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First spin-parity constraint of the 306 keV resonance in ^{35}Cl for nova nucleosynthesis

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Of particular interest in astrophysics is the ^{34}S$(p,\gamma)^{35}$Cl reaction, which serves as a stepping stone in thermonuclear runaway reaction chains during a nova explosion. Though the isotopes involved are all stable, the reaction rate of this significant step is not well known, due to a lack of experimental spectroscopic information on states within the Gamow window above the proton separation threshold of ^{35}Cl. Measurements of level spins and parities provide input for the calculation of resonance strengths, which ultimately determine the astrophysical reaction rate of the ^{34}S$(p,\gamma)^{35}$Cl proton capture reaction. By performing the ^{37}Cl$(p,t)^{35}$Cl reaction in normal kinematics at the Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory, we have conducted a study of the region of astrophysical interest in ^{35}Cl, and have made the first-ever constraint on the spin and parity assignment for a level at 6677 ± 15 keV ($E_r = 306$ keV), inside the Gamow window for novae.

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I. ASTROPHYSICAL MOTIVATION

The ^{34}S$(p,\gamma)^{35}$Cl reaction serves as a step in a larger reaction network which fuels the thermonuclear runaway of nova explosions. In a reaction network sensitivity study of novae [1], Iliadis *et al.* indicate that the cross section of the ^{34}S$(p,\gamma)^{35}$Cl reaction could be unknown to several orders of magnitude in the critical temperature range, and that these uncertainties correspond to large variations in the final abundances of several heavier elements. For a variation in rate of a factor of ±100, the final abundances of several key nuclei, including ^{34}S, ^{35}Cl, and ^{37}Ar, were found to vary by as much as 10–100 times. This magnitude of rate variation was a reasonable assumption, since the rate used in the sensitivity study is the result of a theoretical statistical model with no experimental input. Some presolar grains are known to condense in the ashes of novae [2,3], making observed isotopic ratios into "thermometers" of the explosion; for masses above A ∼ 20, these ratios are influenced by potential reaction cycles within the nucleosynthesis flow at various nuclei including ^{35}Cl, and chlorine abundances are strongly correlated with peak nova temperature [3]. In addition, any low-spin resonances within the Gamow window for ^{34}S$(p,\gamma)^{35}$Cl, if found, could improve our understanding of the limitations of statistical rate models in this mass region. In all these cases, reliable nuclear physics data are needed as input.

Previous studies of the ^{34}S(p,γ) reaction [4–10] have mostly focused on energies 1–3 MeV above the proton threshold at 6370.6 keV [11], higher in energy than is relevant to most astrophysical scenarios including novae. One direct measurement [10] was able to determine the strength of a resonance of unknown spin-parity in ^{34}S + p around $E_r = 500$ keV; but direct measurements at lower energies will become increasingly difficult, with cross sections dropping by orders of magnitude as the Gamow window is approached. Indirect studies can therefore play an important role in providing information relevant to astrophysical reaction rates of interest. Though studies of the mirror nucleus ^{35}Ar, with a half-life of under two seconds, have been undertaken (see, for example, Ref. [12]), level assignments within the region of interest based on mirror arguments are lacking, and many structure studies (see Ref. [13]) have been effectively limited to bound states by requiring high-statistics detection of γ cascades for structure information. Reaction studies which did probe this energy region included ^{37}Cl$(p,t)^{35}$Cl [14] and ^{32}S$(\alpha,p)^{35}$Cl [15]; the former suffered from background and resolution issues, while the latter, utilizing a broad-range magnetic spectrograph, measured a high-resolution level scheme but could not provide spin and parity information.

