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Study of Astrophysically Important Resonant States in ^{30}S Using the ^{32}S(p,t)^{30}S Reaction

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A small fraction ($<$ 1%) of presolar SiC grains is suggested to have been formed in the ejecta of classical novae. The ^{29}P(p,γ)^{30}S reaction plays an important role in understanding the Si isotopic abundances in such grains, which in turn provide us with information on the nature of the probable white dwarf progenitor's core, as well as the peak temperatures achieved during nova outbursts. This rate is determined by two low-lying 3^+ and 2^+ resonances above the proton threshold in ^{30}S at 4399 keV. Despite several experimental studies in the past however, the 3^+ resonance has only been recently observed in one experiment and no definitive evidence for the 2^+ state has been published yet. We have studied the ^{30}S nuclear structure via the ^{32}S(p,t)^{30}S reaction at 5 laboratory angles between 9° to 62°. We have observed between 8 to 14 states above the proton threshold including two levels at 4695.5 $\pm$ 3.5 keV and 4814.9 $\pm$ 3.5 keV that are candidates for the 3^+ and previously "missing" 2^+ state, respectively.

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1. Introduction

Classical novae are stellar explosions powered by thermonuclear runaway (TNR). They occur in close interacting binary systems consisting of a compact white dwarf and a low-mass Main Sequence companion, and are characterized by a sudden rise in optical brightness with peak luminosities reaching $10^4 - 10^5$ $L_\odot$ [1]. The temperature that can be reached during the outburst is of order of 0.1 to 0.4 GK. Such dramatic stellar explosions can release energies of the order of 10^{45} ergs, and can eject 10^{-5} - 10^{-4} $M_\odot$ of material into the interstellar medium.

The dominant nova nucleosynthetic paths followed by the TNR are very sensitive to the details of the explosions, which can be inferred by studying the Si isotopic abundance ratios (^{29}Si/^{28}Si and ^{30}Si/^{28}Si) in presolar grains of probable nova origins [2, 3]. To calculate the Si isotopic abundances in presolar grains with high precision, it is critical to know the rates of the thermonuclear reactions which affect the Si production and destruction in novae. One such reaction is the ^{29}P(p,γ)^{30}S. Variation in the ^{29}P(p,γ) rate within its currently prescribed limits has the effect of changing ^{29,30}Si abundances by a factor of 3 [4, 5]. The ^{29}P(p,γ) reaction rate not only affects the abundances of silicon isotopes, but also has a profound influence on the abundances of some heavier isotopes beyond silicon [4].

The ^{29}P(p,γ) reaction rate remains quite uncertain, and depends significantly on the properties of ^{30}S resonances above the proton threshold at $S_p = 4399 \pm 3$ keV [4]. ^{30}S is located near the beginning of the *rp*-process reaction path [6], and its level structure above the proton threshold is not well understood. Iliadis *et al.* [7] concluded that at nova temperatures the ^{29}P(p,γ) reaction rate is dominated by low energy 3^+ and 2^+ resonances, whose energies were predicted by using the isobaric multiplet mass equation to be 4733 ± 40 keV and 4888 ± 40 keV, respectively [7]. 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,γ) reaction rate relied on the predicted excitation energies, and uncertainties of 40 keV would translate into several orders of magnitude of uncertainty in the reaction rate since the reaction rate depends exponentially on the resonance energy.

In 2007, to search for these unobserved resonances Bardayan *et al.* studied the level structure of ^{30}S via the ^{32}S(p,t)^{30}S reaction at the ORNL Holifield Radioactive Ion Beam Facility (HRIBF) [4]. In their experiment, they observed a previously unknown level at 4704 ± 5 keV, which was considered to be the missing 3^+ state, and no evidence of the 2^+ state was seen. In addition to this experiment, Galaviz *et al.* also studied the ^{30}S level structure just above the proton threshold by studying the de-excitation of the ^{30}S produced via the ^{31}S(^{12}C,^{12}C n)^{30}S* reaction at the National Superconducting Cyclotron Laboratory (NSCL) [6]. In their preliminary analysis they have obtained the excitation energies of the 3^+ and 2^+ states to be 4686 keV and 4790 keV, respectively [10]. 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 3 better than that of Bardayan *et al.* (80 - 120 keV) [4]. 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 preliminary results.

2. The 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 μg/cm^2 ± 10% CdS foil supported by a 20 μg/cm^2 natural carbon substrate. In addition to this target, a free standing 311 ± 31 μg/cm^2 natural Si foil as well as an 75 μg/cm^2 isotopically pure ^{13}C (95.6% purity) 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, ΔE, of the particles which deposited their residual energies, E, into a plastic scintillator [11].

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 using fixed magnetic field strengths B = 9.5 and 10 kG, at spectrograph angles $\theta_{\text{lab}} = 9^\circ$, 10°, 20°, 22° and 62°, and with horizontal and vertical spectrograph entrance-aperture settings of $\Delta\theta = \pm$ 20, 30 mrad and $\Delta\phi = \pm$ 40 mrad, respectively.

