Measurement of the $E_{c.m.} = 184$ keV Resonance Strength in the $^{26g}Al(p,\gamma)^{27}Si$ Reaction

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The strength of the $E_{c.m.} = 184$ keV resonance in the $^{26g}Al(p,\gamma)^{27}Si$ reaction has been measured in inverse kinematics using the DRAGON recoil separator at TRIUMF's ISAC facility. We measure a value of $\omega\gamma = 35 \pm 7$ μeV and a resonance energy of $E_{c.m.} = 184 \pm 1$ keV, consistent with p-wave proton capture into the 7652(3) keV state in ^{27}Si, and discuss the implications of these values for ^{26g}Al nucleosynthesis in typical oxygen-neon white-dwarf novae.

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Introduction.—The recent detection of decaying ^{26g}Al [$t_{1/2} = (7.2 \pm 0.2) \times 10^5$ yr] via its characteristic 1.809 MeV γ ray by the RHESSI and INTEGRAL satellites has furthered our understanding of the production sites of this radioisotope [1,2]. The COMPTEL all-sky map of the 1.809 MeV line [3] points to young, high-mass progenitors such as core collapse supernovae (CCSN) and Wolf-Rayet stars [4]. Though previous studies suggested that all of the ^{26g}Al in the Galaxy [presently measured as $2.8 \pm 0.8 M_\odot$ [5]] could have been entirely produced in CCSN [6], these new results have suggested that CCSN may be a much less dominant component, and that other sources must contribute, thought chiefly to be Wolf-Rayet stars [7].

However, classical novae are one potential source of ^{26g}Al and it has been shown that up to $0.4 M_\odot$ of the Galactic abundance could have been produced in these sites [8]. Of particular importance to the calculation of nova-synthesized ^{26g}Al abundances are the $^{25}Al(p,\gamma)^{26}Si$ and $^{26g}Al(p,\gamma)^{27}Si$ reaction rates, the former being the most uncertain. The $^{26g}Al(p,\gamma)^{27}Si$ reaction rate at typical oxygen-neon white-dwarf nova (ONeWD) temperatures is dominated by a single resonance around $E_{c.m.} = 188$ keV [9,10].

An unpublished measurement of this resonance strength in normal kinematics yielded a value of 55 ± 9 μeV [9]. The final abundance of ^{26g}Al synthesized in a typical ONeWD hydrodynamic calculation is somewhat sensitive to this strength. Because of the long lifetime of ^{26g}Al, space-based γ-ray observatories such as INTEGRAL are unable to detect it from individual sources. Therefore, the likely primary progenitors can only be inferred from the Galactic ^{26g}Al distribution. However, with a firm understanding of the $^{26g}Al(p,\gamma)^{27}Si$ rate we can infer solid upper limits for the nova contribution to Galactic ^{26g}Al as a secondary source.

Experimental method.—This measurement was performed using the DRAGON recoil separator in the ISAC radioactive ion beam facility at TRIUMF. A high-power *SiC* target [11] was bombarded with up to 70 μA of 500 MeV protons from TRIUMF's sector focussing cyclotron, producing radioactive ^{26g}Al which then diffused out of the target and into a rhenium surface-ionization tube. An enhancement to the surface ionization was provided using on-line laser ionization within the tube [12]. $A = 26$ products were separated using a high resolution mass separator. This beam was injected into a radio-frequency quadrupole accelerator (RFQ) for initial acceleration up to 0.15 A MeV and stripped to a higher charge state using a thin carbon foil before being injected into a continuously variable energy drift-tube linear accelerator (DTL) which allowed acceleration between 0.15–1.8 A MeV [13]. The beam was delivered in bunches separated by 86 ns in time with a bunch width of less than two nanoseconds FWHM and an energy spread of typically 1% FWHM at 0.2 A MeV.

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The DRAGON facility [14,15] consists of a windowless hydrogen-recirculating gas target surrounded by an array of 30 bismuth germanate (BGO) detectors, and a two-stage electromagnetic recoil separator. Each stage includes a dipole magnet and an electrostatic dipole unit. The total separator length from the center of the gas cell to the final m/q focus is 20.42 m, with a double-sided silicon strip detector (DSSD) placed 65 cm downstream from the focus. A collimated silicon surface barrier detector placed at 30° from the center of the gas cell was used to detect protons elastically scattered by the incoming beam during the run as a means of normalization.

