PROCEEDINGS OF SCIENCE

Reaction rate of ^{15}O(α,γ)^{19}Ne via indirect measurements

PoS(NIC-IX)023

W. P. Tan[*], J. Görres, J. Daly, M. Beard, M. Couder, A. Couture, S. Falahat[†], L. Lamm, P. J. LeBlanc, H.Y. Lee, S. O'Brien, A. Palumbo, E. Stech, E. Strandberg, and M. Wiescher,
Department of Physics, University of Notre Dame, Notre Dame 46556
E-mail: `wtan@nd.edu`

^{15}O(α,γ) is the critical breakout reaction from the hot CNO cycles, which triggers the thermonuclear runaways or X-ray bursts occurring in accreting neutron stars. Recent studies have shown that this reaction is critical for the burst amplitude and periodicity of X-ray bursters. However, a direct measurement of this reaction rate at astrophysically relevant temperatures is not feasible yet due to the lack of very high intensity radioactive ^{15}O beams. There has been considerable effort in the past to investigate this reaction rate indirectly by obtaining gamma and alpha decay widths of the alpha-unbound states in ^{19}Ne. While this approach has been successful for investigating higher energy resonances, the critical level at 4.03 MeV remains unknown. This leaves the reaction rate largely uncertain since previous attempts have only provided limits on its gamma width and its alpha decay branching ratio. We present new experimental work conducted at the University of Notre Dame. Lifetimes of the 4.03 MeV state and other relevant states in ^{19}Ne have been measured successfully using the ^{17}O(^{3}He,n-γ) reaction. We will also present the results of our recent measurement of the alpha-decay branching ratios. Alpha-unbound states in ^{19}Ne were populated via the reaction ^{19}F(^{3}He,^{3}H-α) and triton-alpha coincidences were observed using a low energy particle detection Silicon array and the TWINSOL facility. The first experimental reaction rate is proposed and its astrophysical implications will be discussed.

International Symposium on Nuclear Astrophysics — Nuclei in the Cosmos — IX
June 25-30 2006
CERN, Geneva, Switzerland

---

[*] Speaker.

[†] Current address: University of Mainz, Institut fuer Kernchemie, Fritz-Strassmann-Weg 2, 55128 Mainz, Germany

1. Introduction

Explosive burnings on the surface of mass-accreting white dwarfs and neutron stars have been observed as novae and X-ray bursts, respectively. Studies have shown that the breakout from hot CNO cycles and the ensuing thermonuclear processes after the breakout play a principal role in energy production and nucleosynthesis in these explosive environments[1]. In particular, the ^{15}O(α,γ) breakout reaction is critical for the explanation of the burst amplitude and periodicity of X-ray bursters[2]. While the direct measurement of this reaction rate is an important goal for radioactive beam facility proposals from ISAC [3] to RIA [4], the presently available ^{15}O beam intensities are clearly not sufficient for a direct measurement [5]. Therefore past studies has focused mainly on the use of indirect techniques to probe the reaction rate. These studies aimed at the measurement of the characteristic nuclear structure features of the ^{19}Ne compound nucleus for the determination of the resonance parameters for the reaction rate [6, 7, 8, 9, 10, 11, 12, 13]. But none of the studies were successful in determining a model independent reaction rate. Since this breakout reaction become effective in explosive hydrogen burning environments at high temperatures (0.2-2 GK), the direct capture contribution is negligible[14] while the resonances near the alpha-decay threshold in ^{19}Ne, especially the one at excitation energy of 4.03 MeV, dominate the reaction rate over the astrophysical temperature range. Thus, we need to obtain the resonant rate as follows[15],

$$N_A < \sigma v >_{res} \propto (kT)^{-3/2} \Sigma \frac{\Gamma^i_\alpha \Gamma^i_\gamma}{\Gamma^i_\alpha + \Gamma^i_\gamma} \frac{(J_i+1)}{2} \exp(-\frac{E_i}{kT}) \tag{1.1}$$

where J_i, E_i, Γ^i_α, and Γ^i_γ represent the spin, energy, alpha and gamma decay widths of resonance i, respectively.