The result is a significant gap in the knowledge of the structure of ^{35}Cl around the proton threshold, in the $E_x \approx$ 6–7 MeV

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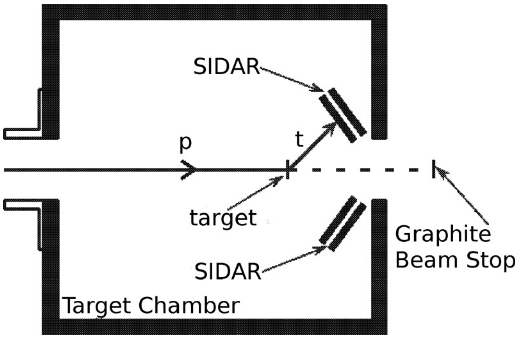

FIG. 1. Experimental setup for the (p,t) experiment, not to scale. Not shown is the large aluminum plate upstream of the detectors, which was roughly centered in the target chamber.

range. Any $\ell = 0$ s-wave resonances within this region have the potential to greatly alter the $^{34}\mathrm{S}(p,\gamma)^{35}\mathrm{Cl}$ reaction rate in novae, thus altering the expected final abundances of specific nuclei within the novae ejecta.

II. EXPERIMENT

To better understand the astrophysical $^{34}\mathrm{S}(p,\gamma)^{35}\mathrm{Cl}$ reaction rate, a study of the $^{37}\mathrm{Cl}(p,t)^{35}\mathrm{Cl}$ reaction was undertaken at the Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory. The (p,t) reaction has been used for years as a probe of nuclear structure, because of the relative ease of beam production, low background, high efficiency, and good energy and angular resolution. A beam of ~0.5 pnA, 30 MeV protons was impinged upon each of two chloride targets. The first target was ~600 μg $\mathrm{PbCl_2}$, enriched in $^{37}\mathrm{Cl}$ to roughly 95%, on a 20 $\mu\mathrm{g/cm^2}$ parylene ($\mathrm{C_8H_8}$) backing, which provided roughly 160 $\mu\mathrm{g/cm^2}$ $^{37}\mathrm{Cl}$. For background measurements, a natural chlorine target was also fabricated, which was ~415 $\mu\mathrm{g/cm^2}$ $\mathrm{PbCl_2}$ (~110 $\mu\mathrm{g/cm^2}$ $^{\mathrm{nat}}\mathrm{Cl}$) on a 10 $\mu\mathrm{g/cm^2}$ parylene backing (natural chlorine contains ~24% $^{37}\mathrm{Cl}$). The choice of lead chloride was to facilitate fabrication, as zinc chloride is highly hygroscopic, silver chloride (used in Ref. [14]) cannot be exposed to light, and lighter salts (such as NaCl or $\mathrm{MgCl_2}$) are difficult to form into functional target foils.

To detect the tritons from the $^{37}\mathrm{Cl}(p,t)^{35}\mathrm{Cl}$ reaction, the annular silicon detector array (SIDAR) [16] was used in "lamp-shade" mode, covering laboratory angles of ~18°–50° (~19°–53° in the center of mass for the $^{35}\mathrm{Cl}$ ground state) with ΔE-E telescopes (100 and 1000 μm thickness, respectively, for ΔE and E). The basic setup is demonstrated in Fig. 1. A thick aluminum plate with a small collimating hole was mounted just upstream of the target ladder, protecting the detectors from any scattered beam and aiding in providing a centered, localized beam spot. As a diagnostic, beam current was periodically read out from a picoammeter connected to a graphite beam stop located downstream of the target chamber, with no line of sight to the SIDAR silicon detectors, but this current value was not recorded in the data. This experimental configuration is similar to other (p,t) reaction studies at the facility [17–20], but was optimized to examine the region of astrophysical interest in $^{35}\mathrm{Cl}$. The detectors were calibrated with an α source of known intensity to determine energy response and geometric efficiency, and the subsequent excitation energy spectra were adjusted to account for energy loss in the target foils and detector dead layers. This secondary calibration utilized a linear fit of four known peaks from the $^{\mathrm{nat}}\mathrm{Cl}$ target data: the ground state of $^{35}\mathrm{Cl}$, and the ground state, first excited state, and 2.975 MeV state in $^{33}\mathrm{Cl}$ [13] (goodness of linear fit parameter $R^2 = 0.99999$). This secondary calibration was applied to the data from both the natural and enriched chlorine targets. Substituting the $^{35}\mathrm{Cl}$ ground-state peak position from the enriched target data in the calibration instead of the position from the natural target resulted in a shift of less than 1 keV at 6 MeV excitation energy. The energy resolution was on the order of 0.4%, or ~60–100 keV depending on angle.

