Spectroscopic Study of ^{39}Ca for Endpoint Nucleosynthesis in Classical Novae

J Liang[1], A A Chen[1], M Anger[3], S Bishop[3], T Faestermann[3], C Fry[2], R Hertenberger[4], A Psaltis[1], D Seiler[3], P Tiwari[2], H-F Wirth[4], C Wrede[2]

[1] Department of Physics and Astronomy, McMaster University, Hamilton, Ontario, L8S 4M1, Canada

[2] Department of Physics and Astronomy, National Superconducting Cyclotron Laboratory, Michigan State University, 640 S. Shaw Ln., East Lansing, MI, 48864, USA

[3] Department of Physics, Technical University Munich, James-Franck-Str. 1, 685748, Garching, Germany

[4] Faculty of Physics, Ludwig-Maximilians-Universität München, Munich, Geschwister-Scholl-Platz 1, 80539 Munich, Germany

E-mail: LiangJ27@mcmaster.ca

Abstract. Classical novae are environments which can produce heavier elements up to mass A $\sim$ 40. These nuclides at the endpoint of nova nucleosynthesis consist of elements such as Ar, K, and Ca. There is an order of magnitude discrepancy with the predicted and theoretical abundances of these endpoint nuclides produced in a classical nova. The uncertainty in the theoretical ^{38}K(p,γ)^{39}Ca reaction rate has been shown to affect the abundances by an order of magnitude or more. The only direct measurement of this reaction rate was performed with the DRAGON facility at TRIUMF; however additional spectroscopic data could aid the interpretation of this data as well as motivate further study of this reaction rate. In this study, we present the preliminary results of a spectroscopic study of ^{39}Ca using the ^{40}Ca(d,t)^{39}Ca reaction carried out at the Maier-Leibnitz Laboratory in Garching, Germany.

1. Introduction

Classical novae occur in interacting binaries consisting of a white dwarf (WD) and a red dwarf/main sequence star that fills its Roche lobe. This mass transfer from the companion star leads to an accretion disk on the white dwarf, and the material is compressed and the bottom layer will become degenerate. Hydrogen burning via the CNO cycle on this degenerate layer will result in thermonuclear runaway, which ultimately leads to an explosive outburst. Temperatures can reach between 0.1 - 0.4 GK (depending on the size and rate of accretion), and the outburst can eject up to 10^{-4} - 10^{-5} $M_{\odot}$. [1]

Spectroscopic Study of ^{39}Ca for Endpoint Nucleosynthesis in Classical Novae

In this process, heavier nuclides are produced through (p,γ), (p,α), and β^- decays, with the endpoint of this nucleosynthesis occurring near A $\sim$ 40.

Currently, observations of classical novae predict an order of magnitude enhancement of endpoint elements, such as Ar, K, and Ca, relative to solar abundances; however, simulations predict abundances closer to that of solar abundances [1, 2].

Sensitivity studies examining the effect of reaction rates on the abundances of these elements have shown that the reaction ^{38}K(p,γ)^{39}Ca can change the abundances of endpoint nuclides by an order of magnitude or more [3]. In temperatures characteristic of this environment, this reaction rate is dominated by ℓ=0 resonances within the Gamow window. These were previously identified as excited states in ^{39}Ca at 6157(10), 6286(10), and 6460(10) keV. This reaction rate was directly measured with the DRAGON facility in TRIUMF, where the highest resonance was instead observed at a lower energy of $6450\pm^{+2}_{-1}$(stat.) ±1(sys.), keV and the other 2 resonances were unobserved, setting upper limits for their respective resonance strengths [4].

High resolution spectroscopic studies of ^{39}Ca could provide more information on the various resonances that lie in the Gamow window, and illuminate additional undiscovered states corresponding to low-ℓ capture resonances. To that end, we have conducted a spectroscopic study of ^{39}Ca using the ^{40}Ca(d,t)^{39}Ca reaction to populate excited states in ^{39}Ca relevant to astrophysics.

