Unbound States of ^{32}Cl Relevant for Novae

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The ^{31}S(p,γ)^{32}Cl proton–capture reaction is expected to be the dominant breakout pathway of the SiP cycle, which is important for understanding nucleosynthesis in some novae [1]. At novae temperatures, the ^{31}S(p,γ)^{32}Cl reaction rate is dominated by ^{31}S+p resonances. Discrepancies in the ^{32}Cl resonance energies were reported in previous measurements [1, 2]. We used the ^{32}S(^{3}He,t)^{32}Cl charge–exchange reaction to produce unbound states in ^{32}Cl and determine their excitation energies by detecting tritons at the focal plane of the Enge Spectrograph at the Yale University's Wright Nuclear Structure Laboratory. Proton branching ratios were determined by detecting the decay protons coming from the residual ^{32}Cl states using a silicon array in the spectrometer's target chamber. The improved energy values of excited levels in ^{32}Cl and measurements of the proton-branching ratios should significantly improve our understanding of the ^{31}S(p,γ)^{32}Cl reaction rate.

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1. Motivation

A nova is a star in a binary system that undergoes a sudden brightening caused by explosive burning of hydrogen accreted onto the surface of a white dwarf from its companion star. A sequence of thermonuclear reactions produces an increase in luminosity followed by the ejection of matter from the white dwarf. The time scales of explosive hydrogen burning processes are influenced by the duration of reaction cycles closed by (p,α) reactions, with breakout via (p,γ) reactions competing with β-decays. In the SiP cycle the ^{31}S(p,γ)^{32}Cl reaction is believed to be the dominant breakout reaction [1]. The SiP cycle is necessary to understand observations of novae like Nova Her 1991 that appear to show that sulfur is highly overabundant compared to solar values [3, 4]

At novae temperatures the rate of the ^{31}S(p,γ)^{32}Cl reaction is dominated by resonances. Previous measurements of ^{32}Cl excitation energies near the threshold of the ^{31}S(p,γ)^{32}Cl reaction disagree at the 2 sigma level [1, 2]. To help resolve this discrepancy, we have studied the proton–unbound states in ^{32}Cl to measure precisely their excitation energies and proton–branching ratios.

2. Experimental Setup

The excited states in ^{32}Cl were populated by the charge-exchange reaction ^{32}S(^{3}He,t)^{32}Cl.
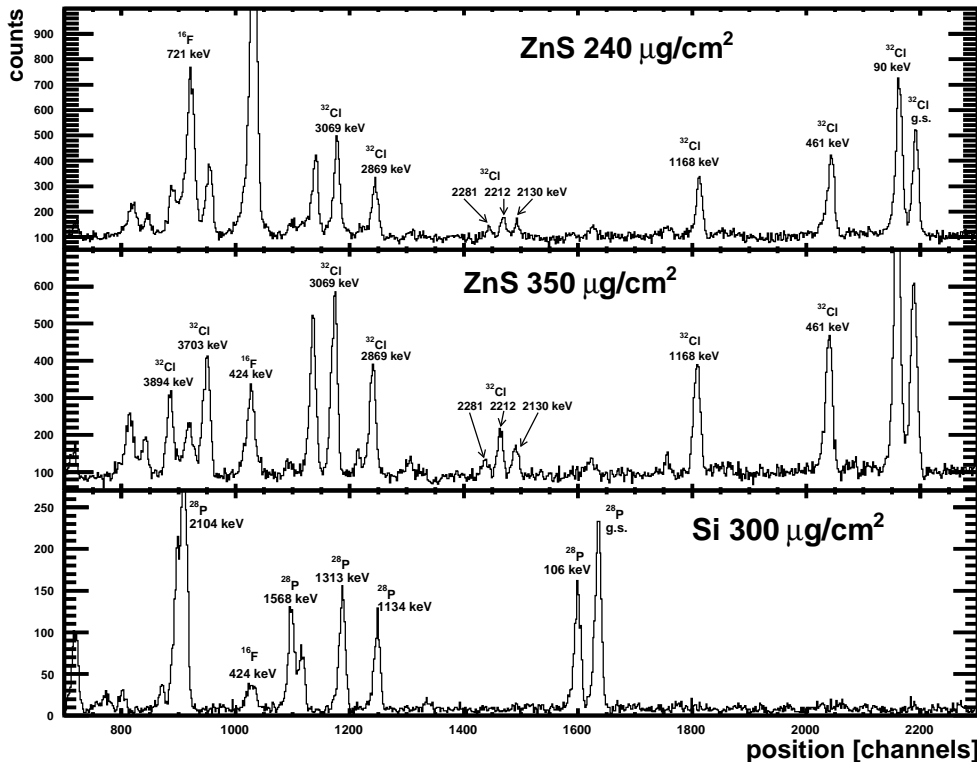

Figure 1: Spectra showing position of tritons at the focal plane measured by the gas chamber with the Enge spectrograph set at 3 degrees. Three spectra show results from measurements with three targets, 350 μg/cm^2 ZnS, 240 μg/cm^2 ZnS and a 300 μg/cm^2 Si target. Peaks can be identified as levels in ^{32}Cl, ^{28}P together with ^{16}F coming from oxygen contamination in the target.

