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Study of Astrophysically Important Resonant States in ^{30}S Using the ^{28}Si(^{3}He, $n\gamma$)^{30}S Reaction

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The ^{29}P(p,γ)^{30}S reaction rate strongly affects explosive hydrogen burning in classical novae and type I X-ray bursts, and depends on the structure of proton unbound ^{30}S states. The rate in the temperature characteristic of nucleosynthesis in novae and X-ray bursts had been previously predicted to be dominated by two low-lying, unobserved, $J^{\pi} = 3^{+}$ and 2^{+} resonances above the proton threshold in ^{30}S. Since then, two states have been found at 4699(6) keV and 4814(3) keV, which were tentatively assigned to be the 3^{+} and 2^{+} states, respectively. To confirm the existence of these two levels and their energies, the structure of ^{30}S was investigated via an in-beam γ-ray spectroscopy experiment using the ^{28}Si(^{3}He, $n\gamma$)^{30}S reaction at University of Tsukuba Tandem Accelerator Complex in Japan. This work describes the experimental setup and presents the preliminary results.

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1. Astrophysical Motivation

The ^{29}P$(p,\gamma)^{30}$S reaction is important in two astrophysical contexts: classical novae and type I x-ray bursts. Classical novae are the second most energetic stellar explosions (after supernovae) powered by thermonuclear runaway in close interacting binary systems, consisting of a compact white dwarf and a low-mass main sequence companion. The temperature characteristic of explosive hydrogen burning in novae is on the order of 0.1 to 0.4 GK. The silicon isotopic abundance ratios (^{29}Si/^{28}Si and ^{30}Si/^{28}Si) in presolar grains of potential nova origin [1, 2] may help determine the dominant nova nucleosynthetic paths followed by the thermonuclear runaway [3]. To improve the predicted silicon isotopic abundances in novae ejecta, it is important to know the rates of the thermonuclear reactions that affect the silicon production and destruction in novae. One such reaction is ^{29}P$(p,\gamma)^{30}$S. Si isotopes are strongly affected by the changes in the ^{29}P$(p,\gamma)^{30}$S rate [4].

The ^{29}P$(p,\gamma)^{30}$S reaction rate furthermore governs the nucleosynthesis in type I x-ray bursts (peak T $\approx$ 1.5 GK), which result from thermonuclear runaways in hydrogen- and helium-rich material accreted onto the neutron star surface in an x-ray binary system [5, 6]. The ^{29}P$(p,\gamma)^{30}$S reaction is one of the most important reactions in the overall flow as the burst temperature approaches its peak [7], and has a profound influence on the reaction flow through the waiting-point nucleus ^{30}S ($t_{1/2} = 1.178$ s). As the temperature rises in the ignition region of the x-ray burst, ^{30}S is produced via the ^{29}P$(p,\gamma)^{30}$S reaction but since the 284(7) keV Q-value of the ^{30}S$(p,\gamma)^{31}$Cl reaction [8] is very low, the photo-disintegration of ^{31}Cl prevents a significant flow through proton capture of ^{31}Cl, and thus the nucleosynthetic path must pass through ^{30}S$(\beta^+,\nu)^{31}$P, which is the slowest weak interaction process in this region of the path [9]. This results in a substantial bottleneck for the reaction flow, and thus affects the energy generation and nucleosynthesis in type I x-ray bursts, along with their duration and light-curve structures.

2. The ^{29}P$(p,\gamma)^{30}$S Reaction Rate and the Structure of ^{30}S

The ^{29}P$(p,\gamma)^{30}$S reaction rate is strongly influenced by the properties of ^{30}S states above the proton threshold (S$_p$ = 4399(3) keV [10]), which are not well understood. Iliadis *et al.* [11] predicted that in the nova temperature regime, the ^{29}P$(p,\gamma)^{30}$S reaction rate is dominated by two low energy, unobserved, $J^\pi = 3^+_1$ and 2^+_3 resonances, whose energies were predicted [11] by using the isobaric multiplet mass equation to be 4733(40) keV and 4888(40) keV, respectively.