III. ANALYSIS AND RESULTS

Triton spectra from both the natural and enriched targets are overlaid in Fig. 2. In the triton spectra from the $^{37}\mathrm{Cl}$-enriched target, a peak located inside of the anticipated Gamow window (for 0.2 to 0.4 GK novae), was observed in most of the SIDAR strips. Combining results from each SIDAR strip (angle) for which the peak was reliably populated resulted in an excitation energy of $E_x = 6677 \pm 15$ keV (resonance energy $E_r = 306$ keV; see bottom panel of Fig. 2). Due to differences in Q value, no levels in $^{33}\mathrm{Cl}$ from the contaminant $^{35}\mathrm{Cl}(p,t)^{33}\mathrm{Cl}$ reaction overlap the astrophysically relevant region in $^{35}\mathrm{Cl}$, as is apparent in Fig. 2. Similarly, large differences in kinematics rule out background peaks in the region around the $^{34}\mathrm{S} + p$ Gamow window from the $^{208}\mathrm{Pb}$ in the target (which produces a smooth background continuum), as well as other possible contaminants such as carbon or oxygen.

The location of a doublet at $(6656.0 \pm 3.1) + (6680.8 \pm 3.1)$ keV, as measured by Ref. [15], falls approximately 300 keV above the proton threshold in $^{35}\mathrm{Cl}$. This places the doublet at a crucial energy, within the Gamow window for $^{34}\mathrm{S} + p$ in novae, and makes the spin and parity assignments of these individual levels integral to the knowledge of the astrophysical rate of $^{34}\mathrm{S}$ proton capture, particularly since sensitivity studies to date [1] have used only statistical cross sections. The peak observed in the current work at $E_x = 6677 \pm 15$ keV, as shown in the bottom panel of Fig. 2, falls directly in the expected Gamow window, where this doublet is expected. A more recent measurement [21] observed the gamma decay of a level at 6660 keV which they assigned as $\frac{11}{2}^-$; they did not see evidence of a doublet. In the current work, the systematic population of higher E_x than would be expected for the 6656 keV level indicates we likely do not see this member of the doublet, as demonstrated in Fig. 3.

To make a spin-parity assignment, the peak observed inside the Gamow window, at $E_x = 6677 \pm 15$ keV, was analyzed using the distorted-wave Born approximation (DWBA) formalism with TWOFNR [22]. The global optical model parameters of Koning-Delaroche [23] and Pang [24] for the incoming and outgoing channels, respectively, were used, because these provided a good fit to the known $\frac{3}{2}^+$ $^{35}\mathrm{Cl}$ ground-state angular