A 30 MeV ^{3}He^{2+} beam was provided by the Van de Graaf accelerator at the Wright Nuclear Structure Laboratory at Yale University and was used to bombard ZnS targets produced via evaporation at Oak Ridge National Laboratory. Targets with two thicknesses, 240 μg/cm^2 and 350 μg/cm^2 on 5 μg/cm^2 C backings were used in the experiment. The thickness was measured by the energy loss of alpha particles from a ^{241}Am source. A 300 μg/cm^2 Si target was also employed for calibration purposes. The Enge split–pole spectrograph was used to determine the energy of the reaction products. The spectrograph separates particles according to their magnetic rigidities Bρ so that the position at the focal plane corresponds to momentum. Position at the focal plane was determined by the gas–filled, position–sensitive ionization drift chamber. As the ions pass through the gas, the cathode determines the energy losses (ΔE) in the detector. The residual energy (E) has been measured by a thick plastic scintillator that is located behind the ionization chamber. The reaction was measured at laboratory angles of 3°, 5°, 10° and 20°. For the setting with the 3° angle the protons emitted from excited states in ^{32}Cl were detected by Yale Lamp Shade Array (YLSA) [5] consisting of four 16-strip silicon detectors arranged in a lamp-shade configuration positioned to cover backward angles.

3. Analysis

The reaction products were identified in E vs. ΔE 2–dimensional spectra from the gas chamber and the scintillator. With the E-ΔE gates applied, the peaks in the focal–plane position spectra corresponding to excited levels in the residual nuclei were identified, see Fig. 1. An energy resolution for the tritons of 40 keV (FWHM) was achieved. Centroids were obtained by fitting a Gaussian function to each peak.

A relation between magnetic rigidity and a position at the focal plane was calibrated using known states populated in the ^{28}Si(^{3}He,t)^{28}P reaction, the 424 keV ^{16}F state populated from oxygen
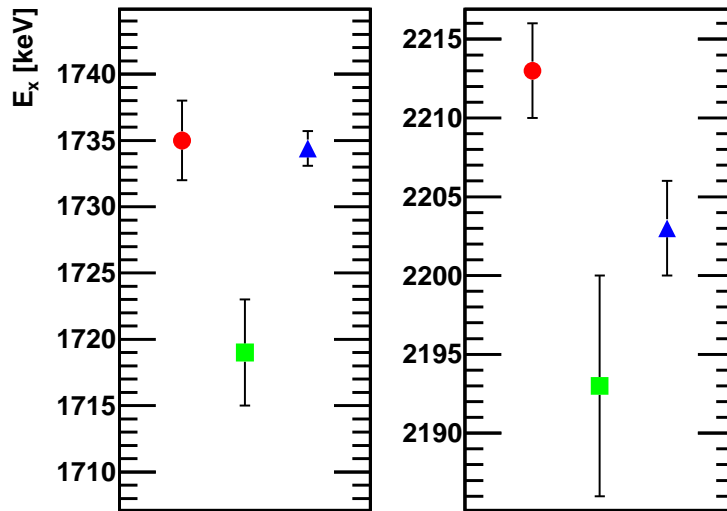

Figure 2: A comparison of level energies in ^{32}Cl relevant for novae measured by [1] (red circles) and [2] (green squares) with preliminary results of this measurement (blue triangles), from left to right. Only statistical uncertainties are shown.

contaminants in the target, and the ground and 90 keV first-excited state in ^{32}Cl. Small corrections were made for the energy loss of the 30 MeV ^{3}He and recoiling tritons in the target using the energy loss code STOPIT [7]. The energies of the recoiling tritons were calculated from the reaction kinematics with the newest atomic mass values implemented [8, 9], including new values of ^{28}P and ^{32}Cl obtained recently [10]. In particular, a correct mass value for ^{28}P, ME = –7147.5(1.2) keV, was crucial for this analysis as it has corrected the previous value of ME = –7159(3) [8]. Our analyses are consistent only with the new mass values. The relation between the magnetic rigidity and focal–plane position for all angles was fitted with a 4th–order polynomial function through all reference peaks, the calibration was used to obtain new excitation energies for levels of interest. The proton branching ratios were determined by comparing the number of counts in a given triton peak with the number in coincidence with a decay proton detected by YLSA, and correcting for detection efficiency as determined from the Monte Carlo code. [5].

