First Measurement of Excited States in the Very Proton Rich Nucleus ^{24}Si and the Consequences for ^{22}Na Nucleosynthesis in Novae

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The ^{28}Si$(\alpha, ^{8}$He$)^{24}$Si reaction has been used to measure the energies of the first two excited states in ^{24}Si. The excitation energies were found to be 1.879 ± 0.011 and 3.441 ± 0.010 MeV. These data allow for the first time the calculation of the stellar reaction rate of ^{23}Al$(p, \gamma)^{24}$Si on the basis of experimental information. This reaction is of considerable interest, since it might lead to a decrease of the ^{22}Na production in nova explosions, and solve the discrepancy between the ^{22}Na yield predictions of nova models and recent COMPTEL observations. We show, however, that the temperatures and densities required for a significantly reduced ^{22}Na yield are not reached in current nova models. [S0031-9007(97)04602-4]

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About 30% of the observed nova explosions belong to the subclass of neon novae that show ejecta strongly enriched in neon. Neon novae are believed to be powered by explosive hydrogen burning of material accreted onto relatively massive ($>1.2M_\odot$) O-Ne-Mg white dwarfs. White dwarf material is mixed into the accreted layer, which is then burned explosively at high temperatures (up to 0.36 GK) and densities (up to 10^4 g/cm^3) via rapid proton capture (rp process [1,2]), synthesizing isotopes along the proton drip line up to mass $A = 45$ or even beyond. After the discovery of neon novae it was quickly realized that these scenarios might produce considerable amounts of ^{22}Na. Once ejected, ^{22}Na could be observable by the characteristic 1.275 MeV γ ray following its β^+ decay (2.6 yr half-life) [3–6]. Considerable efforts were undertaken in the search for a galactic 1.275 MeV γ line, but so far only upper limits could be derived. The most stringent come from recent COMPTEL observations in the direction of relatively close neon novae like nova Cyg 1992 or nova Her 1991, and indicate that neon novae produce substantially less ^{22}Na than suggested by model calculations [7]. Recent nova simulations with an updated nuclear reaction network predict a considerably higher ^{22}Na production (by a factor of 2) [8].

^{22}Na is produced in neon novae by the β^+ decay of ^{22}Mg [9]. Like other even Z, $T = 1$ nuclei, ^{22}Mg becomes strongly enriched, since the depletion through proton capture has a low rate and the weakly bound proton in ^{23}Al is easily removed by photodisintegration. It was, however, pointed out recently [10] that despite the strong photodisintegration of ^{23}Al a considerable $2p$-capture flow through ^{22}Mg could be established via proton capture on the small ^{23}Al equilibrium abundance (equilibrium $2p$ capture [11,12]). Then the $2p$-capture rate on ^{22}Mg depends only on the proton separation energy of ^{23}Al, which fixes the equilibrium ^{23}Al abundance, and the ^{23}Al$(p, \gamma)^{24}$Si rate. This mechanism could reduce the effective lifetime of ^{22}Mg and thus the amount of ^{22}Na produced in neon novae, which would be in better agreement with observations. However, a conclusive determination of the effectiveness of this mechanism has been hampered by the large uncertainties in the ^{23}Al$(p, \gamma)^{24}$Si reaction rate, since no experimental information on ^{24}Si was available except for the ground state mass.

The properties of the excited states in ^{24}Si for the most recent calculation of the ^{23}Al$(p, \gamma)^{24}$Si reaction rate [10] had to be obtained from the experimentally known levels in the mirror nucleus ^{24}Ne and from shell model calculations to determine the Ormand-Brown and Thomas-Ehrman shifts. These calculations predict excited states in ^{24}Si at 1.95, 3.62, 4.05, 4.17, and 4.47 MeV, which were obtained by shifting the corresponding mirror states in respect to the ground state by -0.03, -0.25, 0.09, -0.59, and -0.42 MeV, respectively. The calculations show that the only relevant contribution to the reaction rate comes from resonant proton capture via the 3.62 MeV state. However, a reliable calculation of the reaction rate is strongly handicapped by the large uncertainty in the resonance energy (typically 100–150 keV for sd-shell nuclei) which goes through the exponential dependence into an uncertainty of 4–7 orders of magnitude in the reaction rate at 0.2–0.4 GK.

