, was measured using a calibration source. For a more complete description of the efficiencies and their contribution to the experimental errors, see ref. [15].

The resonance strengths for the 5.226 MeV and 5.122 MeV runs were calculated using the well-known thick-target formula for isolated narrow resonances:

$$\omega\gamma = \frac{2\varepsilon Y}{\lambda^2}\frac{M_H}{M_H + M_{Al}},$$

where λ is the de Broglie wavelength in the c.m. system, ε is the beam energy loss per target atom per unit area (measured by the difference in field strength of the first magnetic dipole required to bend the beam with and without target gas), and M_H and M_{Al} are the masses of the target and projectile respectively. A value of $\omega\gamma = 35 \pm 5_{sys} \pm 4_{stat}$ was found for the 5.226 MeV data, while a value of $\omega\gamma = 36 \pm 6_{sys} \pm 8_{stat}$ was found for the 5.122 MeV data.

* chosen to place the resonance, thought to be at 188 keV [9], at the centre of the gas target.

The resonance energy was obtained by measuring the location of the resonant capture within the extended gas target via the pattern of hits in the BGO array (figure 2). By comparing this distribution to GEANT3 simulations and the strong $^{24}Mg(p,\gamma)^{25}Si$ reaction, the resonance energy was found to be 184±1 keV.

These results represent a 36% reduction in resonance strength and 2% reduction in resonance energy with respect to the unpublished measurement of ref. [9]. The $^{26g}Al(p,\gamma)^{27}Si$ reaction rate over the Gamow window is therefore reduced by almost 20% compared to the previously used rate, resulting in more ^{26}Al surviving the nova explosion.

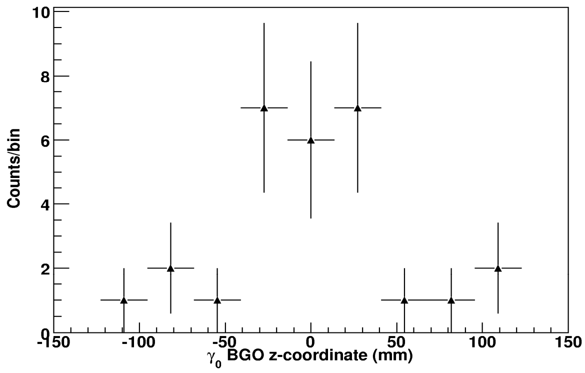

Figure 2: Distribution of BGO hits along the beam axis, enabling extraction of the resonance energy from the centroid position and stopping power information.

4. Implications

Although the exact contribution of novae to the Galactic distribution of ^{26}Al cannot be obtained, due in part to the large uncertainty in the $^{25}Al(p,\gamma)^{26}Si$ reaction rate, we can analyse the impact these results have on the amount of ^{26}Al produced in novae by computing a representative case. A simulation of an accreting O-Ne white dwarf of 1.25 solar masses, from onset to explosion and ejection, was performed using a spherically-symmetric, implicit hydrodynamic code in Lagrangian formulation [16]. A comparison of the yields of ^{26}Al in the ejecta when the old resonance strength [10] and new resonance strength (this work) are used shows a ~20% increase in ^{26g}Al yield for this particular model. This is the first confirmation, based on published experimental work, that novae are likely contributors of a small amount of ^{26}Al to the interstellar medium[†]. Also, because the slight increase in synthesized ^{26}Al is not large compared to the unpublished value (which implied a contribution of ~20% of the total galactic abundance [7]), the paradigm that massive stars and not novae are the dominant source of Galactic ^{26}Al is supported.

† The previous uncertainty in this rate was up to three orders of magnitude [17].

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