4. Results

Preliminary results of the excitation energy determination for two states relevant for novae are shown in Fig. 2, compared with the previous measurements [1] and [2]. We also discovered an excited state of ^{32}Cl at 2610 keV, see Fig. 3. that was not observed before. A state was predicted to exist based on the mirror nucleus ^{32}P and estimated to be at 2574(50) keV using the IMME equation [6], in good agreement with our result. While this state is too high in excitation energy to be important at novae temperatures, it may make a significant contribution to the reaction rate at X-ray burst temperatures.
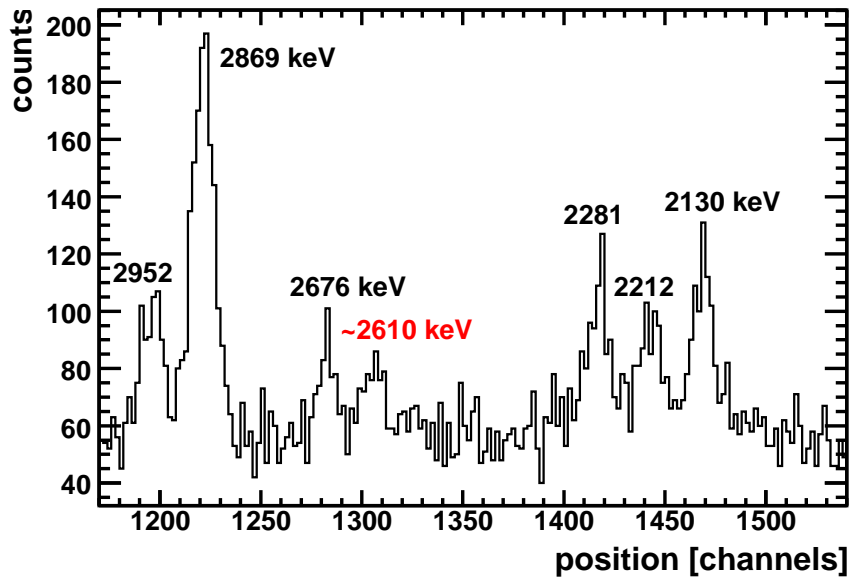

Figure 3: Position spectrum at 10 degrees showing the newly discovered ∼2610 keV state.

Proton–branching ratios were determined for all observed states with E$_x$>2 MeV. A preliminary analysis assuming an isotropic distribution for the emitted protons indicates that states with

E_x>3 MeV decay via proton emission nearly 100% of the time. However, angular distributions for some states are not consistent with isotropy. While the analysis is still in progress, we expect to determine branching ratios to better than 10% uncertainty for most states.

5. Conclusions

We have determined improved values for resonance energies in the ^{31}S(p,γ)^{32}Cl reaction and determined proton branching ratios for the most important resonances. The resonance reaction rate is proportional to the resonance strength, which in turn is defined by the product of proton branching ratio and the gamma partial width. The only significant factors entering into the reaction rate that are not now directly determined experimentally are the gamma widths of states and the proton branching ratio of the lowest energy resonance. The gamma width can be estimated from lifetime measurements in the mirror nucleus for most states. Unfortunately, only upper limits currently constrain the lifetime of the most important 1^+ state, corresponding to a lower limit on the gamma width. We are currently using the results of our measurement with theoretical guidance to arrive at an improved value for the reaction rate and its uncertainty. The overall uncertainty of the ^{31}S(p,γ)^{32}Cl reaction rate has been significantly reduced, with the largest contribution coming from the uncertain gamma widths of some resonances. To better constrain the reaction rates an additional direct measurement is required, such as a measurement of Γ_γ at Munich [11].

References

[1] S. Vouzoukas et al., Phys. Rev. C **50**, (1994) 1185.

[2] C. Jeanperrin et al., Nucl. Phys. **A503** (1989) 77.

[3] R. E. Williams, et al., Astrophys. J. Suppl. Ser. **90** (1994) 297.

[4] T. Matheson, et al., Astrophys. J. **418** (1994) L29.

[5] D.W. Visser, PhD Thesis, Yale University (2003).

[6] Ch. Iliadis et al., Astrophys. J. **524** (1999) 434.

[7] K. Braune, et al. Proceedings of the Spring Meeting of the German Phys. Soc., Verhandlugen 4/1978
     K. Braune, Diplom, Heidelberg 1979

[8] G. Audi et al., Nucl. Phys. **A729** (2003) 3.

[9] www.nuclearmasses.org

[10] C. Wrede et al., Phys. Rev. C **81**, (2010) 055503.

[11] S. Bishop, priv. comm. 2010.