We developed an experimental technique that measures excitation energies in very proton rich $T = 2$ nuclei like ^{24}Si using the $(\alpha, ^{8}$He$)$ reaction on the corresponding stable $T = 0$ target. This type of reaction had been used before to determine ground state masses (for example, [13] for ^{24}Si). We report here the first application of this method to the measurement of excited states in ^{24}Si via the ^{28}Si$(\alpha, ^{8}$He$)^{24}$Si reaction. A self-supporting Si target (Si

wafer) with natural isotopic composition and a thickness of 1.77 mg/cm^2 was bombarded with a 177.7 MeV α beam delivered by the Indiana University Cyclotron Facility (IUCF) cyclotron. The reaction products were detected in the focal plane of the K600 spectrometer. Because of the strongly forward peaked reaction cross section the K600 was operated in transmission mode [14]. In this mode the angle acceptance covers the range from 0° to 3° (3.5 msr solid angle) with the incident α beam being transmitted through the spectrometer and dumped in a well shielded external Faraday cup at the focal plane. The focal plane detector system consisted of a set of four wire chambers, allowing measurements of position and direction of the individual particle tracks. This yields the particle momentum and, via ray tracing, the scattering angle. The wire chambers were followed by a stack of three plastic scintillators that were designed to stop $Z = 2$ reaction products in the center detector. The resulting energy and energy loss information was used for particle identification, together with the time of flight through the spectrograph measured with the center plastic scintillator relative to the cyclotron rf. The last plastic scintillator was used as a fast hardware veto for $Z = 1$ particles. This veto counter as well as extensive shielding around the beam dump and the inner edges of the K600 dipoles permitted beam currents as high as 85 particle nA.

Figure 1 shows the ^{8}He position spectrum after 70 hours of beam time. The data have been corrected for the kinematic momentum variation of the events over the angle range of 0°–3° covered by the spectrograph (91 keV maximum correction). The angle needed for this correction has been obtained via ray tracing. Clearly seen are the transitions to the ^{24}Si ground state as well as to the first and second excited states in ^{24}Si. Despite the small forward scattering angles (including 0°) the peak to background ratio is excellent (130 for the ^{24}Si ground state). The observed events correspond to a cross section of approximately 15 nb/sr for the ground state transition and 2.7 nb/sr for the excited states. No structures from the ^{29}Si(α, ^{8}He)^{25}Si reaction (ground state expected 6.25 MeV above the ^{24}Si ground state at channel 3282 in Fig. 1) and the ^{30}Si(α, ^{8}He)^{26}Si reaction (ground state expected outside the observable range) are visible. The FWHM of the peaks is 140 keV (115 keV due to target energy loss, 68 keV due to target straggling, and about 40 keV intrinsic resolution added quadratically). Also shown in Fig. 1 is the ^{6}He spectrum obtained simultaneously. Well known states in ^{26}Si, ^{27}Si, and ^{28}Si are populated via the ^{28}Si(α, ^{6}He)^{26}Si, ^{29}Si(α, ^{6}He)^{27}Si, and ^{30}Si(α, ^{6}He)^{28}Si reactions. The peaks in the ^{6}He spectrum are well distributed around the ^{8}He peaks and provide an excellent focal plane calibration. In order to determine this calibration, the energy of the incident α beam and the difference of the energy loss between ^{6}He and ^{8}He particles in the target have to be known. The energy of the incident α beam was monitored using time-

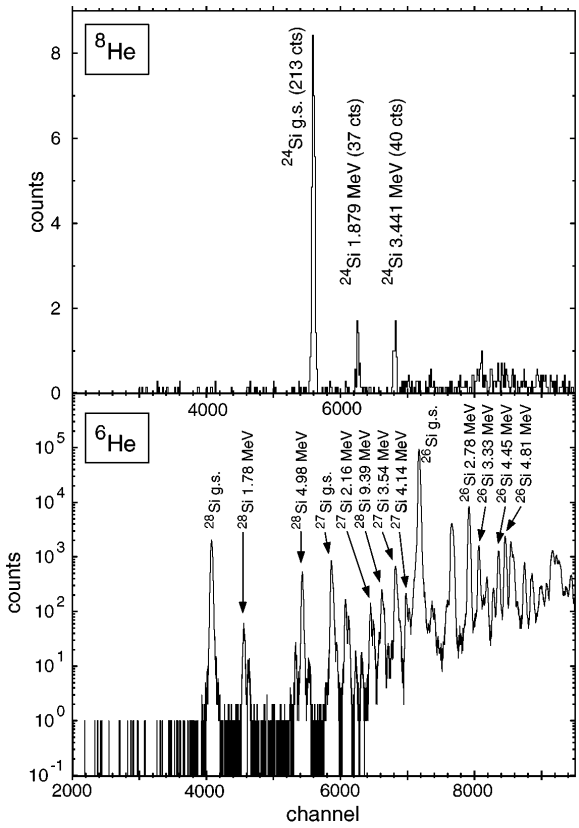

FIG. 1. The simultaneously obtained ^{6}He and ^{8}He position spectra from the Si target. In the ^{8}He spectrum the ground and first two excited states of ^{24}Si can be identified. The ^{6}He spectrum shows states in ^{26}Si, ^{27}Si, and ^{28}Si. The low-lying states indicated were used for the focal plane calibration.

of-flight measurements with capacitive pickups along the beam line. This system was calibrated using the ^{6}He and ^{8}He position spectra obtained with a ^{13}C target. The masses of the observed ^{9}C ground state as well as the excited states in ^{11}C are well known. The evaluation of these spectra gave the energy of the incident α beam with a precision of ± 90 keV. The target thickness was determined by measuring the energy loss of a collimated 8.67 MeV α beam from a ^{226}Th source. The resulting target thickness from measurements before and after the experiment is 1.77 ± 0.13 mg/cm^2. The uncertainty reflects the inhomogeneities in the target thickness.

