^{30}P(p,γ)^{31}S Reaction Rate for Classical Novae: An Indirect Approach

D Irvine

Department of Physics and Astronomy, McMaster University, Hamilton, ON, L8S 4M1, Canada

E-mail: irvinedt@mcmaster.ca

Abstract. Isotopic abundance ratios of ^{30}Si/^{28}Si found in presolar SiC grains of suspected nova origin agree qualitatively with proposed oxygen-neon (ONe) nova composition but fail to agree quantitatively with ejecta predictions made by hydrodynamic ONe nova models. The Astrophysical ^{30}P(p,γ)^{31}S reaction rate is a key quantity used in nova models that predict isotopic abundances produced during nucleosynthesis leading up to the outburst. Currently, there is a large uncertainty in the rate at nova temperatures ($0.1 < T < 0.4$ GK) causing the predicted ^{30}Si abundance ratio to vary by a factor of 4. The ^{30}P(p,γ)^{31}S reaction rate can be determined indirectly by measuring triton momenta from ^{32}S(d,t)^{31}S reactions. ^{31}S Resonant states measured up to 600 keV above the proton threshold of 6131 keV and within the Gamow window which contribute most significantly to the rate can then be used to re-evaluate the rate for nova temperatures and reduce the uncertainty.

1. Introduction

The ^{30}P(p,γ)^{31}S reaction rate is an important quantity of interest as input to current hydrodynamic classical nova models. The reaction has a very strong impact on the abundances of nuclei produced during nucleosynthesis for Oxygen-neon (ONe) novae in the A=30-37 mass region [1]. A Reaction rate sensitivity study [2] performed in 2001 has shown that variations in the ^{30}P(p,γ)^{31}S rate (obtained by statistical model calculations), up to a factor of 100, greatly affected the abundances of observable isotopes in the Si-Ar mass region by factors of 2-500. Furthermore, the ^{30}P(p,γ)^{31}S acts as a bottleneck for which the reaction network must pass through on the way to the heaviest nuclear species that can be produced in ONe novae leading up to the outburst (^{40}Ca, confirmed by spectroscopic observations of nova ejecta) [3].

An interesting comparison to the abundances predicted by nova models arises with observations made from abundance ratios in presolar grains of possible nova origin. Of particular importance to ONe nova nucleosynthesis, is the higher than solar ^{30}Si/^{28}Si abundance found in Silicon-carbide (SiC) grains originating from a time before our solar system. The amount of ^{30}Si produced in ONe novae is directly related to the rate of the ^{30}P(p,γ)^{31}S reaction since ^{30}P can either proceed through (p,γ) or β^+ decay to form ^{30}Si ($t_{1/2}$=2.5 min). Early nova models [4] predicted ^{30}Si/^{28}Si abundance ratios which were higher than the solar value but only agreed qualitatively with abundances observed in the grains, providing motivation for fine-tuning model input quantities and thus determining a well defined ^{30}P(p,γ)^{31}S reaction rate.

Due to the unavailability of a radioactive ^{30}P beam with an intensity required for sufficient analysis, a direct measurement of the rate of the ^{30}P(p,γ)^{31}S reaction (Q=6130.9(4) [5, 6]) for nova temperatures

(0.1< T < 0.4 GK) is currently not possible. Indirectly, the rate can be determined using nuclear structure information for resonant states in ^{31}S up to 600 kev above the ^{30}P + p threshold.

Over the relevant temperature range, the ^{30}P(p,γ)^{31}S reaction rate $N_A\langle\sigma\upsilon\rangle$ is dominated by contributions from narrow, isolated resonances r such that

$$N_A\langle\sigma\upsilon\rangle = \left(\frac{2\pi}{\mu kT}\right)^{3/2} \hbar^2 \sum_r (\omega\gamma)_r e^{-E_r/kT} \quad (1)$$

where $\hbar$ is the reduced Planck constant, k is the Boltzmann constant, μ is the reduced mass and E_r is the resonance energy in the center-of-mass frame. The resonance strength for each resonance is given by the equation

$$(\omega\gamma)_r = \frac{(2J_r + 1)}{(2J_p + 1)(2J_P + 1)} \left(\frac{\Gamma_p \Gamma_\gamma}{\Gamma}\right)_r \quad (2)$$

where J_r is the spin of the resonance, J_p and J_P are the spins of the particles in the entrance channel, Γ_p and Γ_γ are the proton and γ–ray partial widths of the resonance, respectively, with the total width $\Gamma = \Gamma_p + \Gamma_\gamma$.