A variety of particle groups (p, d, t and α) were present and were identified by plotting focal plane position (equivalent to momentum), ΔE and E in 2D histograms. Tritons were selected by applying software gates in such histograms, and spectra of focal plane position were plotted for the ^{32}S(p,t)^{30}S reaction at each spectrograph angle (see Fig. 1). Background peaks from the ^{12}C(p,t)^{10}C$^{\text{g.s.}}$ 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) present in the CdS target. The ^{30}S spectra were fitted using least-squares fits of multiple and in some cases individual gaussian functions to find the centroid of each peak. Isolated, easily identifiable peaks corresponding to the first to the 4th excited states of ^{26}Si from the ^{28}Si(p,t)^{26}Si reaction were used to calibrate the focal plane at each angle from which the excitation energies of ^{30}S at that angle 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 [12], and those measured by Seweryniak *et al.* [13]. Finally, a statistically weighted average excitation energy with its uncertainty was calculated for each level of ^{30}S. A universal uncertainty of 3.16 keV was also present due to the uncertainties in masses of ^{26}Si (± 1 keV) [8] and ^{30}S (± 3 keV) [9]. These uncertainties were mutually independent and were added together in quadrature.

3. Preliminary Results and Future Outlook

With the energy resolution obtained in our experiment, at each angle (except 10° and 20°, where a blocker was used to block the elastically scattered beam particles) we were able to observe two states below the proton threshold, and between 8 to 14 states above the proton threshold. In spite of low statistics in the region of interest, as can be seen from Fig. 1, there is evidence that there are two states at 4695.5 ± 3.5 keV and 4814.9 ± 3.5 keV which may be the "missing" 3^+ and 2^+ states, respectively. These two states were most visible at 22° but were observed at all 5 angles. If the ^{32}S(p,t)^{30}S reaction produced the peaks, the excitation energies should not change with angle. At 9°, 10°, 20° and 62° there is also evidence of two peaks which occur at the same energy, and thus it seems likely that these peaks belong to ^{30}S. Our result for the 3^+ state agrees with that of Bardayan *et al.* [4] and is close to the preliminary result of Galaviz *et al.* [10]. Our energy for the 2^+ state is about 25 keV higher than the preliminary result of Galaviz *et al.* [10].

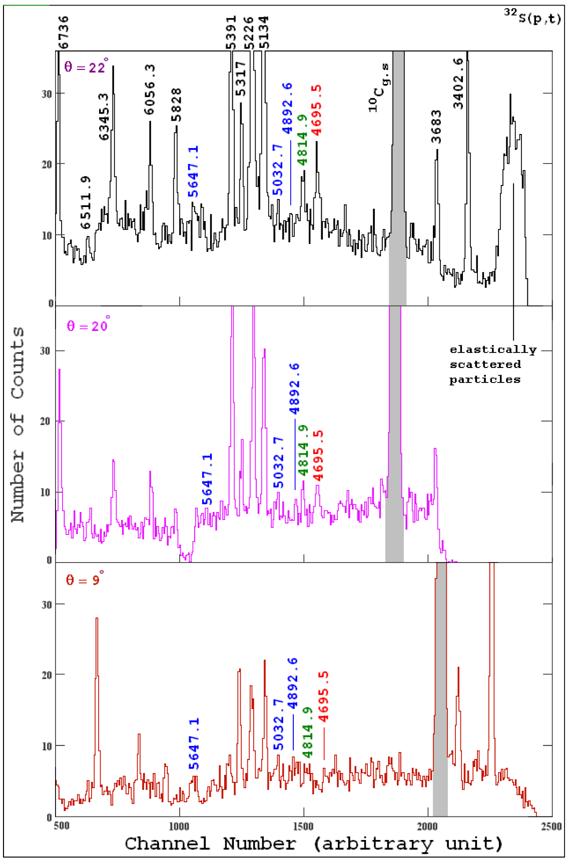

Figure 1: Triton momentum spectra corresponding to the ^{30}S states from the ^{32}S(p,t) reaction shown at selected angles. The spectra are shifted relative to one another. The background peak of ^{10}C$^{g.s.}$ is shaded in light grey. Peaks are labeled with the weighted average excitation energies in keV from this work. The 3^+, 2^+ and other potentially new states are labeled with red, green and blue, respectively.

In addition to the two important resonances above the proton threshold, we have also seen possible evidence of three additional peaks above the proton threshold. These peaks were not populated as significantly as the 3^+ and 2^+ states at any angle and the statistics under the peaks was substantially lower than that of the 3^+ and 2^+ states. For instance, at 22° the counts under the 2^+ state was $\sim$ 181, whereas the average counts under these peaks was $\sim$ 55. These peaks were most visible at 9° (see Fig. 1) but at 62° they almost look like background. Our preliminary analysis suggests that the excitation energies averaged over all angles for these states are 4892.6 ± 3.5 keV, 5032.7 ± 3.4 keV, and 5647.1 ± 3.5 keV. In our analysis we first assumed that they may belong to ^{11}C via the ^{13}C(p,t)^{11}C reaction or some isotope of oxygen. In this case, the resultant excitation energies changed significantly by changing angle. The only nucleus for which the excitation energies of these peaks moved kinematically and did not change by angle was ^{30}S. So, we suspect that they may also belong to ^{30}S as opposed to the contaminants; however, the population is not strong enough at all angles to make a definitive statement on their existence. In Fig. 1, we have shown the three angles where all the states were most visible.

In future analysis, we aim to determine the differential cross sections for each angle so as to ascertain the angular distributions for those ^{30}S levels which were populated in our experiment. Afterwards, we will perform a DWBA calculation to extract the spins and parities of the levels observed. As a future complementary experiment, we are preparing an implanted ^{32}S target into an isotopically pure ^{12}C substrate at The University of Western Ontario in collaboration with Prof. William Lennard[1], which will be used to study the ^{30}S nucleus with the ^{32}S(p,t) reaction. Since such an implanted target does not contain the unwanted stable sulfur isotopes, Cd or ^{13}C, it will help reduce the background, resulting in a cleaner triton spectrum. A future experiment with such a target will help us determine whether or not the probable new states belong to ^{30}S.

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