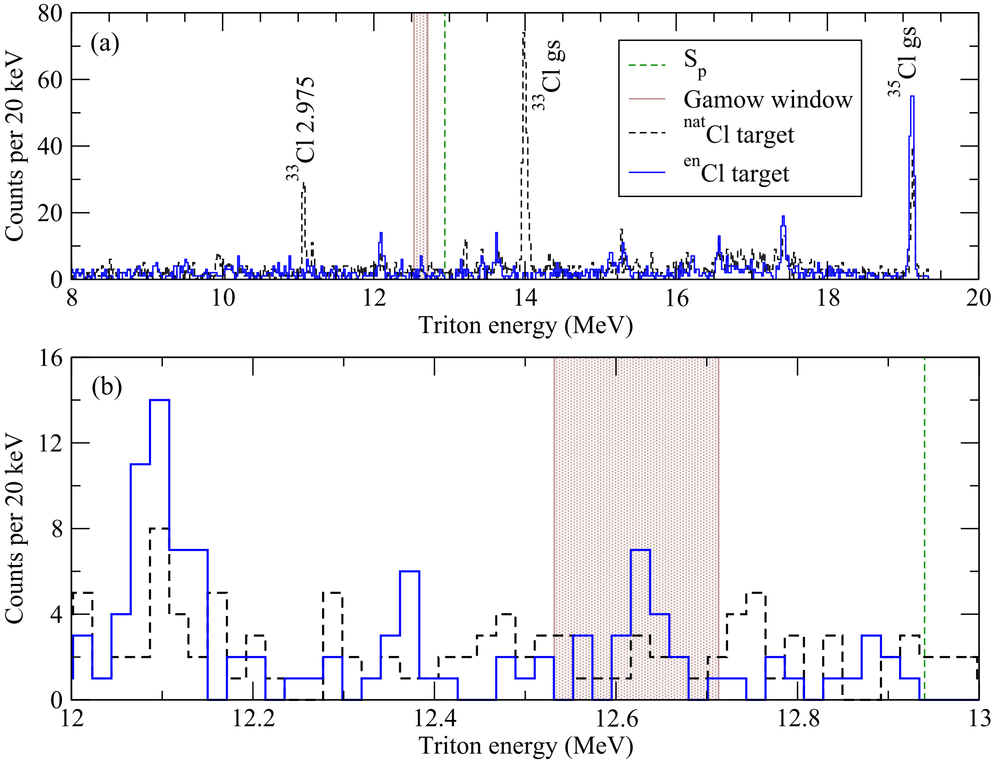

FIG. 2. Triton energy spectrum (for $\theta_{\mathrm{lab}} \sim 22^\circ$ in one SIDAR telescope) for both a natural chlorine target (black dashed) and enriched chlorine (^{37}Cl) target (blue solid), showing the locations of select ^{33,35}Cl levels, the proton separation energy in ^{35}Cl (green dashed line), and the Gamow window for ^{34}S$(p,\gamma)^{35}$Cl in novae (brown hatching). The relative normalization of the spectra is arbitrary and was chosen to enable qualitative comparisons. (a) Full triton energy spectrum; (b) same spectra zoomed into the area around the Gamow window for ^{34}S$(p,\gamma)^{35}$Cl in novae. The peak inside the Gamow window has an energy of $E_x = 6677 \pm 15$ keV.

distribution, as demonstrated in Fig. 4. The angular distribution and DWBA calculations for the 6677 keV level are shown in Fig. 5. DWBA calculations are shown normalized to the data in both Figs. 4 and 5 because no absolute cross-section normalization was available. Because ^{37}Cl is an odd-even nucleus with a ground-state spin and parity of $\frac{3}{2}^+$, the angular momentum of the final state is not usually unique for a given L transfer, as is the case for spin-zero targets [19,20,25]. While (p,t) will tend to populate neutron-hole states, midshell nuclei exhibit significant wave-function mixing, such that the strength of particle (such as proton, as is of interest for ^{34}S + p) or hole states is shared across many levels which may be observed. Indeed, the (p,t) reaction in this mass range has already been successfully used to populate levels of interest to proton