The separator was set to transmit charge-state 4^+ silicon recoils from the reaction $^{26g}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$, which were then detected using the DSSD in coincidence with prompt γ rays detected at the BGO array. The majority of unreacted 4^+ beam ended up impinging on a slit at the m/q focus after the first electric dipole, but a small fraction (1×10^{-9}) were transmitted to the DSSD. These "leaky-beam" particles, in random coincidence with background radiation in the BGO array, constituted a significant background under the true coincidence peak in a time-of-flight spectrum (Fig. 1). These ions had slightly higher energy than the ^{27}Si recoils in the DSSD energy spectrum. The BGO background came from ^{26}Na in the beam and from room radioactivity.

The contaminants in the beam were primarily radioactive ^{26}Na ($t_{1/2} = 1.07$ s) and ^{26m}Al ($t_{1/2} = 6.345$ s) created in the *SiC* target. The level of these contaminants in the beam was monitored during the run; the ^{26}Na via its characteristic 1809 keV γ ray from beta decay to the first excited state of ^{26}Mg using a high-purity germanium detector; the ^{26m}Al via paired 511 keV γ rays created from electron-positron annihilation caused by β^+ decays of this isomer at the mass slits. The ^{26}Na contaminant was the major source of background in the experiment due to the small amount of beam implanted in the entrance aperture to the gas cell causing a high rate in the BGO array leading to random coincidences. With a combination of a mechanical iris upstream of the gas cell (designed to remove the source of beam decay away from the detectors) and some fine-tuning of the mass separator optics, we were able to reduce the level of ^{26}Na in the beam from 1:32 000 to 1:337 000, with a contribution to the BGO rate equal to that of room radioactivity. The level of ^{26m}Al contaminant remained at around 1:30 000 during the run.

During the run, a gas-target pressure of 6 Torr was maintained to within $\pm 1.6\%$. Initially, a beam energy of 5.226 MeV ($E_{\mathrm{c.m.}} = 0.195$ MeV) was chosen to place the resonance at the center of the gas target and over 179 hours of data were taken at an average intensity of $2.5 \times 10^9\ \mathrm{s}^{-1}$ at this energy, although peak intensities of over $5 \times 10^9\ \mathrm{s}^{-1}$ were achieved. Some 49 hours of data were taken at an energy of 5.122 MeV ($E_{\mathrm{c.m.}} = 0.191$ MeV), and an "off-resonance" background run was taken at 5.850 MeV

