Study of astrophysically important resonant states in $^{30}$S using the $^{32}$S(p,t)$^{30}$S reaction

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Abstract. A small fraction ($<1\%$) of presolar SiC grains is suggested to have been formed in the ejecta of classical novae [1]. Classical novae are stellar explosions powered by thermonuclear runaway, which occur in close binary systems consisting of a compact white dwarf and a low-mass Main Sequence companion. The temperature that can be reached during these outbursts is of order of 0.1 to 0.4 GK. Analyzing the Si isotopic abundance ratios ($^{29}$Si/$^{28}$Si and $^{30}$Si/$^{28}$Si) in presolar grains of nova origins help us understand the chemical composition of the white dwarf and the thermal history of the white dwarf’s convective envelope [1], which will in turn help us to determine the dominant nova nucleosynthetic paths followed by the thermonuclear runaway.

To calculate the Si isotopic abundances in presolar grains, it is critical to know the rates of the thermonuclear reactions which affect the $^{29,30}$Si production and destruction in novae. One such reaction is the $^{29}$P(p,γ)$^{30}$S reaction [2]. The $^{29}$P(p,γ) reaction rate depends significantly on the $^{30}$S resonances above the proton threshold ($S_p = 4399 \pm 3$ keV [3]), whose properties are not well understood. Iliadis et al. [2] concluded that at nova temperatures the $^{29}$P(p,γ) reaction

1. Introduction
A small fraction ($<1\%$) of presolar SiC grains is suggested to have been formed in the ejecta of classical novae [1]. Classical novae are stellar explosions powered by thermonuclear runaway, which occur in close binary systems consisting of a compact white dwarf and a low-mass Main Sequence companion. The temperature that can be reached during these outbursts is of order of 0.1 to 0.4 GK. Analyzing the Si isotopic abundance ratios ($^{29}$Si/$^{28}$Si and $^{30}$Si/$^{28}$Si) in presolar grains of nova origins help us understand the chemical composition of the white dwarf and the thermal history of the white dwarf’s convective envelope [1], which will in turn help us to determine the dominant nova nucleosynthetic paths followed by the thermonuclear runaway.
rate is dominated by low energy 3$^+$ and 2$^+$ resonances, whose energies were predicted to be $4733 \pm 40$ keV and $4888 \pm 40$ keV, respectively [2]. Prior to 2007, despite several experiments that attempted to observe these two levels, no evidence of their existence was published. Thus, the $^{29}$P(p,$\gamma$) reaction rate, which depends exponentially on the resonance energy$^4$, remained quite uncertain.

In 2007, to search for these unobserved resonances, two experiment were performed separately by Bardayan et al. [3] and by Galaviz et al. [4]. In the same year, we also performed a $^{32}$S(p,t) experiment to measure the level energies of $^{30}$S at the Wright Nuclear Structure Laboratory at Yale University. We were interested in the region just above the proton threshold at 4399 keV in $^{30}$S. Our energy resolution was $\sim 30$ keV, which is a factor of $\sim 3$ better than that of Bardayan et al. (80 – 120 keV) [3]. Thus, we were able to resolve levels better.

This contribution aims to describe the experimental setup and the detection system used to study the level properties of $^{30}$S, as well as to present our results.

2. Experimental Procedure and Data Analysis

The $^{32}$S(p,t)$^{30}$S reaction was studied using proton beams, which were accelerated by the Yale ESTU tandem Van de Graaff accelerator to fixed energies of 33.5 and 34.5 MeV. Our main target was a 249 $\mu$g/cm$^2 \pm 10\%$ CdS foil supported by a 20 $\mu$g/cm$^2$ natural carbon substrate. In addition to this target, a free standing 311 $\mu$g/cm$^2$ natural Si foil as well as an 75 $\mu$g/cm$^2$ isotopically pure $^{13}$C target foil were used for calibration and contamination subtraction purposes, respectively. The Yale high resolution Enge split pole magnetic spectrograph accepted light reaction products through a rectangular aperture and momentum analyzed them. Tritons were focused at the focal plane of the spectrograph, where a position sensitive ionization drift chamber measured the position and energy loss, $\Delta E$, of the particles which deposited their residual energies, E, into a plastic scintillator.

The $^{32}$S(p,t)$^{30}$S, $^{28}$Si(p,t)$^{26}$Si and $^{13}$C(p,t)$^{11}$C reactions were measured over seven days at spectrograph angles $\theta_{lab} = 9^\circ$, 10$^\circ$, 20$^\circ$, 22$^\circ$ and 62$^\circ$. The spectrograph angles were selected so that the location of the background peaks would allow a clear observation of important resonances of $^{30}$S.