Recently, there has been a significant amount of experimental work done for the purposes of establishing the ^{30}P(p,γ)^{31}S reaction rate [3, 7–11]. A study by Parikh et al. [3] presents further structure constraints based on indirect methods and a re-evaluation of the current reaction rate and points to a state at ~6403 keV in which no structure information is known as the leading contributor to the rate uncertainty as well as ambiguities in J^π values of the 6543 and 6586 keV states. One promising method for studying important resonances in ^{31}S is via the ^{32}S(d,t)^{31}S reaction ($Q = -8.7862(4)$ MeV [6]). A previous measurement of this reaction was carried out at Yale University [7]. While two known levels in the energy region of interest were populated, the experiment suffered from relatively poor resolution and from contaminants in the target. In the present work, we have improved on this study by performing a high-resolution measurement of the reaction with a Q3D spectrometer and improved implanted ^{32}S targets.

2. Experiment

2.1. Beam production and characteristics

The experiment was performed at the Maier-Leibnitz-Laboratorium (MLL) of the Technische Universität München and of the Ludwig-Maximilians-Universität. A 24 MeV ^{2}H beam with a current of about 500 enA was delivered using the MLL MP tandem Van de Graaff accelerator. The ion source was an electron cyclotron resonance (ECR)-like ion source [12]. The beam was first focused through a removable 1 x 3 mm collimator at the target location and then allowed to impinge on the target. The beam current was integrated at a Faraday cup located at 0°.

2.2. Target characteristics

Targets of ^{32}S were prepared at the ion implantation facility of the University of Western Ontario. In this process, ~10 μg/cm^2 of ^{32}S was implanted on a 40 μg/cm^2 foil of isotopically enriched ^{12}C. The target composition was chosen in order to minimize contamination from (d,t) reactions on other stable isotopes of sulphur and on ^{13}C.

2.3. Triton detection and measurement: The Q3D and focal plane detector

Tritons were momentum-analyzed with a quadrupole-dipole-dipole-dipole (Q3D) magnetic spectrograph upon leaving the target. The slits located between the target chamber and the Q3D were set to vertical and horizontal dimensions of x= 21 cm and y= 24.5 cm corresponding to a total (fully

open) acceptance of 13.9 msr. The magnetic field values were then set accordingly to focus tritons corresponding to ^{31}S excited states on the focal plane with the ~6636 keV state chosen to appear roughly in the center of the focal plane. Measurements were performed for spectrograph angles of θ_{lab}= 15°, 20°, 25°, 49°, 53.75° and 58.5° over a period of 4 days. Angles were selected to optimize the triton angular distributions, to avoid contaminant peaks in the spectra and to identify unambiguous ^{31}S states based on analysis of their kinematic shifts across the focal plane with changes in Q3D angle.

The focal plane detector comprised of two multiwire gas-filled proportional counters, 255 position sensitive cathode strip detectors and backed by a plastic scintillator [13], was used to measure the position, energy loss and residual energy of the tritons for particle identification. The energy resolution for the ^{32}S(*d*,*t*)^{31}S experiment was found to be ~9 keV FWHM.

2.4. Triton detection and measurement: Background and particle identification

Potential background sources are from (*d*,*t*) reactions on target contaminants such as carbon, oxygen and silicon. Background tritons were measured with a 20 μg/cm^2 thick 99% enriched ^{12}C target and a self sustained 25 μg/cm^2 ^{28}Si target.

Two dimensional histograms for each angle were plotted using energy loss, residual energy and particle position information in the detector. Offline, tritons were identified by applying a series of gates on this data and a final triton focal-plane position spectrum was produced for each spectrograph angle. Excited states in ^{31}S in the 6.3-7 MeV region were observed at each angle.