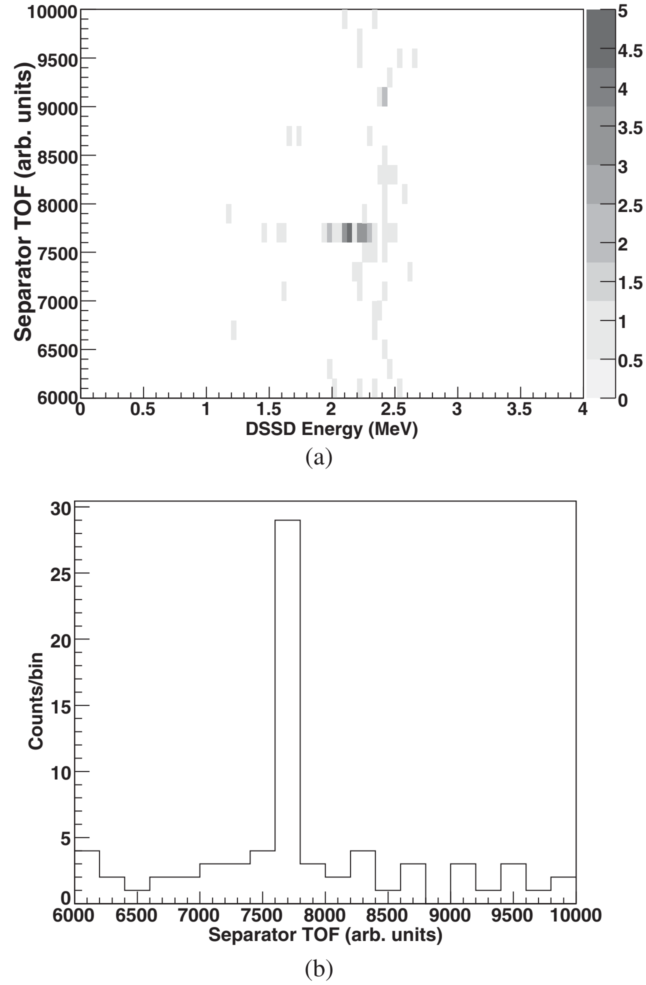

FIG. 1. (a) Separator time-of-flight for coincident gamma-ray–heavy-ion events vs detected particle energy for the 5.122 MeV run. The true ^{27}Si recoils are bunched tightly in time, and are peaked at lower energy than the randomly coincident "leaky" beam particles. (b) Projection of (a) onto the time-of-flight axis showing the true recoil peak.

($E_{\mathrm{c.m.}} = 0.218$ MeV) for 30 hours. In addition, a beam of ^{28}Si was produced in the ISAC off-line microwave ion source by extracting $A = 31$ ($^{28}\mathrm{SiH}_3^+$) molecules into the RFQ and selecting $^{28}\mathrm{Si}^{5+}$ for acceleration through the DTL. This beam was used to study the charge-state distribution of silicon ions exiting the gas target at different pressures in order to account for charge states not measured in the experiment.

Analysis.—From the coincident gamma-ray–heavy-ion data for each set of runs at a particular energy, true recoil events were identified by their time of flight through the separator. Since most random coincidences were caused by γ rays from decaying ^{26}Na atoms upstream of the gas-target and leaky-beam particles at the DSSD, these were uncorrelated in time and resulted in a flat background in the separator time-of-flight spectrum. The recoils protrude from the flat time-of-flight background as a tightly bunched peak, and are also peaked at lower energy than the leaky beam in the DSSD spectrum, as can be seen in Fig. 1.

Candidate $^{26}Al(p,\gamma)^{27}Si$ events were selected by a narrow window (200 ns) on time-of-flight (TOF) set around the coincidence peak. The number of background events in the narrow window was estimated from the number of events in a much wider window in a randoms-only region of the TOF spectrum. The backgound-subtracted numbers for the 5.226 MeV and 5.122 MeV runs were 119 ± 14 recoils and 28 ± 6 recoils, respectively. The number for the off-resonance run at 5.850 MeV was derived using the Feldman-Cousins prescription for non-Poissonian low-statistics data [16] leading to a limit of <3.72 recoils at 90% confidence level.

After the subtraction of measured contaminants was made, the normalization procedure described above resulted in values for the number of incident ions of 1.5×10^{15} (5.226 MeV runs), 3.5×10^{14} (5.122 MeV runs), and 2.9×10^{14} (5.850 MeV runs). The absolute reaction yields [(reactions)/(incidention)] for these same runs were $(2.5 \pm 0.5) \times 10^{-13}$, $(2.6 \pm 0.7) \times 10^{-13}$, and $<4.0 \times 10^{-14}$, respectively.

The detected yields were corrected for the measured charge-state fraction for 4^+ recoils exiting the gas target ($\eta_{\mathrm{Si4+}} = 0.42 \pm 0.02$), the separator acceptance ($\eta_{\mathrm{sep}} = 0.98 \pm 0.02$), the efficiency of the BGO array ($\eta_{\mathrm{bgo}} = 0.76 \pm 0.1$), and the previously known DSSD efficiency ($\eta_{\mathrm{DSSD}} = 0.97 \pm 0.01$). η_{sep} was found by simulating the reaction in a full Monte Carlo implementation of the DRAGON recoil separator in GEANT3, including interaction of the γ rays with the BGO array and the ion-optical tracking of charged particles through the separator. Uncertainties in the beam energy, energy spread, position, and direction within the gas cell were included in the simulation. The maximum cone angle of recoils from the reaction is around 15 mrad, and consequently a very small fraction of recoils are close to the acceptance design limit of the separator when factoring in beam emittance. As a result, a small fraction of recoils do not make it through the system. η_{bgo} was determined using the GEANT3 simulation also [17], taking into account the effect of hardware thresholds and unknown γ-ray angular distributions. The sensitivity of the efficiency to the γ-ray branching ratios from the 7652 keV state was also investigated; the work of Vogelaar [9] reported branching ratios for a three γ-ray cascade, and evidence for such a cascade was also seen in our data though branching ratios could not be extracted due to poor statistics. Thus simulations of a variety of three γ-ray cascades with deliberate two γ-ray secondary branches were simulated, exploring all possible scenarios except direct decay to the ground state for which we saw no evidence. These possibilities were included in the experimental uncertainty, contributing less than that of the absolute uncertainty (10%) in the simulation as determined from calibration source measurements.