Apparently, a complete approach for measuring the rate indirectly includes measurements of the structural information (spin, excitation energy, Γ_γ, and Γ_α) of the α-unbound states in ^{19}Ne, particularly the ones just above the alpha-decay threshold. The excitation energies of these states have been determined very well especially after the recent work[13]. So is the case for most of the spin values. The remaining task of measuring the decay widths has been pursued via various reactions but in a similar way, that is, by populating the levels in ^{19}Ne and then measuring the lifetimes/Γ_γ's and α-decay branching ratios B$_\alpha$'s.

Here we report the first successful laboratory measurement of lifetimes and α decay branching ratios of the α-unbound states in ^{19}Ne which provides an experimental rate of ^{15}O(α,γ)^{19}Ne.

2. Lifetimes

Our measurement via the reaction of ^{17}O(^{3}He, n-γ) [13] has given not only the first results on lifetimes but more accurate energy and spin values as well. In Table 1, our results are shown in comparison with the previous work that set only upper limits on lifetimes. Another interesting comparison to the measured lifetimes of the analog states in ^{19}F is also presented. The similar values for the analog states in both ^{19}Ne and ^{19}F may indicate a fair approximation of mirror symmetry. By comparing the decay scheme in ^{19}Ne to that of the mirror states in ^{19}F with well assigned spin values, we can confirm or better determine most of the spin assignments for the levels in ^{19}Ne. For the 4.14 and 4.20 MeV states, however, we found out that the previous tentative

Previous work[16]				Our work[13]		
E_X(keV)	J^π	τ_m (fs)	τ_m (^{19}F) (fs)	E_X(keV)	J^π	τ_m (fs)
4032.9±2.4	$\frac{3}{2}^+$	<50	9±5	4034.5±0.8	$\frac{3}{2}^+$	13^{+9}_{-6}
4140±4	$(\frac{9}{2})^-$	<300	19±7	4143.5±0.6	$\frac{7}{2}^-$*	18^{+2}_{-3}
4197.1±2.4	$(\frac{7}{2})^-$	<350	67±15	4200.3±1.1	$\frac{9}{2}^-$*	43^{+12}_{-9}
4379.1±2.2	$\frac{7}{2}^+$	<120	<11	4377.8±0.6	$\frac{7}{2}^+$	5^{+3}_{-2}
4549±4	$(\frac{1}{2},\frac{3}{2})^-$	<80	17^{+10}_{-8}	4547.7±1.0	$\frac{3}{2}^-$	15^{+11}_{-5}
4600±4	$(\frac{5}{2}^+)$	<160	<50	4601.8±0.8	$\frac{5}{2}^+$	7^{+5}_{-4}
			6.5±3.5[17]			
4635±4	$\frac{13}{2}^+$	$>1\times10^3$	$3.7\pm0.4\times10^3$	4634.0±0.9	$\frac{13}{2}^+$	$>1\times10^3$

* Previous spin assignments were wrong (see text).

Table 1: Measured values of excitation energies, spins, and lifetimes of the α-unbound states in ^{19}Ne from our work are compared to the previous values for ^{19}Ne and ^{19}F from Ref. [16]

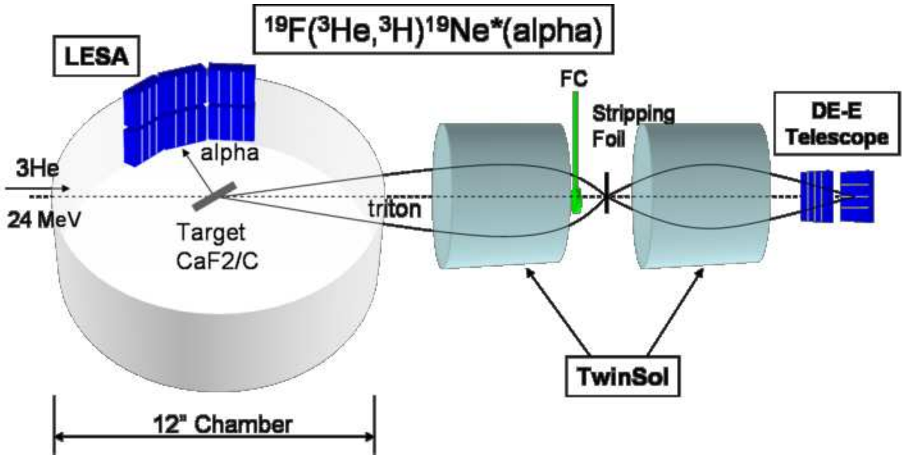

Figure 1: Schematic setup of the B_α's experiment is shown (not to scale for better presentation).

spin assignments should have been exchanged as shown in Table 1. This is important as we will demonstrate the significance of these two states in the discussion of the reaction rate below.