The $J^\pi = 3^+_1$ resonance in ^{30}S remained unobserved, until a ^{32}S$(p,t)^{30}$S experiment, performed by Bardayan *et al.* [12] at the ORNL Holifield Radioactive Ion Beam Facility (HRIBF), revealed a state at 4704(5) keV for the first time, and a tentative spin-parity assignment of $J^\pi = 3^+$ was suggested for that state. However, they found no evidence for the existence of the $J^\pi = 2^+_3$ state. Shortly afterwards, to search for this resonance, another ^{32}S$(p,t)^{30}$S experiment was performed at Yale University's Wright Nuclear Structure Laboratory with $\sim$ 3 times higher energy resolution than that of Bardayan *et al.* using a magnetic spectrograph [13]. A state was observed at 4693(5) keV, whose measured energy agrees with that of Ref. [12] at the 2σ level, and thus is a candidate for the $J^\pi = 3^+_1$ resonance. Moreover, for the first time a state was discovered at 4814(3) keV, which is the candidate for the $J^\pi = 2^+_3$ resonance. The ^{29}P$(p,\gamma)^{30}$S rate was found to be solely dominated by this latter resonance for most of the astrophysically relevant temperature range (0.3 GK – 1.5 GK). In both experiments, the J^π assignments are tentative.

We therefore have performed another experiment with a different reaction mechanism and an even better energy resolution with the purpose of confirming the existence of these two levels and their energies, as well as obtaining their spins and parities. The experiment was an in-beam γ-ray spectroscopy measurement using the ^{28}Si(^{3}He, $n\gamma$)^{30}S reaction at the University of Tsukuba Tandem Accelerator Complex in Japan.

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

3. Experimental Setup

In the present work, the ^{28}Si(^{3}He, $n\gamma$)^{30}S reaction was studied with improved energy resolution relative to that of the previous ^{28}Si(^{3}He, $n\gamma$)^{30}S experiment [14], in order to investigate the structure of ^{30}S just above the proton threshold at 4399(3) keV [10].

The experiment was carried out over a three-day period at the University of Tsukuba Tandem Accelerator Complex (UTTAC) in Japan. ^{3}He^{2+} particles were accelerated by the 12UD Pelletron tandem accelerator to 9 MeV with intensities of up to 0.5 enA, and impinged on a 25 μm thick natural Si target provided by the Lebow Company[1].

The single-γ measurements and γ-γ coincidence measurements were performed with two high purity Ge-detectors located at 90° and 3.5 cm away from the target, and at 270° and 3 cm away from the target. The respective efficiencies were 70% and 140% relative to the efficiency of a 3″ × 3″ NaI detector located 25 cm away from the target. The angles at which the detectors were located were measured with respect to the direction of the beam axis. The energy resolution of each Ge-detector was determined to be 3.5 keV (FWHM) at $E_{\gamma} = 1333$ keV ^{60}Co line. A NE-213 liquid scintillator of size 25 cm diameter × 10 cm long, located at 40° with respect to the beam axis and 21 cm away from the target was employed to detect neutrons for measurements of n-γ coincidences with the purpose of reducing the potentially large background of γ-rays arising from the competing (^{3}He, p) reactions on the target nuclei. Fig. 1 shows a schematic diagram of the experimental setup.

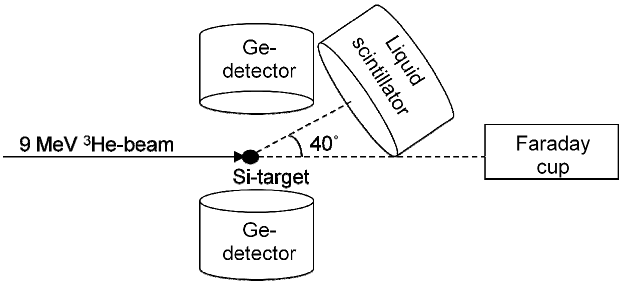

Figure 1: The schematic diagram of the present experimental setup. The Ge-detectors were located at 90° and 270° with respect to the direction of the beam axis, and were 3.5 cm and 3 cm away from the target, respectively. The liquid scintillator was located at 40° with respect to the direction of the beam axis and was 21 cm away from the target. The distances are not to scale.