Stopping powers for the different beam energies in the H_2 gas were measured by taking the difference between the field strengths of the first-stage magnetic dipole required to center the beam at an energy-dispersed focus with and without gas in the target. This procedure was calibrated using some well-known narrow radiative capture resonances [15].

Resonance strengths were calculated using the formula

$$\omega\gamma = \frac{2\epsilon Y}{\lambda^2}\frac{M_{\mathrm{H}}}{M_{\mathrm{Al}} + M_{\mathrm{H}}}, \tag{1}$$

where λ is the de-Broglie wavelength in the c.m. system, ϵ is the beam energy loss per target atom per unit area, Y is the reaction yield, and M_{H}, M_{Al} are the masses of the target and projectile, respectively.

The reaction yield is given by

$$Y = N_{\mathrm{det}}/(N_{\mathrm{inc}}\eta_{\mathrm{bgo}}\eta_{\mathrm{sep}}\eta_{\mathrm{Si4+}}\eta_{\mathrm{DSSD}}), \tag{2}$$

where N_{det} and N_{inc} are the total number of detected recoils and incident ions, respectively. Table I shows the resulting resonance strengths and their associated errors.

The location of the resonant capture within the extended gas target was deduced from the pattern of hits in the BGO array, shown in Fig. 2. The associated error on this measurement is ± 9 mm. The energy of the resonance was calculated by correcting the incident beam energy for energy loss before reaching the resonance position. The calculated resonance energy is 184 ± 1 keV.

The resonance strength obtained in this work is only 64% of the unpublished value of Ref. [9], while the resonance energy is measured to be 2% smaller. This has the effect of reducing the reaction rate over the region of the Gamow window for this resonance by nearly a factor of 1.2. A slower reaction rate means that for a given temperature, more ^{26}Al will survive a nova explosion.

TABLE I. Table showing the percentage contributions to the systematic error for the parameters which go into the calculation of the resonance strength, $\omega\gamma$, for the 5.226 MeV and 5.122 MeV runs. Also tabulated are the obtained resonance strengths and associated errors (see text for definitions).

	Percentage contribution to error							
E_{beam} (MeV)	$\Delta\epsilon$	$\Delta\eta_{\mathrm{DSSD}}$	$\Delta\eta_{\mathrm{BGO}}$	$\Delta\eta_{\mathrm{sep}}$	$\Delta\eta_{\mathrm{Si4+}}$	ΔN	Total systematic error	$\omega\gamma$ (μeV)
5.226	5%	1%	13%	2%	5%	3%	15%	$35 \pm 5_{\mathrm{sys}} \pm 4_{\mathrm{stat}}$
5.122	5%	1%	13%	2%	5%	8%	17%	$36 \pm 6_{\mathrm{sys}} \pm 8_{\mathrm{stat}}$

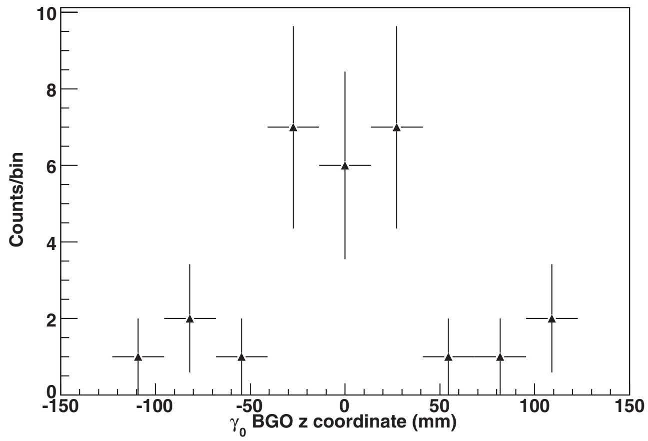

FIG. 2. Plot of z coordinate of the BGO detector struck by the highest energy γ ray coincident with a heavy-ion detection for the 5.122 MeV runs, showing the distribution of hits peaked at the center of the array.