2. Experiment

The experiment was carried out at the Maier-Leibnitz Laboratory (MLL). The ^{2}H beam was accelerated to an energy of 22 MeV using the 14-MV MP-Tandem, which impinged the production target: a 40 μg/cm^2 CaF_2 on a isotopically pure ^{12}C target. The tritons from the reaction were momentum analyzed using the Quadrupole-Dipole-Dipole-Dipole (Q3D) spectrograph. The position data for the tritons was taken using a position sensitive focal plane detector consisting of 255 electrically isolated cathode strips arranged opposite to an anode wire in an isobutane gas filled chamber. When a triton passed through the gas, it deposited energy via ionization of the surrounding gas, inducing a charge on the cathode strips closest to the triton event. By observing the amount of charge on specific cathode strips, the position of the triton could be deduced.

The focal plane was then calibrated using the position spectrum of a ^{32}S target, since the excitation energies of ^{31}S populated by the ^{32}S(d,t)^{31}S are known, therefore allowing us to convert the positions of the tritons to the triton energies (and by conservation of energy the residual nucleus energies).

3. Analysis and Results

Peaks corresponding to energy levels in ^{39}Ca were fitted using a Gaussian function modified with an exponential. This combined function produces an asymmetric Gaussian that accounts for the asymmetry from the low energy tail of tritons. The triton

Journal of Physics: Conference Series **1668** (2020) 012025 doi:10.1088/1742-6596/1668/1/012025

Table 1. Preliminary important astrophysical resonance energies and new state of ^{39}Ca determined in the current work compared to previously evaluated values. New state at 6446 keV in bold.

NDS evaluated energy (keV)	This work (keV) (±) stat
6451 (2)	6474(1)
	6446(1)
6286 (10)	6301(1)
6157 (10)	6160.4(6)

spectrum (Figure 1) contains a significant background from the fluorine content in the production target, which produced tritons through the ^{19}F(d,t)^{18}F reaction. However the distribution of tritons was continuous and slowly varying over the focal plane, and could be approximated linearly on local scales underneath the peaks. Thus, a linear function was also added into the fitting function.

The centroids of these asymmetric Gaussian peaks gives information regarding the positions of the tritons on the focal plane, however they must be calibrated in order to find the corresponding energies of the tritons. This is done by using the ^{32}S calibration target to populate known states in ^{31}S. These known states - and therefore the energies of the tritons from those states - are assigned to the peaks on the position spectrum, and a polynomial function is calculated with a Markov chain Monte Carlo [5] fitting to convert the position data to the energies of the triton. From there, using conservation of energy and momentum, the energy of the residual nucleus in the ^{39}Ca spectrum can be found for each respective peak in the triton position spectrum. Preliminary energies and a new state discovered at 6446(1) keV in this work are tabulated in Table 1.

There is a systematic difference of $\sim$ +10 keV when comparing the excitation energies from this work to that of the previous literature values. This difference could be explained by the usage of more current mass measurements: Since this analysis depends heavily on the Q-value of the reaction, the energies determined are extremely sensitive to the masses of each nuclide in the reaction. Between the 2003 and 2012 Atomic Mass Evaluations (2003AME, and 2012AME respectively) [6], the mass excess of ^{39}Ca changed by -8 keV, increasing the Q-value by 8 keV. This effect systematically shifts the resonance energies. When the 2003AME mass table is used in the calculation of the residual energy in the ^{39}Ca nucleus, the weighted averages are within error of tabulated values prior to the DRAGON measurement, as seen in Table 2. No difference was observed when using the 2016AME [7] compared to the 2012AME.

One potential explanation to the DRAGON measurement's anomalous results for the state found at $6450\pm^{+2}_{-1}$(stat.) ±1(sys.) keV is that the new state found in this work at 6446(1) keV is being observed instead. Additional measurements on ^{39}Ca have been performed with the ^{39}K(^{3}He,t)^{39}Ca reaction at the Triangle Universities Nuclear Laboratories (TUNL) and will verify the existence of this new resonance and determine

Table 2. Preliminary resonance energies of ^{39}Ca determined in the current work using 2003AME compared to evaluated values prior to the DRAGON measurement. New state recalculated with 2003AME in bold.

NDS evaluated energy (keV)	This work (keV) (±) stat
6460 (10)	6459.2(6)
	6431(2)
6286 (10)	6289(1)
6157 (10)	6150.7(1)

the spin and parity of this resonance. It will also serve to increase precision on known states.