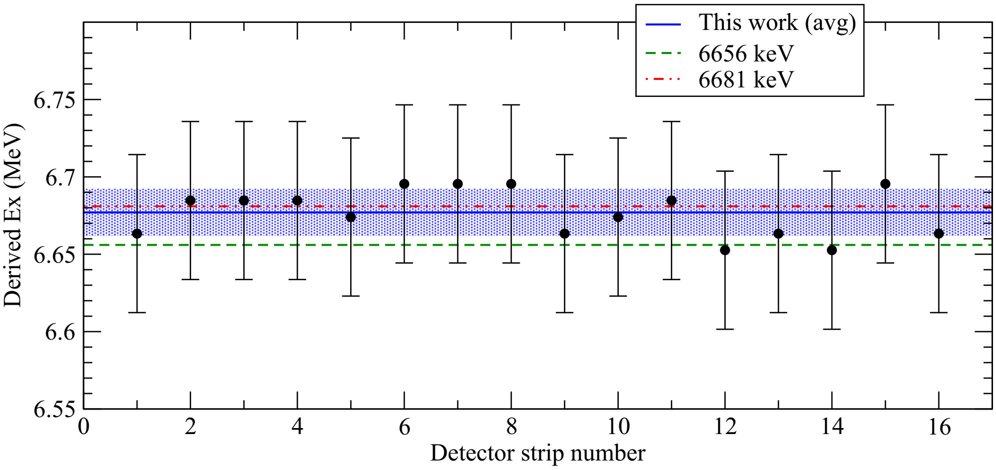

FIG. 3. Extracted excitation energy for the peak within the Gamow window as a function of detector strip (larger strip numbers correspond to larger laboratory angles). The uncertainties shown for the data are the experimental resolution. The blue band represents the standard deviation of the data.

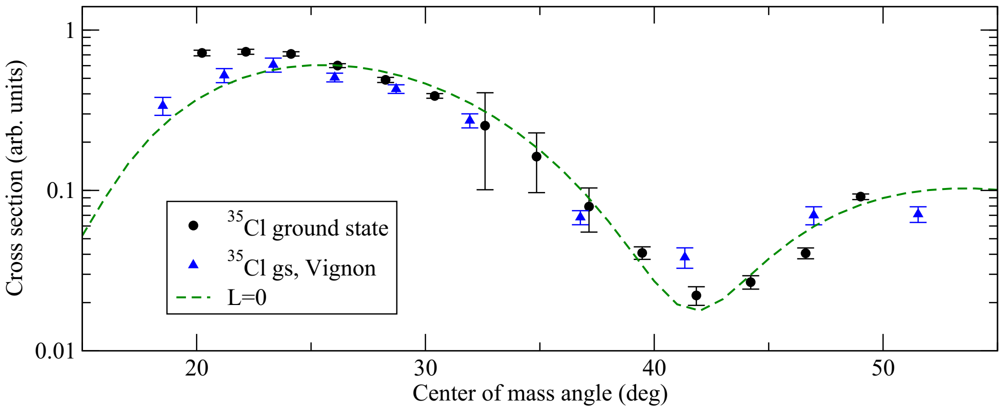

FIG. 4. Angular distribution (black circles) and DWBA calculation (green dash) for the known $\frac{3}{2}^+$ ^{35}Cl ground state. A previous study of this level with a 40 MeV proton beam [14] assigned an L-transfer value of zero, consistent with the current results. The digitized Vignon data [14] are shown (blue triangles) for comparison; the divergence at small angles is likely due to a small $L = 2$ admixture which is more evident at the lower beam energy.

capture in the case of ^{26}Si [20]. Each angular distribution was compared to the different DWBA predictions, and a χ^2 minimization was performed to determine the best fit of each DWBA curve to the measured data. Because absolute normalization to get spectroscopic factors is not always robust for multinucleon transfer such as (p,t), we do not here adopt the single-nucleon transfer technique of normalizing to the peak of the distribution, as is necessary to extract spectroscopic factors. The L-transfer assignments for (p,t) to the 6677 keV angular distribution in this work are, based on goodness of fit, $L = 2$, $\chi^2 = 25.5$; $L = 0$, $\chi^2 = 43.6$; $L = 1$, $\chi^2 = 57.6$; and $L = 3$, $\chi^2 = 65.1$. A transfer of $L = 5$ would be required to populate the $\frac{11}{2}^-$, 6656 keV member of the doublet, but this angular distribution peaks at $\theta_{\mathrm{c.m.}} \sim 50^\circ$, inconsistent with the measured distribution. While additional statistics and coverage of a larger angular range would allow a stronger assignment, we adopt an assignment of $L = 2$, which results in possible J^π assignments of $(\frac{1}{2}^+, \frac{3}{2}^+, \frac{5}{2}^+, \frac{7}{2}^+)$. Combinations of angular momentum transfer, such as $L = 0 + 2$ or $L = 1 + 3$, are possible, but would not alter the conclusion regarding possible spin and parity assignments. Because $L = 2$ and $L = 0$ are better fits than $L = 1$ and $L = 3$, a positive parity assignment for the 6677 keV level is strong, and if $J^\pi = \frac{1}{2}^+$, only $L = 2$ is possible. If this peak does indeed indicate the presence of a $\frac{1}{2}^+$ level (an $\ell = 0$ resonance) in ^{35}Cl right inside the Gamow window for $^{34}\mathrm{S} + p$ in novae, then it has the potential to greatly influence the astrophysical $^{34}\mathrm{S}(p,\gamma)^{35}\mathrm{Cl}$ reaction rate.