3. α-decay Branching Ratios

There have been a number of reactions used for populating the excited states in ^{19}Ne and measuring the corresponding α-decay branching ratios. So far the two best attempts for determining B_α of the 4.03 MeV state have been done via p(^{21}Ne,t) and ^{3}He(^{20}Ne,^{4}He) reactions by the KVI [10] and ANL[11] groups who set the upper limit of $< 4.3\times10^{-4}$ and $< 6\times10^{-4}$, respectively.

We used the ^{19}F(^{3}He,t) reaction to populate α unbound states in ^{19}Ne; their α-decay branchings were determined through t-α coincidence measurements. The detection system was optimized for the measurement of low energy α particles (as low as 200 keV) and an overall detection efficiency sufficient for probing branching ratios as low as 10^{-4}.

E_x (MeV)	4.03	4.14 & 4.20	4.38
Magnus90[6]			0.044 ± 0.032
RIKEN[18]	<0.03		<0.04
Laird02[9]	<0.01	<0.01	
Rehm03[11]	$<6\times10^{-4}$		$16\pm5\times10^{-3}$
Davids03[10]	$<4.3\times10^{-4}$		$<3.9\times10^{-3}$
Visser04[12]			(>0.0027) tentative
This Work	$2.9\pm2.1\times10^{-4}$	$1.2\pm0.5\times10^{-3}$	$1.2\pm0.3\times10^{-3}$

E_x (MeV)	4.55	4.60	4.71	5.09
Magnus90[6]	0.07 ± 0.03	0.25 ± 0.04	0.82 ± 0.15	0.90 ± 0.09
RIKEN[18]	$0.09^{+0.04}_{-0.02}$	$0.29^{+0.06}_{-0.04}$	$0.67^{+0.23}_{-0.14}$	$1.11^{+0.17}_{-0.13}$
Laird02[9]	0.32 ± 0.03 (3 levels combined)			1.8 ± 0.9
Rehm03[11]				0.8 ± 0.1
Davids03[10]	0.16 ± 0.04	0.32 ± 0.04	0.85 ± 0.04	0.90 ± 0.06
Visser04[12]	0.06 ± 0.04	0.208 ± 0.026	$0.69^{+0.11}_{-0.14}$	$0.75^{+0.06}_{-0.07}$
This Work	0.07 ± 0.02	0.26 ± 0.03	0.80 ± 0.15	0.87 ± 0.03

Table 2: Our measured B_α's for ^{19}Ne are compared to the previous results. See text for detailed discussion.

A schematic drawing of the experimental setup is shown in Fig. 1. The ^{3}He beam of 24 MeV was produced at the FN tandem accelerator of the University of Notre Dame and bombarded at a 40 μm/cm^2 thick CaF$_2$ target that was evaporated onto a 20 μm/cm^2 Carbon foil. The target was positioned at 30^o from the beam to effectively double the target thickness at no expense of more energy loss of alpha particles decaying from ^{19}Ne. A Dual In-Line Superconducting Solenoid Ion-Optical System (TwinSol), mainly for low-energy radioactive beam studies at Notre Dame, was used as a large-acceptance momentum separator to select tritons from the other reaction products. The separated tritons were then detected by a large area ΔE-E tracking telescope.

A Low Energy Silicon-strip Array (LESA) was designed to detect the low energy α particles from the decay of the excited states in ^{19}Ne. It consists of six identical 300 μm thick silicon-strip detectors, each of which has 4 strips and an area of 4x4 cm^2. LESA was positioned 8 cm away from the target covering a solid angle about 10% of 4π for $60^o \leq \theta \leq 150^o$ in the lab frame. To reduce the detection threshold, the dead layer of these silicon detectors was limited to a thickness of < 0.05 μm. This translates into an energy loss of $<$ 14 keV for 200 keV α particles. The particle identification in LESA was achieved by the time of flight analysis.

