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The ^{33}S(p,γ)^{34}Cl reaction in classical nova explosions

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The analysis of microscopic grains within primitive meteorites has revealed isotopic ratios largely characteristic of the conditions thought to prevail in various astrophysical environments. Recently, several grains have been identified with isotopic signatures similar to those predicted within the ejecta of nova explosions on oxygen-neon white dwarfs. A possible smoking gun for a grain of nova origin is a large ^{33}S abundance: nucleosynthesis calculations predict as much as 150 times the solar abundance of ^{33}S in the ejecta of oxygen-neon novae. This overproduction factor may, however, vary by factors of at least 0.01 – 3 because of uncertainties in the ^{33}S(p,γ)^{34}Cl reaction rate over nova temperatures. In addition, better knowledge of this rate would help with the interpretation of nova observations over the S-Ca mass region, and contribute towards the firm establishment of a nucleosynthetic endpoint in these phenomena. Finally, constraining this rate may help to finally confirm or rule out the decay of an isomeric state of ^{34}Cl (E_x = 146 keV, $t_{1/2}$ =32 min) as a source for observable gamma-rays from novae.

Direct examinations of the ^{33}S(p,γ)^{34}Cl reaction in the past have only identified resonances down to E_r = 434 keV. At nova temperatures, lower-lying resonances could certainly play a dominant role. Several recent, complementary studies dedicated to improving our knowledge of the ^{33}S(p,γ)^{34}Cl rate, using both indirect methods (measurement of the ^{34}S(^{3}He,t)^{34}Cl and ^{33}S(^{3}He,d)^{34}Cl reactions with the Munich Q3D spectrograph) and direct methods (in normal kinematics at CENPA, University of Washington, and in inverse kinematics with the DRAGON recoil mass separator at TRIUMF) are presented here. Our results affect predictions of sulphur isotopic ratios in nova ejecta (e.g. ^{32}S/^{33}S) that may be used as diagnostic tools for the nova paternity of grains.

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1.Introduction

Classical nova explosions occur through thermonuclear ignition in a shell of hydrogen-rich material accreted by a white dwarf star in a binary star system. Current hydrodynamic models, constrained by spectroscopic observations, show that while nucleosynthesis in novae is concentrated around the CNO region, heavier species such as neon, aluminum or other elements up to the calcium region can also be produced [1]. In particular, models find that nova explosions only on very massive oxygen-neon white dwarfs (ONe WDs), reaching temperatures T > 0.3 GK, are likely to synthesize elements in the Si – Ca mass range [2]. A powerful test of these models would be the detection of a large amount of ^{33}S in a presolar grain of nova paternity. Grains possibly of nova origin have been identified based upon other isotopic signatures [3,4,5], and, models of explosions on massive ONe WDs indicate that novae could yield a large overproduction factor of ^{33}S relative to solar ($X_{33}/X_{33_\odot}$ ~ 150 [2]); indeed, this signature could help to identify future grains of nova paternity. However, the extent of nucleosynthesis in the Si-Ca mass region as well as the utility of ^{33}S as a diagnostic for grains originating in novae depends significantly on the $^{33}S(p,\gamma)^{34}Cl$ rate adopted in these environments: studies of nova nucleosynthesis show that the present uncertainty in this rate could affect production of S, Cl and Ar isotopes by factors of 10 – 1000 [6], and vary the predicted $^{32}S/^{33}S$ isotopic ratio (relevant for grain measurements) between 30 – 9700 [7]. Finally, improving this rate would help to test the viability of another possible probe of nova nucleosynthesis in the Si-Ca region through gamma-ray line astronomy. The isomeric state of ^{34}Cl (E_x = 146 keV, $t_{1/2}$ = 32 min) beta-decays to ^{34}S (55.4% of the time) through the emission of several gamma-ray lines [8]. Given the short lifetime of this isomer relative to the time necessary for the nova cloud to become transparent to gamma-rays (hours to days), detection of any such gamma-ray signature is severely hindered [2,9]. A firm $^{33}S(p,\gamma)^{34}Cl$ rate could help to finally rule out the possible observation from novae of gamma-rays from the ^{34}Cl isomer.

