Experimental Efforts to Determine the $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$ Reaction Rate

Barry Davids, TRIUMF
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Type I X-Ray Bursts: Dependence on $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$

Fisker et al., ApJ 650, 332 (2006): reaction rate must be above certain value or accreted matter burns stably without bursting
No direct measurement is presently feasible ($^{15}\text{O}$ is radioactive)
- Reaction proceeds resonantly at temperatures characteristic of x-ray bursts
- For narrow, isolated resonances, contributions add incoherently
- Contribution of each resonance to reaction rate proportional to its strength $\omega \gamma$
- Resonance strength $\omega \gamma \propto \Gamma_\alpha \Gamma_\gamma / \Gamma$
- $\Gamma_\alpha \Gamma_\gamma / \Gamma = B_\alpha (1- B_\alpha) \hbar / \tau$, where $B_\alpha$ is the alpha-decay branching ratio and $\tau$ the mean lifetime of the state
Experimental Technique: $B_\alpha$

- Decay properties of excited states in $^{19}$Ne determine reaction rate
- Populate states via transfer reaction, study decays
- States of interest decay exclusively by $\alpha$ or $\gamma$ emission
- Populate states, count relative numbers of $\alpha$ & $\gamma$ decays to obtain $B_\alpha$
- Used $^{21}$Ne + p $\rightarrow$ $^{19}$Ne + t reaction at KVI, Groningen, Netherlands
Experimental Setup at KVI’s Big-Bite Spectrometer

Triton determines $^{19}$Ne excitation energy
Heavy ion in coincidence reveals decay mode
Gamma Decay

![Gamma Decay Graph](image)
Alpha Decay

\[ \text{Counts / 20 keV} \]

\[ \text{Ne Excitation Energy (MeV)} \]

\[ \text{O-triton coincidence (α decay)} \]

\[ 15^\text{O} \text{ coincidence} \]

\[ 4.033, 4.379, 4.549, 4.600, 4.712, 5.092, 5.424, 5.539, 5.832 \]
<table>
<thead>
<tr>
<th>Excitation Energy (MeV)</th>
<th>Spin &amp; Parity</th>
<th>$B_\alpha$ (this work)</th>
<th>$B_\alpha$ (Magnus et al.)</th>
<th>$B_\alpha$ (Laird et al.)</th>
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</thead>
<tbody>
<tr>
<td>4.033</td>
<td>3/2$^+$</td>
<td>$&lt; 4.3 \times 10^{-4}$</td>
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<tr>
<td>4.379</td>
<td>7/2$^+$</td>
<td>$&lt; 3.9 \times 10^{-3}$</td>
<td>0.044 ± 0.032</td>
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<tr>
<td>4.549</td>
<td>(3/2)$^-$</td>
<td>0.16 ± 0.04</td>
<td>0.07 ± 0.03</td>
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<tr>
<td>4.600</td>
<td>(5/2$^+$)</td>
<td>0.32 ± 0.04</td>
<td>0.25 ± 0.04</td>
<td>0.32 ± 0.03</td>
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<tr>
<td>4.712</td>
<td>(5/2$^-$)</td>
<td>0.85 ± 0.04</td>
<td>0.82 ± 0.15</td>
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<tr>
<td>5.092</td>
<td>5/2$^+$</td>
<td>0.90 ± 0.06</td>
<td>0.90 ± 0.09</td>
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</tbody>
</table>

Notre Dame $B_\alpha$ Measurement?

- Recent PRL from Tan et al. claims to detect $\alpha$ decay from states below $E_x = 4.5$ MeV
- Data do not warrant claim
- Background poorly understood and modeled
- Statistical analysis flawed
- Reported branching ratios of 4.03, 4.14/4.20, and 4.38 MeV states are unreliable
- KVI data have highest sensitivity
Lifetime Measurements

- Lifetimes measured via Doppler shift of emitted $\gamma$ rays
- Fast decay $\Rightarrow$ large Doppler shift, slow decay $\Rightarrow$ small Doppler shift
- Shapes of detected $\gamma$ ray lines yield lifetime; sensitive to fs lifetimes
Notre Dame Data:

$^{17}\text{O} + ^{3}\text{He} \rightarrow ^{19}\text{Ne} + n$

Measured ten lifetimes, precisely determined transition energies

Lifetime of 4.03 MeV state = 13 (+ 9, - 6) fs
TRIUMF Measurement

- $^3\text{He}$-implanted gold foil target
- $^{20}\text{Ne} + ^3\text{He} \rightarrow ^{19}\text{Ne} + \alpha$
- $\alpha$ particles detected in Si $\Delta$ E-E telescope
- $^{19}\text{Ne}$ emits a $\gamma$ ray after slowing down in gold foil
- Detect Doppler-shifted de-excitation $\gamma$ rays from $^{19}\text{Ne}$ states
TRIUMF Data

- Measured lifetimes of 6 states above $\alpha$ threshold
- Two states observed via two transitions, other states only seen in one transition
- In general, lifetimes are consistent with and more precise than Notre Dame measurements
Transitions of 4.03 MeV State

- Two transitions observed, direct to ground state and also to 1536 keV state
- Two inferred lifetimes are mutually consistent
Lifetime of 4.03 MeV State

Joint likelihood analysis of two transitions yields
\[ \tau = 6.9 \pm 1.5 \text{ (statistical)} \pm 0.5 \text{ (systematic)} \text{ fs} \]
Lifetime of 4.38 MeV State

\[ \tau = 2.9 \pm 1.4 \text{ (statistical)} \pm 0.4 \text{ (systematic)} \text{ fs} \]
## Comparison of Notre Dame and TRIUMF Lifetime Measurements

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<td>1536</td>
<td>1297.8(4)</td>
<td>16±4</td>
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<td>6.9±1.5±0.5</td>
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<td>4547.7(10)</td>
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<td>18.4±3.3±1.9</td>
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<tr>
<td>4602</td>
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<td>7.6±2.0±0.7</td>
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</table>
Lifetimes are now well measured

$B_\alpha$ of important low-lying states @ 4.03 and 4.38 MeV still only constrained from above by upper limits

Combining best experimental measurements, upper limit on reaction rate still much larger (~100 times) than theoretical lower limit

New theoretical upper limit from Cooper and Narayan 2006: find that bursts would be observed from rapidly accreting neutron stars from which only stable burning is seen, if reaction rate were more than ~ 1/25 of experimental upper limit

Theoretical bounds on rate are presently tightest (if they are to be believed)

More sensitive $B_\alpha$ measurements required to make further progress
Credits

- Jacob Fisker, Lawrence Livermore National Lab (x-ray burst calculations)
- Wanpeng Tan, University of Notre Dame (lifetime measurements)
- Mythili Subramanian, TRIUMF and University of British Columbia (lifetime measurements)