Tritons were identified by plotting focal plane position (equivalent to momentum), $\Delta E$ and E in 2D histograms, and were selected by applying software gates in such histograms. Thus, the $^{30}$S spectra at each spectrograph angle were plotted (see Fig. 1). Background peaks from the $^{12}$C(p,t)$^{10}$C-$^{8}$S, (higher states of $^{10}$C from the $^{12}$C(p,t)$^{10}$C reaction were not on the focal plane) and $^{13}$C(p,t)$^{11}$C reactions were produced by the natural carbon backing in the CdS target and were identified kinematically. In addition, a roughly flat background existed which was attributed to the Cd component of the target as well as other stable sulfur isotopes ($^{33,34,36}$S$^{6}$) present in the CdS target. The spectra of $^{30}$S were analyzed using a least-square fit of multiple $\sim 30$ keV-FWHM Gaussian function (our energy resolution $\sim 30$ keV), from which the peak centroids were determined. Then the focal plane spectra at each angle was calibrated by isolated easily identifiable peaks corresponding to the first, second and the 3rd excited states of $^{26}$Si produced from the $^{28}$Si(p,t)$^{26}$Si reaction and thus the excitation energies of $^{30}$S at all angles were determined. For the excitation energies of $^{26}$Si, we used a weighted average between the excitation energies listed in the Nuclear Structure and Decay Databases [5], and those

\[ <\sigma v >_R = \left( \frac{2\pi}{\mu kT} \right)^\frac{1}{2} h^2 (\omega)R \exp \left( -\frac{E_R}{kT} \right) \quad (1) \]

Where $<\sigma v >_R$ is the reaction rate, $\mu$ is the reduced mass, $k$ is the Boltzmann factor, $T$ is the temperature in GK, ($\omega$)$_R$ is the resonance strength and $E_R$ is the resonance energy in keV.

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$^4$ In the case of narrow resonances for which the total width $\Gamma$ of the resonance is much smaller than the resonance energy (typically, if $\frac{\Gamma}{E_\Gamma} < 0.1$), the resonance reaction rate can be calculated using the following formula:
measured by Seweryniak et al. [6]. After determining the excitation energies of $^{30}$S states at each angle, a statistically weighted average excitation energy was calculated for each level. In addition to uncertainties in location of the peaks on the focal plane spectra, which translated into uncertainties in excitation energies, a universal uncertainty of 3.0 keV was also present due to the uncertainties in masses of $^{26}$Si ($\pm 0.17$ keV) [7] and $^{30}$S ($\pm 3$ keV) [8]. These uncertainties were mutually independent and were added together in quadrature.

3. Results and Future Outlook

With the 30 keV energy resolution obtained in our experiment, at all angles we were able to observe two peaks, most visible at 22° (see Fig. 1), just above the proton threshold. In spite of low statistics, since the excitation energies of these two peaks did not change with angle, we concluded that they belong to $^{30}$S. For these two levels, we extracted excitation energies averaged over all angles of 4692.7 ± 4.5 keV and 4813.8 ± 3.4 keV, respectively. In addition to these two states, we have also observed nine more levels of $^{30}$S up to 6.7 MeV (see Fig. 2). A more comprehensive description of these levels, including data from the methods outlined below, is underway, and those results will be published in the future. Our result for the energy of the $3^+$ state agrees very well with the energy of this state obtained in Galaviz’s experiment [9] and it differs from that of Bardayan et al. by 1.8 keV. Our result for the energy of the $2^+$ state is close to that of Galaviz et al. result [9].

Our CdS target produced a high roughly flat background. To obtain cleaner spectra, we implanted $^{32}$S into 40 µg/cm$^2$ isotopically pure $^{12}$C foils. Rutherford backscattering spectroscopy revealed that there is 10.4 ± 0.3 µg/cm$^2$ of $^{32}$S in this target. We then repeated the $^{32}$S(p,t) experiment recently with this target and were able to achieve our goal of reducing the background. The analysis of this new data is still in progress.

In late July 2009, we also performed an in-beam $\gamma$-ray spectroscopy experiment using the $^{28}$Si($^3$He,n$\gamma$)$^{30}$S reaction at the University of Tsukuba Tandem Accelerator Complex (UTTAC) in Japan. In the latter experiment, the energies of the excited states of $^{30}$S were studied via the n-$\gamma$ and $\gamma\gamma$ coincidence measurements using a liquid scintillator to detect neutrons as well as two high energy resolution Ge-detectors. The analysis of this data is currently in progress.
**Figure 2.** Level Scheme of $^{30}\text{S}$ with energies in keV from this work unless indicated by an asterisk. The uncertainties are in energies are in two last digits, e.g. a level with $E_x = 2209.8$ keV has an uncertainty of 3.1 keV. The spins and parities of the $^{30}\text{S}$ levels extracted from this work are still preliminary so they are not shown here. For information on the properties of levels with energy higher than 6.7 MeV, see Ref. [3]. Note that the level at 3666.3 keV could not be resolved in our work, and thus it is taken from Ref. [10].

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