IV. CONCLUSION

The data in this work indicate that a possible s-wave resonance in the Gamow window for the $^{34}\mathrm{S}(p,\gamma)^{35}\mathrm{Cl}$ reaction in novae exists at $E_x = 6677 \pm 15$ keV in ^{35}Cl, ~300 keV above the proton threshold. This peak is likely associated with the higher excitation energy level of the previously

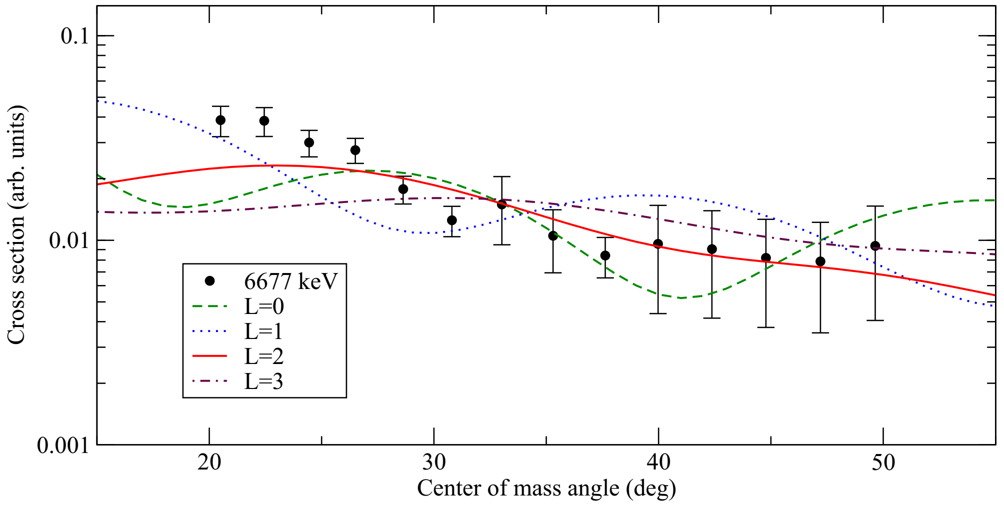

FIG. 5. Angular distribution (black circles) and DWBA calculations ($L = 0$, green dashed; $L = 1$, blue dotted; $L = 2$, red solid; $L = 3$, purple dot-dashed) for the peak falling inside the Gamow window, at 6677 ± 15 keV. The y-axis scale is the same as in Fig. 4. The $L = 2$ curve has the lowest χ^2 value.

described doublet at 6656.0 + 6680.8 keV [15]. The peak at 6677 ± 15 keV, based on the current work, is most likely of positive parity, with a spin assignment of $(\frac{1}{2},\frac{3}{2},\frac{5}{2},\frac{7}{2})$. Further study, including indirect measurements to identify potential resonances as well as direct measurements of the proton capture cross section centered around $E_r = 300$ keV, is needed to determine if the astrophysical $^{34}\mathrm{S}(p,\gamma)^{35}\mathrm{Cl}$ reaction rate will require substantial alteration due to previously unexpected $\ell = 0$ resonances in ^{35}Cl.

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