4. Conclusions

In this work, a spectroscopic study of ^{39}Ca using the ^{40}Ca(d,t)^{39}Ca reaction has shown a new state in ^{39}Ca in the Gamow window. In addition, with more current mass measurements, the resonance energies calculated have changed relative to previous literature values tabulated in ENSDF. Future work at TUNL will be carried out to verify the excited states of ^{39}Ca in the Gamow window. Once verified, a remeasurement of the astrophysically important resonance strengths of the ^{39}Ca(p,γ)^{39}Ca reaction (i.e. reactions populating $5/2^+$ and $7/2^+$ states in ^{39}Ca) is recommended.

Journal of Physics: Conference Series **1668** (2020) 012025 doi:10.1088/1742-6596/1668/1/012025

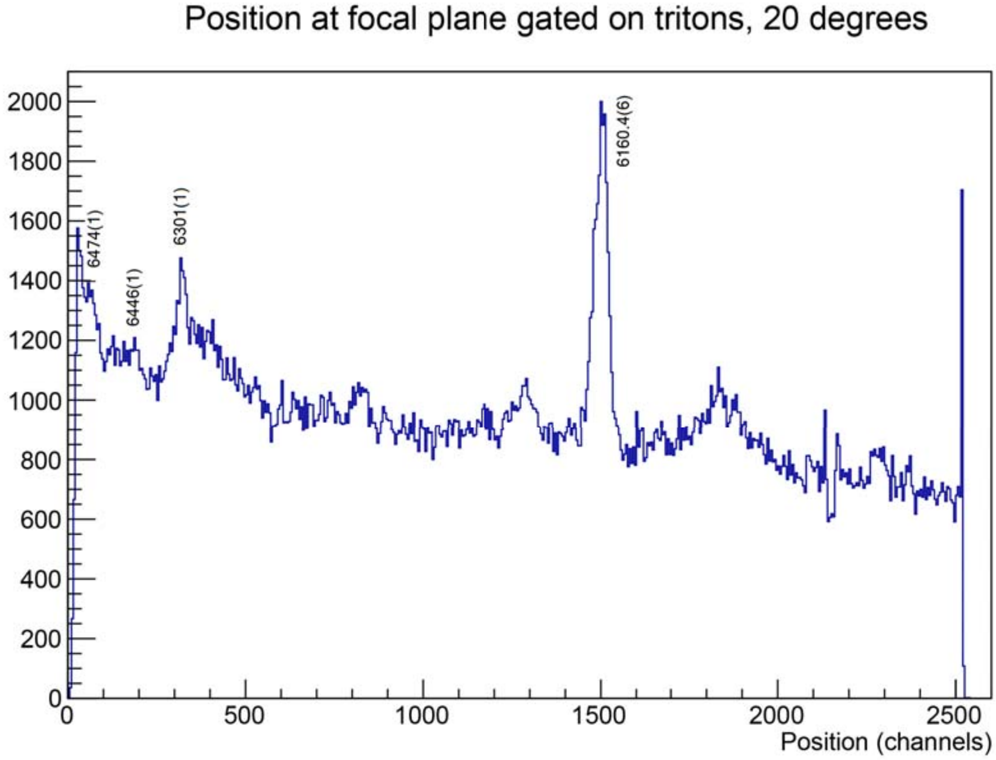

Figure 1. Position spectrum of tritons, spectrometer angle of 20 degrees. Significant number of tritons from ^{19}F(d,t)^{18}F causes locally linear background, however peaks from ^{39}Ca can be easily seen atop the background.

[1] S. Starrfield, C. Iliadis, W.R. Hix, F.X. Timmes, and W.M. Sparks, Astrophys. J. **692**, 1532 (2009).
[2] J. Andrea, H. Dreschsel, and S. Starrfield, Astron. Astrophys. **291**, 869 (1994).
[3] C. Iliadis, A. Champagne, J. Jose, S. Starrfield, and P. Tupper, Astrophys. J. Suppl. Ser. **142**, 105 (2002).
[4] G. Lotay et al. Phys. Rev. Lett. **116**, 132701 (2016).
[5] C. Marshall, et al., IEEE Transactions on Instrumentation and Measurement, vol. 68, no. 2, pp. 533-546, (2019).
[6] G. Audi, A.H. Wapstra, C. Thibault, Nuclear Physics A, Volume 729, Issue 1, 337-676, (2003).
[7] M. Wang et al., Chinese Phys. C **41** 030003, (2017)