Astrophysical implications: synthesis of ^{26}Al *in nova outbursts.*—An analysis of the impact of the new ^{26g}Al$(p, \gamma)^{27}$Si rate on the synthesis of ^{26g}Al in novae has been performed. We will not attempt to reach final conclusions on the precise contribution of novae to the Galactic ^{26g}Al levels because of the uncertainties facing such calculations [including the important role played by nuclear uncertainties affecting the ^{25}Al$(p, \gamma)^{26}$Si rate, a channel that bypasses the synthesis of ^{26g}Al in novae through ^{25}Al$(p, \gamma)^{26}$Si$(\beta^+)^{26m}$Al$(\beta^+)^{26}$Mg; see [18] for details]. Current estimates suggest that novae contribute less than 20% of the Galactic ^{26g}Al abundances [8]. However, we can outline the extent to which this new rate affects ^{26g}Al synthesis in novae by computing a representative case. Hence we have computed new simulations of nova outbursts, assuming an accreting ONe white dwarf of 1.25$M_\odot$, from the onset of accretion up to the explosion and ejection stages, by means of a spherically symmetric, implicit, hydrodynamic code, in Lagrangian formulation [19]. We have compared the mean ^{26}Al yields in the ejecta when two different prescriptions for the ^{26g}Al(p, γ) rate are adopted: one corresponding to the unpublished [Vogelaar [9]] rate and a second with the rate presented in this Letter.

As a result of the lower strength associated with the $E_{\rm c.m.} = 188$ keV resonance, the net reduction of the overall ^{26g}Al$(p, \gamma)^{27}$Si rate favors the synthesis of ^{26g}Al in nova outbursts. The results obtained from the two hydrodynamic simulations lead to mean ^{26g}Al yields in the ejecta of 6.1×10^{-4} by mass, when Vogelaar's values for the strength and energy of the 184 keV resonance are adopted (cf. 55 μeV and 188 keV), or 7.4×10^{-4}, when the present values are used. This represents an increase of $\sim$20% of the overall ^{26g}Al yield, for this particular model, representative of a neon-type nova. The importance of the results obtained from these hydrodynamics simulations is twofold: first, it confirms that classical novae are likely sites for the synthesis of a fraction of the Galactic ^{26g}Al; and second, the moderate increase in the final ^{26g}Al yield is compatible with the current paradigm for the origin of the Galactic ^{26g}Al, namely, young massive star progenitors, with the likely contribution of secondary sources such as novae and AGB stars.

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[1] D. M. Smith, Astrophys. J. Lett. **589**, L55 (2003).
[2] J. Knödlseder, New Astron. Rev. **48**, 189 (2004).
[3] R. Diehl *et al.*, Astron. Astrophys. **298**, 445 (1995).
[4] N. Prantzos and R. Diehl, Phys. Rep. **267**, 1 (1996).
[5] R. Diehl *et al.*, Nature (London) **439**, 45 (2006).
[6] F. X. Timmes *et al.*, Astrophys. J. **449**, 204 (1995).
[7] N. Prantzos, Astron. Astrophys. **420**, 1033 (2004).
[8] J. José, M. Hernanz, and A. Coc, Astrophys. J. **479**, L55 (1997).
[9] R. B. Vogelaar, Ph.D. thesis, California Institute of Technology, 1989.
[10] R. B. Vogelaar *et al.*, Phys. Rev. C **53**, 1945 (1996).
[11] P. Bricault *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. B **204**, 319 (2003).
[12] J. Lassen *et al.*, Hyperfine Interact. (to be published).
[13] R. E. Laxdal, Nucl. Instrum. Methods Phys. Res., Sect. B **204**, 400 (2003).
[14] D. A. Hutcheon *et al.*, Nucl. Instrum. & Methods Phys. Res., A **498**, 190 (2003).
[15] S. Engel *et al.*, Nucl. Instrum. & Methods Phys. Res., A **553**, 491 (2005).
[16] G. J. Feldman and R. D. Cousins, Phys. Rev. D **57**, 3873 (1998).
[17] D. G. Gigliotti, J. G. Rogers, and A. H. Hussein, Nucl. Instrum. Methods Phys. Res., Sect. B **204**, 671 (2003).
[18] J. José, A. Coc, and M. Hernanz, Astrophys. J. **520**, 347 (1999).
[19] J. José and M. Hernanz, Astrophys. J. **494**, 680 (1998).