Detailed analysis procedure will be presented in a forthcoming paper[19]. Here we only summarize our results and focus on the aspects relevant for the determination of the reaction rate. Table 2 shows our new branching ratio results in comparison with previous measurements. For the 4.03-4.38 MeV states listed in the upper part of Table 2, there was essentially no measurement besides some upper limit constraints (see discussion below for the controversial values for the 4.38 MeV state). Our work, for the first time, presents the experimental values of B_α's for these states. In particular, an α-decay branching ratio of $2.9\pm2.1\times10^{-4}$ was measured for the 4.03 MeV state consistent with the previous upper limits[10, 11]. The two states at 4.14 and 4.20 MeV could not be resolved but a combined branching ratio of $1.2\pm0.5\times10^{-3}$ was determined, which

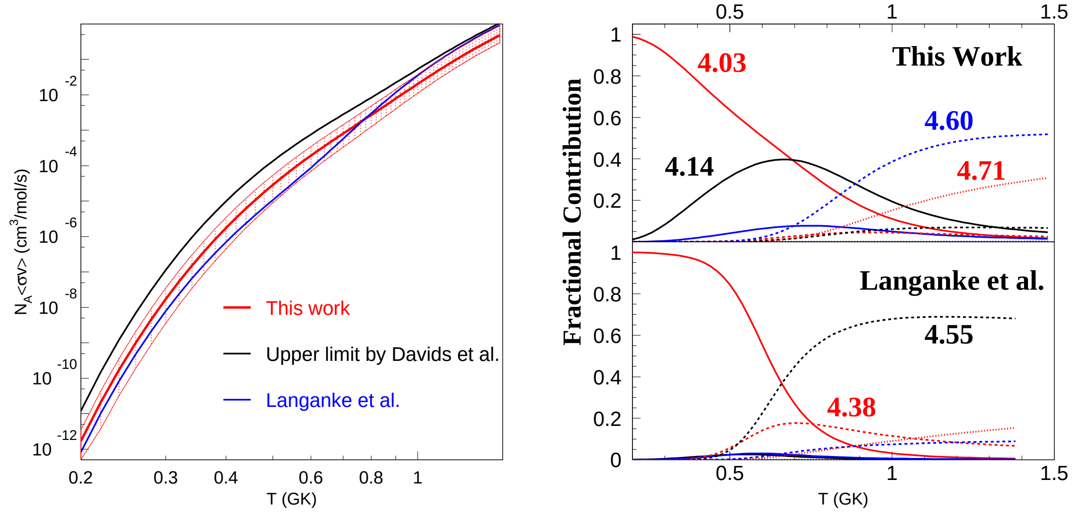

Figure 2: Left figure: the new ^{15}O(α,γ) reaction rate (red line) is plotted with one sigma uncertainty indicated by the hatched area; the previous upper limit by Davids et al.[10] and the widely used theoretical rate by Langanke et al.[14] are also shown. Right figure: fractional contributions from individual states are plotted from this work (upper panel) and the estimate of Langanke et al.[14] (lower panel).

is surprisingly large compared to previous predictions and assessments[14, 11]. These two states have been ignored in the past in calculating the ^{15}O(α,γ) reaction rate because of the previously believed smaller branching ratios. However, as will be seen below, their contribution to the rate can not be neglected and can be dominant at some temperatures. As for the 4.38 MeV state, the previous results are in discord with each other. Our value agrees with the previous upper limit set by Davids et al[10] which exlcuded the large values provided by refs. [6] and [11]. In ref.[6], their measurement for the 4.38 MeV state was handicapped by very poor statistics. On the other hand, the experiment in ref. [11] could not resolve the states in ^{19}Ne and thus any contamination from higher lying states with large B_α's would overwhelm the possible decay from the 4.38 MeV state.

As for the states at excitation energies of 4.55-5.09 MeV that have much larger α-decay branching ratios, our new measurements are in good agreement with previous results. The 4.64 MeV state could not be identified but it is a high spin ($13/2^+$) state with a negligible α-decay branching ratio on the order of 10^{-5}[14].