3. Analysis

Figure 1 shows a triton position spectrum at a spectrograph angle of 25°. The triton peaks were fitted with Gaussian functions to determine peak centroids and yields. The background was assumed to be either constant or a low order polynomial function depending on the quality of fit. For the energy calibration, polynomial least-squares fits of momentum vs. centroid channel were determined using well defined ^{31}S calibration peaks at each angle. The fits were then used to determine all ^{31}S excited states on the focal plane at each angle which were then averaged to obtain a final value for each observed excited state. The energies obtained in the present work seem to be in good agreement with recent measurements such as the study performed by Parikh et al. [3]. Results from triton angular distributions are still pending and therefore currently, there are no firm spin-parity assignments concluded from the present study.

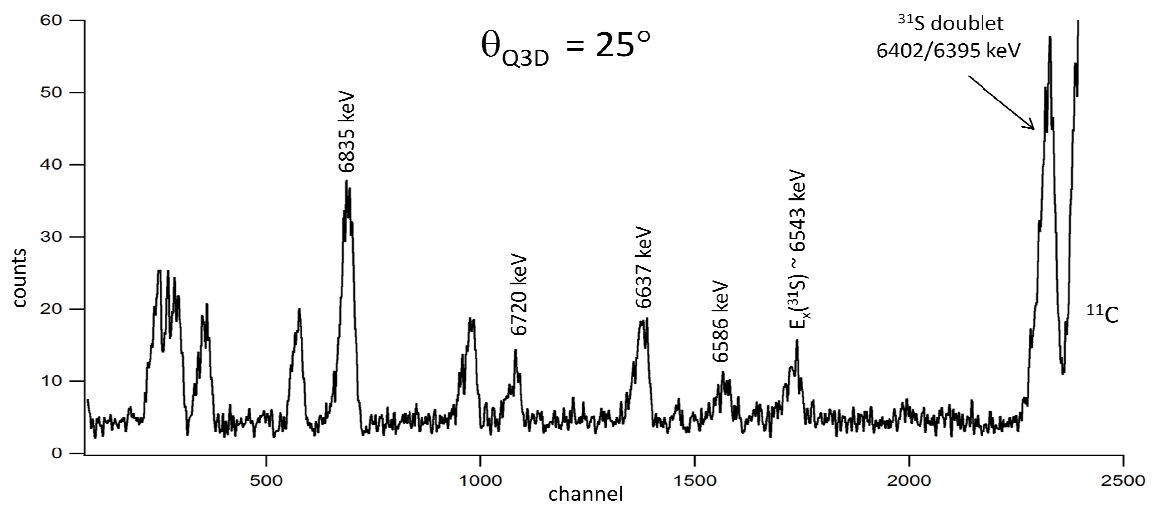

Figure 1. Triton position spectrum at a spectrograph angle of 25° obtained in the present work. Peaks correspond to excited states in ^{31}S. Energies listed are taken from [3].

4. Discussion

Based on further level structure constraints yet to be determined in the present work for ^{31}S resonant states up to 600 keV above the proton threshold for the ^{30}P(p,γ)^{31}S reaction, a new reaction rate can be calculated. The rate will be determined using a similar method as outlined in [3] and will further constrain the rate, reducing the current uncertainty. The rate can then be used as input to current hydrodynamic nova models which estimate quantities such as isotopic abundance ratios present in the ejecta and compared to abundances found in physical samples such as presolar grains. If an agreement is seen, this could suggest a clear picture of nova nucleosynthesis and provide a sufficient identification method for future grains. However, if an agreement is not observed, this could suggest the necessity to constrain other variables in the model or look at other sources of the grains. Another option is to consider determining the resonance-strength ($\omega\gamma$) directly by looking at the ^{30}P(p,γ)^{31}S reaction in the lab. The results of this study could further stress the importance of a radioactive ^{30}P beam (currently in development at more than one facility) with an intensity great enough for analysis (>10^6 pps [3]).

5. Acknowlegements

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