The thermonuclear rate of the $^{33}S(p,\gamma)^{34}Cl$ reaction at temperatures encountered within nova explosions is dominated by contributions from narrow, isolated resonances within roughly 600 keV of the ^{33}S+p threshold in ^{34}Cl ($S_p(^{34}Cl)$ = 5143 keV). This reaction has been directly measured most recently by Waanders et al. [10] and Dassie et al. [11]; these studies determined resonance energies, strengths, J^π values and gamma-decay schemes for states above $E_x(^{34}Cl)$ > 5.57 MeV. (We note that some of these measured gamma-decay schemes are inconsistent with one another, and that some are given without errors [8,10,11]. This is relevant e.g., for production of the ^{34}Cl isomer via $^{33}S(p,\gamma)$.) Indirect studies have determined several proton-threshold states in ^{34}Cl below 5.57 MeV [8], but no experimental information exists for the corresponding resonance strengths. Parameterizations and Hauser-Feshbach calculations have been used to determine this rate in the past [2,12].

2.Experiments

We have performed four independent experiments designed to confirm the energies and strengths of known resonances, search for and measure (or place suitable limits upon) the strengths of new resonances, and improve gamma-decay schemes for states in ^{34}Cl.

The ^{34}S(^{3}He,t)^{34}Cl and ^{33}S(^{3}He,d)^{34}Cl reactions were measured at the Maier-Leibnitz-Laboratorium (MLL) in Garching, Germany over periods of roughly 2.5 days each. These were the first such measurements of these particular reactions over the energy region in ^{34}Cl relevant for ONe novae. High-intensity (~ 600 nA) beams of ^{3}He at 25 MeV were delivered by the MP tandem accelerator to the target position of a Q3D magnetic spectrograph [13]. Targets were prepared at the Technische Universität München for each experiment, including targets of 50 μg/cm^2 Ag_2S (enriched to 99.999% in ^{34}S) and 20 μg/cm^2 Ag_2S (enriched to 99.9% in ^{33}S), each upon a ~10 μg/cm^2 carbon foil. The acceptance of the spectrograph was set to 13.9 msr and 7.0 msr for the ^{34}S(^{3}He,t) and ^{33}S(^{3}He,d) experiments, respectively. Particles were identified through the determination of particle position, energy loss and residual energy via the scinitillator-backed, multiwire gas-filled proportional counter at the focal plane of the spectrograph [14]. Measurements were made at spectrograph angles of 15° and 25° for the ^{34}S(^{3}He,t) reaction [7], and at 5° increments between 10° and 55° for the ^{33}S(^{3}He,d) reaction. For both reactions, states in ^{34}Cl between E_x(^{34}Cl) ~ 5 – 6 MeV were observed on the focal plane at any one spectrograph angle.

In addition, for the first time, the ^{33}S(p,γ)^{34}Cl reaction was directly measured at energies below E_r = 432 keV (E_x = 5572 keV). An experiment in normal kinematics was conducted at the University of Washington's Center for Experimental Nuclear Physics and Astrophysics (CENPA), exploiting the existing setup that had been designed for a previous experiment [15]. Targets containing ~ 3 μg/cm^2 of ^{33}S were created at CENPA by rastering an ion beam over a 5 mm collimator and into OFHC copper plates. The tandem Van de Graaff accelerator provided a proton beam of ~50 μA (rastered over the target) and two HPGe detectors were positioned at ±55° (relative to the beam axis) to measure gamma-rays. Measurements were made over ~120 hours at proton energies corresponding to E_r = 210 – 710 keV (i.e., energies of previously-known resonances [8] and those observed in the indirect studies at the MLL [7]). Finally, the ^{33}S(p,γ)^{34}Cl reaction was measured in inverse kinematics using the DRAGON recoil mass separator at TRIUMF [16]. An intense ^{33}S beam of ~10^{10} ions/s bombarded a windowless, hydrogen-gas target held at a pressure of 6 Torr. Gamma-rays from radiative capture reactions were detected by an array of 30 BGO detectors surrounding the target, and the electromagnetic separator following the target discriminated between ^{34}Cl recoil products and un-reacted ^{33}S beam ions. At the end of DRAGON, two micro-channel plates (MCPs) separated by 60 cm measured time-of-flight ("local TOF"), and a double-sided silicon strip detector (DSSSD) measured the energy of particles. Recoils could generally be identified through the requirement of coincidence between BGO and DSSSD events, and the additional requirement that true recoil events be correlated in time, both for local TOF and for time-of-flight between detection of a gamma-ray in the BGO array and detection of a particle in the DSSSD ("separator TOF"). Measurements were made over ~ 130 hours at beam energies corresponding to proton-capture resonances between E_r = 180 – 495 keV.

3. Preliminary results and discussion

Our measurement of the ^{34}S(^{3}He,t)^{34}Cl reaction revealed 15 new states in ^{34}Cl between E_x = 4.9 – 6.0 MeV, with nine of these states lying within 600 keV of the ^{33}S+p threshold [7].