A good test for the focal plane calibration is the resulting ^{24}Si mass, which had been measured before. Using the 1995 mass tabulations [15] for ^{28}Si, ^{8}He, and ^{4}He, we obtain a ^{24}Si mass excess of 10.731 ± 0.024 MeV in agreement with the two previous measurements of 10.782 ± 0.022 [13] and 10.682 ± 0.052 MeV [16]. The main sources of the quoted error are the 90 keV uncertainty in the beam energy (22 keV), the momentum corrections owing to angular distribution effects (8 keV), the statistical error of the centroid (5 keV), and the target thickness (4 keV). The 7 keV uncertainty in the ^{8}He mass has no influence on the results, since we use the

$^{13}C(\alpha, ^{8}He)^{9}C$ reaction to determine the beam energy. The weighted mean of all ^{24}Si mass excess measurements is 10.753 ± 0.016 MeV.

The resulting excitation energies of the first two excited states in ^{24}Si relative to the ^{24}Si ground state are 1.879 ± 0.011 and 3.441 ± 0.010 MeV, respectively. The contributions to the uncertainty are the statistical errors of the centroids (11 and 9 keV, respectively) and the momentum corrections owing to angular distribution effects (3 keV). All other sources of error are negligible. Our energies for the first and second excited states in ^{24}Si are 71 and 179 keV below the shell model predictions. Consequently, the energy of the dominant resonance in the $^{23}Al(p, \gamma)^{24}Si$ reaction corresponding to the second excited state in ^{24}Si is reduced to 141 ± 31 keV (compared to 320 keV as predicted by the shell model). The error in the new resonance energy is dominated by the 25 keV uncertainty in the ^{23}Al mass with contributions from the ^{24}Si mass (16 keV) and the excitation energy (10 keV, this work). The corresponding resonance strength based on the spectroscopic factor of [10] and the results of this work are $7.12^{+142}_{-7.02} \times 10^{-6}$ eV. The resulting upper and lower limits of the new $^{23}Al(p, \gamma)^{24}Si$ reaction rate are shown in Fig. 2 together with the previous reaction rate [10]. Despite the drastic change in the resonance energy, the previously used reaction rate lies within our new limits for temperatures between 0.2 and 0.4 GK, which is the relevant temperature range for nova nucleosynthesis. This is a consequence of the compensating effect of the lower proton penetrability, which also leads to a much stronger sensitivity of the reaction rate to the resonance energy. This is the reason that despite the greatly reduced uncertainty in the resonance energy from this work (31 keV instead of 150–200 keV), errors in the reaction rate above 0.1 GK are still quite large. Figure 2 also shows that the direct capture contribution to the $^{23}Al(p, \gamma)^{24}Si$ reaction rate as predicted by shell model calculations [10] is negligible for temperatures below 0.7 GK. Contributions from the resonances corresponding to higher excited states in ^{24}Si are negligible as well.

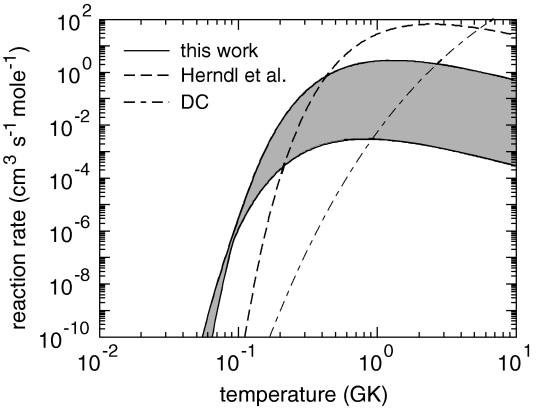

FIG. 2. The upper and lower limits for the resonant stellar $^{23}Al(p, \gamma)^{24}Si$ reaction rate from this work together with the previously used reaction rate based on shell model calculations of the resonance energy (Herndl *et al.* [10]). Also shown is the direct capture component (DC) as predicted by shell model calculations.