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4. Data Analysis and Preliminary Results

The ^{28}Si(^{3}He, p)^{30}P reaction has a higher cross section than the ^{28}Si(^{3}He, $n\gamma$)^{30}S reaction [15]. However, the background from the (^{3}He, p) reaction on the Si-target was not of any concern because the γ-rays from the de-excitations of ^{30}P nuclei and those delayed by the β^{+}-decays of ^{30}P nuclei were successfully identified in the singles spectrum, and they did not obscure any of the γ-rays of interest from decays of the ^{30}S nuclei. All other contaminant γ-rays from different reactions on the target, due to presence of other stable isotopes of silicon in the target, were also identified.

Fig. 2 shows the combined singles spectra from both Ge-detectors. Two γ-rays corresponding to the transitions of the $2_1^+ \rightarrow 0_1^+$ and $2_2^+ \rightarrow 2_1^+$ in ^{30}S are clearly observed and are labeled by the γ-ray energies followed by an asterisk. The γ-γ coincidence analysis is still in progress but from the preliminary analysis, we confirm that all of the states of ^{30}S up to 5.134 MeV have been populated including the two astrophysically important states. Due to low neutron statistics, not much could be learned from the n-γ coincidence measurements.

In another experiment conducted very recently, the angular distributions and angular correlations of the γ-rays emitted from ^{30}S states were measured, and thus the spin-parity assignments of these states can be determined via the method of D̲irectional C̲orrelations of γ-rays from O̲riented (DCO) states of nuclei. The analysis of these new data is still in progress.

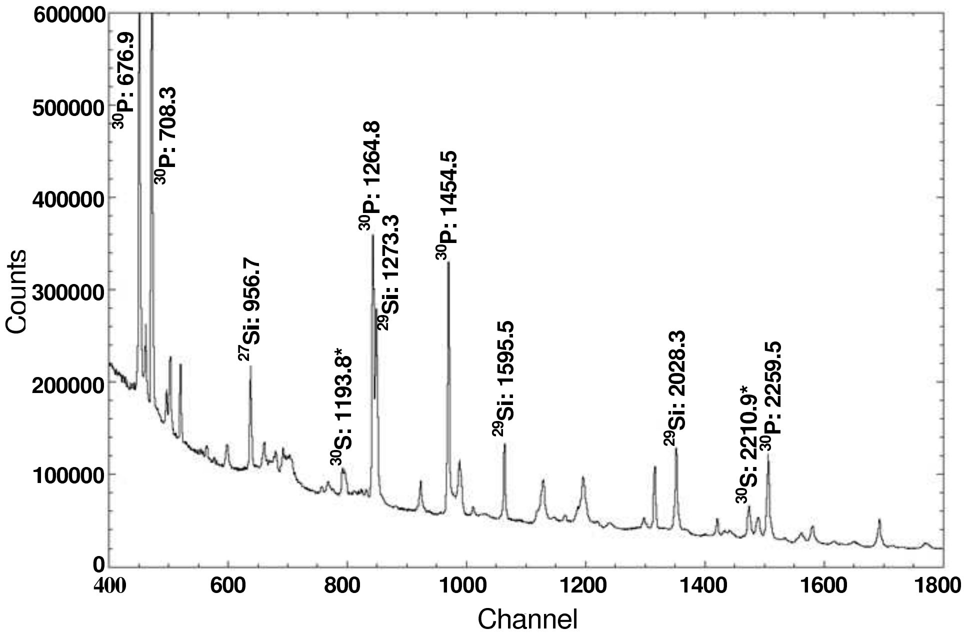

Figure 2: The combined singles spectra from both Ge-detectors obtained in the present work. Some of the stronger γ-ray transitions are labeled with their energies and parent nuclei. All the energies are in keV and are from the present work. The 1193.8-keV and 2210.9-keV transition peaks belong to two transitions in ^{30}S (see text) and are labeled by an asterisk.

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