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Figures 1 and 2 show examples of gamma-ray spectra from the CENPA experiment and TOF spectra from the DRAGON experiment, respectively, both for measurements of the resonance at E_r = 432 keV (this resonance had previously been observed by [10]).

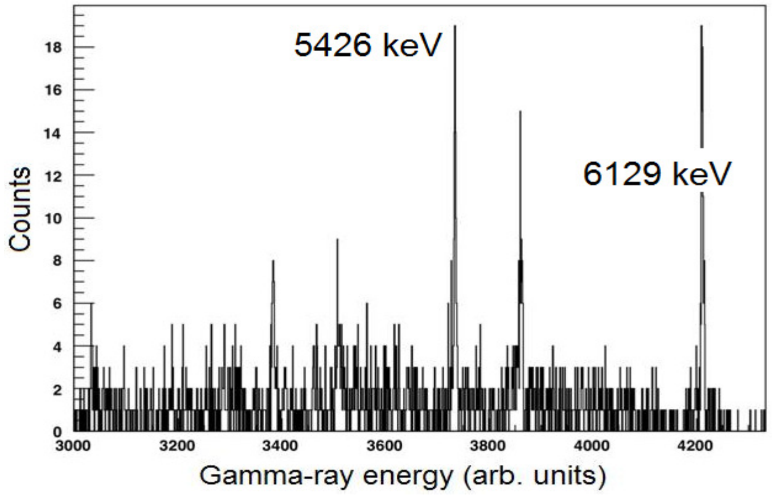

Figure 1: Partial gamma-ray energy spectrum from the experiment in normal kinematics at CENPA. This spectrum was measured at the E_r = 432 keV resonance of the $^{33}S(p,\gamma)^{34}Cl$ reaction over roughly 45 min. The peak labeled at E_γ = 5426 keV results from the decay of the E_x = 5576 keV state in ^{34}Cl [10]. The other peaks shown here arose from background decays and reactions, e.g., that at E_γ = 6129 keV is from the $^{19}F(p,\alpha\gamma)^{16}O$ reaction.

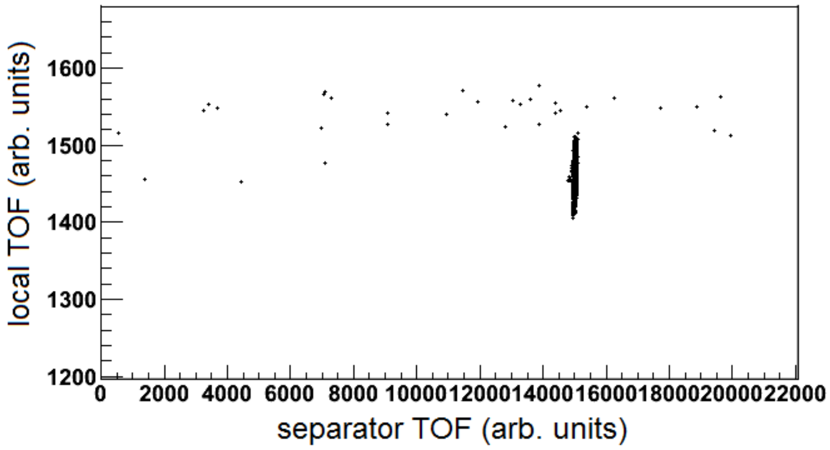

Figure 2: Local TOF vs separator TOF (see text) for coincident BGO-DSSSD events during the DRAGON experiment. This spectrum was measured for the E_r = 432 keV resonance of the $^{33}S(p,\gamma)^{34}Cl$ reaction over roughly 2 hours. The ~1700 true ^{34}Cl recoil events lie at separator TOF ~ 2.3 μs and local TOF ~ 66 ns; they are tightly bunched in separator TOF and displaced in local TOF relative to the few randomly-coincident, un-reacted ^{33}S beam ions.

Preliminary analysis of the CENPA and DRAGON experiments suggests that none of the resonances below E_r = 432 keV will contribute substantially to the thermonuclear rate of the $^{33}S(p,\gamma)^{34}Cl$ in classical nova explosions, and that contributions from higher energy resonances (particularly from that at E_r = 432 keV) will likely dominate. We will also test the agreement between resonance strengths estimated using proton spectroscopic factors (via the

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^{33}S(^{3}He,d)^{34}Cl measurements at the MLL) and those determined directly in the CENPA and DRAGON experiments.

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