To determine the possible impact of the new reaction rate on the ^{22}Na production in novae, we investigated the branching of the reaction flow at ^{22}Mg as a function of temperature and density assuming a hydrogen mass fraction of 0.37. Figure 3 shows the area in the temperature-density plane, where more than 50% of the reaction flow is processed via $2p$ capture on ^{22}Mg (shaded). The lighter shaded area indicates the uncertainty. The boundaries are calculated from the various reaction rates assuming that ^{22}Mg and ^{23}Al are in equilibrium as long as the $^{23}Al(\gamma, p)^{22}Mg$ reaction rate is stronger than the $^{23}Al(p, \gamma)^{24}Si$ reaction rate. Boundary (a) describes the temperatures and densities, where the equilibrium $2p$-capture rate on ^{22}Mg equals the ^{22}Mg β-decay rate. It constrains mainly the density and is determined by the new $^{23}Al(p, \gamma)^{24}Si$ reaction rate presented in this Letter. The shown uncertainty is mainly due to the 25 keV error in the ^{23}Al mass, which affects the ^{23}Al equilibrium abundance and the $^{23}Al(p, \gamma)^{24}Si$ reaction rate strongly. Boundary (b) describes the temperatures and densities, where the $^{22}Mg(p, \gamma)^{23}Al$ reaction rate equals the ^{22}Mg β-decay rate. It constrains mainly the temperature and is determined by the $^{22}Mg(p, \gamma)^{23}Al$ reaction rate [17]. The corresponding uncertainty is due to the error in the resonance energy [17]. The uncertainties indicated in Fig. 3 are lower limits, since the errors in the theoretical input parameters, such as spectroscopic factors, are not included.

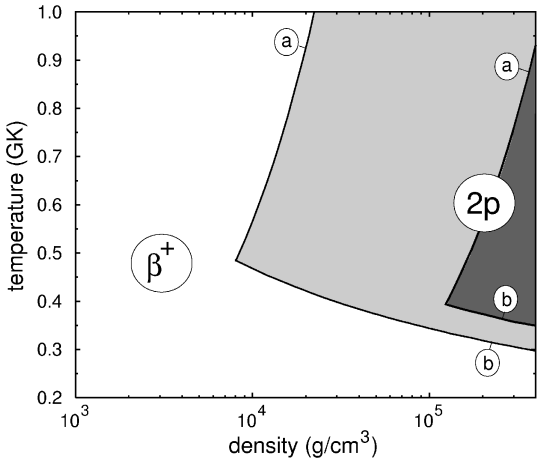

FIG. 3. The shaded area indicates the stellar temperature and density conditions required for a reaction flow of more than 50% via $2p$ capture on ^{22}Mg. Under these conditions the ^{22}Mg production and therefore the final ^{22}Na yield would be strongly reduced. Outside the shaded area, β^+ decay is the dominating destruction mechanism for ^{22}Mg. The lighter shaded area indicates the uncertainty. On boundary (a) the equilibrium $2p$-capture rate on ^{22}Mg equals the ^{22}Mg β-decay rate; on boundary (b) the $^{22}Mg(p, \gamma)^{23}Al$ reaction rate equals the ^{22}Mg β-decay rate.

For temperatures and densities within the shaded area in Fig. 3, the lifetime of ^{22}Mg is reduced by more than a factor of 2 compared to its β decay. If these conditions occur during a nova explosion, ^{22}Mg will be depleted and as a consequence the final ^{22}Na yield will be significantly reduced. However, Fig. 3 indicates that for a typical nova peak density of 10^4 g/cm^3 temperatures of at least 0.45 GK are required for a significant reduction of the ^{22}Na yield. This is much higher than the peak temperatures of up to 0.36 GK reached in nova models. It also has to be taken into account that nova models predict a significant density drop at the time the peak temperature is reached. Nevertheless it would be desirable to include our new ^{23}Al$(p,\gamma)^{24}$Si reaction rate in dynamical nova calculations, since some smaller impact on the ^{22}Na yield cannot be excluded.

To summarize, we present a new experimental technique that uses the $(\alpha, ^8\mathrm{He})$ reaction for the investigation of low-lying excited states in very proton rich nuclei. This method can be used to study a variety of other nuclei along the rp-process path in the $24 \leq A \leq 36$ mass range. Our measurement of the excitation energies in ^{24}Si revealed larger uncertainties in shell model predictions than previously assumed and allowed for the first time the calculation of the ^{23}Al$(p,\gamma)^{24}$Si reaction rate on the basis of experimental data. The level of accuracy in the nuclear physics data is now sufficient to conclude that temperatures and densities in current nova models are too low for an effective reduction of the ^{22}Na yield via $2p$ capture on ^{22}Mg. This indicates that not the nuclear reaction rates but other input parameters of the nova models will have to be improved in order to bring the predicted ^{22}Na yields in agreement with the observational upper limits.

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