4. Reaction Rate of ^{15}O(α,γ)

Based on our new measurements of B_α's and lifetimes for the α-unbound states in ^{19}Ne, the ^{15}O(α,γ) reaction rate is obtained at temperatures of astrophysical interest according to Eq. 1.1. Fig. 2 shows the new reaction rate with one-sigma uncertainties. The previous upper limit of the reaction rate shown in the left plot is taken from Davids et al[10] who combined their B_α upper limit with the Γ_γ limit of the 4.03 MeV state obtained with the Coulomb excitation approach[8]. As presented also in Fig. 2, the widely used theoretical estimate of the rate by Langanke et al[14] is not too far off overall. However, the contributions from individual resonances shown in the right plots of Fig. 2 are dramatically different from the estimate of Langanke et al to the present work. In particular, the 4.14 MeV state, which has been mostly ignored in the past, contributes significantly to the rate throughout the breakout process and even dominates the rate at $0.7 < T_9 < 0.9$. At peak temperatures (1-2 GK) of an X-ray burst, it is actually the 4.60 MeV state that dominates the rate instead of the 4.55 MeV state as previously thought.

The large contribution from the 4.14 MeV state to the reaction rate is unexpected and may indicate a possible alpha-cluster configuration. In the paper of Davids et al[10], no α decay was observed from the $7/2^-$ and $9/2^-$ states because the (p,t) reaction they used does not favor the population of these states and in reality the combined yield of these two states was factor of more than 20 lower than that of the 4.03 MeV state in their experiment[10]. As for the work by Rehm et al[11], the poor resolution in separating different excited states made it impossible to tell the alpha-decay contribution of these two states from that of higher lying states with much larger B_α's.

Our combined efforts on the measurements of τ's and B_α's of the ^{19}Ne states provide, for the first time, a measured resonant rate for the ^{15}O(α,γ) reaction. Upon the new knowledge of this critical breakout reaction, the understanding of astrophysical phenomena in explosive hydrogen burning environments will be greatly improved. With the new rate, more detailed studies on the dynamics and mechanism of X-ray bursts using multi-zone model simulations are in progress. Important questions like the critical accretion rate in transition from steady state burning to unstable burning will be answered upon further investigation.

This work is supported by the National Science Foundation under grant No. PHY01-40324 and the Joint Institute for Nuclear Astrophysics, NSF-PFC under grant No. PHY02-16783.

References

[1] M. Wiescher, J. Görres, and H. Schatz, J. Phys. G **25**, R133 (1999).

[2] J. L. Fisker, J. Gorres, M. Wiescher, and B. Davids, Astrophys. J. accepted, [`astro-ph/0410561`].

[3] D. A. Hutcheon et al., Nucl. Instr. Meth. Phys. Res. A **498**, 190 (2003).

[4] Report of the rare isotope science assessment committee, URL:
http://www7.nationalacademies.org/bpa/RISAC.html, 2006.

[5] F. Vanderbist et al., Eur. Phys. J. A **27**, 183 (2006).

[6] P. V. Magnus et al., Nucl. Phys. A **506**, 332 (1990).

[7] Z. Mao, H. Fortune, and A. Lacaze, Phys. Rev. Lett. **74**, 3760 (1995).

[8] G. Hackman et al., Phys. Rev. C **61**, 052801(R) (2000).

[9] A. M. Laird et al., Phys. Rev. C **66**, 048801 (2002).

[10] B. Davids et al., Phys. Rev. C **67**, 062808 (2003).

[11] K. E. Rehm et al., Phys. Rev. C **67**, 065809 (2003).

[12] D. W. Visser et al., Phys. Rev. C **69**, 048801 (2004).

[13] W. P. Tan et al., Phys. Rev. C **72**, 041302(R) (2005).

[14] K. Langanke, M. Wiescher, W. Fowler, and J. Görres, Astrophys. J. **301**, 629 (1986).

[15] C. E. Rolfs and W. S. Rodney, *Cauldrons in the Cosmos*, The University of Chicago, Chicago, 1988.

[16] D. Tilley, H. Weller, C. Cheves, and R. Chasteler, Nucl. Phys. A **595**, 1 (1995).

[17] Á. Z. Kiss, B. Nyakó, and E. Somorjai, Nucl. Instr. Meth. Phys. Res. **203**, 107 (1982).

[18] T. Motobayashi, private communication.

[19] W. P. Tan et al., in preparation.