Louisiana State University

LSU Digital Commons

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

K. Setoodehnia
McMaster University

A. A. Chen
McMaster University

J. Chen
McMaster University

J. A. Clark
Argonne National Laboratory

C. Deibel
Argonne National Laboratory

See next page for additional authors

Recommended Citation

Authors

K. Setoodehnia, A. A. Chen, J. Chen, J. A. Clark, C. Deibel, D. Kahl, W. N. Lennard, P. D. Parker, and C. Wrede

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

Kiana Setoodehnia[1,a], Alan A. Chen[1], Jun Chen[1], Jason A. Clark[2], Catherine Deibel[2], David Kahl[1,b], William N. Lennard[3], Peter D. Parker[4], and Christopher Wrede[5]

[1] Department of Physics & Astronomy, McMaster University, Hamilton, ON L8S 4M1, Canada
[2] Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA
[3] Department of Physics & Astronomy, University of Western Ontario, London, ON N6A 3K7, Canada
[4] Wright Nuclear Structure Laboratory, Yale University, New Haven, CT 06520, USA
[5] Department of Physics, University of Washington, Seattle, WA 98195-1560, USA

Abstract. 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, and thus the nova nucleosynthetic path. The ^{29}P(p,γ)^{30}S reaction rate at nova temperatures is determined by two low-lying 3^+ and 2^+ resonances above the proton threshold at 4399 keV in ^{30}S. Despite several experimental studies in the past, however, only one of these two states has only been observed very recently. 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 14 states, eleven of which are above the proton threshold, including two levels at 4692.7 ± 4.5 keV and 4813.8 ± 3.4 keV that are candidates for the 3^+ and the previously "missing" 2^+ state, respectively.

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 on 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 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 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 ± 3 keV [3]), whose properties are not well understood. Iliadis *et al.* [2] 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 to be 4733 ± 40 keV and 4888 ± 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,γ) reaction rate, which depends exponentially on the resonance energy, 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 ∼ 30 keV, which is a factor of ∼ 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.

---

a e-mail: setoodk@mcmaster.ca
b Present address: Center for Nuclear Study (CNS), Graduate School of Science, University of Tokyo, Wako Branch at RIKEN, 2-1 Hirosawa, Wako, Saitama, 351-0198, Japan

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 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.

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 θ_{lab} = 9°, 10°, 20°, 22° and 62°. 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), ΔE 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$^{g.s.}$ (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) present in the CdS target. The focal plane at each angle was calibrated by isolated easily identifiable peaks corresponding to the first to 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 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 (± 0.17 keV) [7] and ^{30}S (± 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
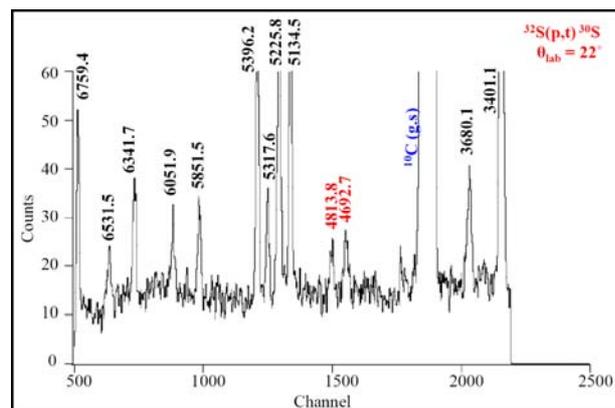

Fig. 1. Focal plane spectra of the ^{32}S(p,t) reaction corresponding to the states of ^{30}S, after gating on tritons, shown at selected angle. The background peak of ^{10}C$^{g.s.}$ is labeled. The states of ^{30}S are labeled by their energies averaged over all angles obtained in this work. All energies are in keV. The states of interest are labeled in red.

of ^{30}S up to 6.7 MeV. A more comprehensive description of these levels is underway, and those results will be published in the future. Our result for the energy of the candidate 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 candidate 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 at 22° recently with this target and were able to reduce the background by 40%.

In late July 2009, we also performed an in-beam γ-ray spectroscopy test experiment using the ^{28}Si(^{3}He,nγ)^{30}S reaction at the University of Tsukuba Tandem Accelerator Complex (UTTAC) in Japan. In the latter experiment, which looked very promising, the energies of the excited states of ^{30}S were studied via the n-γ 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.

In the future, to determine the spin/parity of the states observed in our previous experiment we would like to repeat the ^{32}S(p,t)^{30}S experiment with our ^{32}S-implanted target (to obtain a cleaner spectrum) either at Yale University or at the Technical University of München. At the latter facility, we can obtain an even better energy resolution (< 10 keV) by using the Q3D spectrograph. In addition, we will be able to collect more statistics over a shorter period of time due to a higher proton beam intensity at the Technical University of München. We are also planning to perform the in-beam γ-ray spectroscopy experiment using the ^{28}Si(^{3}He,nγ)^{30}S reaction again to study the nuclear structure of ^{30}S via yet another method to be able to obtain the

spin/parity of the states observed. Once the properties of the states observed are determined, we will calculate the $^{29}P(p,\gamma)^{30}S$ reaction rate more precisely.

4 Acknowledgment

References

1. J. José, M. Hernanz, S. Amari and E. Zinner, Astrophys. J. **612**, 414 (2004)
2. C. Iliadis, J. M. D'Auria, S. Starrfield, W. J. Thompson and M. Wiescher, Astrophys. J. Suppl. Ser. **134**, 151 (2001)
3. D. W. Bardayan *et al.*, Phys. Rev. C **76**, 045803 (2007)
4. D. Galaviz *et al.*, J. Phys. G: Nucl. Part. Phys. **35**, 014030 (2008)
5. Nuclear Structure and Decay Databases *http://www.nndc.bnl.gov/databases*
6. D. Seweryniak *et al.* Phys. Rev. C **75**, 062801 (2007)
7. T. Eronen *et al.*, Phys. Rev. C **79**, 032802(R) (2009)
8. G. Audi, A. H. Wapstra and C. Thibault, Nucl. Phys. A **729**, 337 (2003)
9. D. Galaviz, (Private Communication)