Constraining the key $\alpha$-capture astrophysical reaction rates using the sub-Coulomb $\alpha$-transfer reactions

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Acknowledgements

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Outline

- ANC from Sub-Coulomb $\alpha$-transfer reaction
- Benchmark measurements
- Cascade transitions in $^{12}\text{C}(\alpha,\gamma)$
- The neutron source for s-process - $^{13}\text{C}(\alpha,n)$

Background

- α capture reactions play important role in astrophysics.
- Direct measurements at Gamow energies are not possible because cross section is small due to Coulomb barrier.
- Extrapolations from direct measurements at higher energies often can poorly constrain the contribution from near α-threshold resonances
- Model independent indirect method to determine the contribution from near α-threshold resonances is highly desirable
Method

- Perform \(^6\text{Li},d\) (or \(^7\text{Li},t\)) \(\alpha\)-transfer reaction at sub-Coulomb energy for both the exit and entrance channels.
- Extract Asymptotic Normalization Coefficients (ANC) instead of SF factors.
- Sub-Coulomb energy eliminates dependance of the result on optical model parameters of the DWBA calculations.
- ANC does not depend on the shape of the form-factors or the number of nodes in the cluster wave function.
- There is a direct relation between contribution of the specific state to the \(\alpha\)-capture reaction and its ANC.

Benchmark experiment

Test the sub-Coulomb $\alpha$-transfer using the known widths of the $1^-$ state in $^{20}\text{Ne}$.

$^6\text{Li}(^{16}\text{O},d)^{20}\text{Ne}$

Benchmark experiment

- Use DWBA to extract the ANC for the $1^-$
- Calculate its known width from measured ANC.

The known total width of the $1^-$ state at 5.79 MeV is $28(3)$ eV. The partial $\alpha$ width of the $1^-$ state determined from ANC is $29(6)$ eV.
Constraining cascade transitions in $^{12}$C($\alpha,\gamma$) reaction

- E2 and E1 transition to the ground state dominate.
- The cascade transitions may contribute as well.
- The contribution of the $0^+$ 6.05 MeV transition is uncertain:
  - $25\pm 15$ keV b (15% of the total) [1]
  - $<1$ keV b (negligible) [2]

Constraining cascade transitions in $^{12}\text{C}(\alpha,\gamma)$ reaction

- Spectrum of deuterons from $^6\text{Li}(^{12}\text{C},d)$ reaction. Total energy of the $^{12}\text{C}$ beam is 9 MeV.

- Angular distributions

Constraining cascade transitions in $^{12}\text{C}(\alpha,\gamma)$ reaction

**ANC of all sub-threshold states in $^{16}\text{O}$**

<table>
<thead>
<tr>
<th>$^{16}\text{O}(0^+)^2$ $(10^6 \text{ fm}^{-1})$</th>
<th>$^{16}\text{O}(3^-)^2$ $(10^4 \text{ fm}^{-1})$</th>
<th>$^{16}\text{O}(2^+)^2$ $(10^{10} \text{ fm}^{-1})$</th>
<th>$^{16}\text{O}(1^-)^2$ $(10^{28} \text{ fm}^{-1})$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\ldots)</td>
<td>(\ldots)</td>
<td>2.07 ± 0.80</td>
<td>4.00 ± 1.38</td>
<td>[1]</td>
</tr>
<tr>
<td>(\ldots)</td>
<td>(\ldots)</td>
<td>1.29 ± 0.23</td>
<td>4.33 ± 0.84</td>
<td>[2]</td>
</tr>
<tr>
<td>(\ldots)</td>
<td>(\ldots)</td>
<td>1.96 ± 1.41</td>
<td>3.48 ± 2.0</td>
<td>[3]</td>
</tr>
<tr>
<td>2.43 ± 0.30</td>
<td>1.93 ± 0.25</td>
<td>1.48 ± 0.16</td>
<td>4.39 ± 0.59</td>
<td>This work</td>
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Constraining cascade transitions in $^{12}\text{C}(\alpha,\gamma)$ reaction

Direct capture is completely determined by the ANC of the state the $\alpha$-particle is captured into.

Interference of direct capture with the resonance capture through the tails of the higher lying states is important.
The $K^\pi = 0^+$ cluster band in $^{16}\text{O}$

- $0^+$ at 6.05 MeV; 40% of $\alpha$-SP limit. Reduced width is calculated directly from ANC and compared to the $\alpha$-SP limit.
- Reduced width used in [1] for the $0^+$ at 6.05 MeV was 0.01 MeV$^{1/2}$.

0$^+$ at 6.05 MeV; 40% of $\alpha$-SP limit ($\gamma_\alpha = 0.48$ MeV$^{1/2}$)

- 2$^+$ at 6.91 MeV; 40% of $\alpha$-SP limit.
- 4$^+$ at 10.36 MeV; 50% of $\alpha$-SP limit.
- 6$^+$ at 16.27 MeV; 55% of $\alpha$-SP limit.

The main neutron source for s-process in AGB stars - $^{13}\text{C}(\alpha,n)$ reaction

$^{13}\text{C}(\alpha,n)$ reaction rate has direct influence on final abundances of some s-process isotopes and in some models determines if the $^{60}\text{Fe}$ is produced [S. Cristallo, et al., arXiv:0902.0243v2 (2009)].

The $^{13}\text{C}(\alpha,n)$ cross section at Gamow window is dominated by tails of near $\alpha$ threshold states.
The $^6$Li($^{13}$C,d) reaction at sub-Coulomb energy

- Spectrum of deuterons from $^6$Li($^{13}$C,d) reaction. Total energy of the $^{13}$C beam is 8 MeV.

- Angular distribution

α - ANC for the $1/2^+$ state at 6.356 MeV in $^{17}$O.

Complete R-matrix fit for $^{17}$O

The s-factor for the $^{13}\text{C}(\alpha,n)$ reaction

s-factor [eV b]

Gamow window

$^{13}\text{C}(1/2^-) + \alpha$ with $L=1$

$1/2^+$, $3/2^+$
The $s$-factor for the $^{13}\text{C}(\alpha,n)$ reaction

**$s$-factor [eV b]**

- $^{13}\text{C}(1/2^-) + \alpha$ with $L=1$
- $1/2^+$, $3/2^+$

Gamow window

The $K^{\pi}=1/2^+$ and $1/2^-$ cluster band in $^{17}$O

The $K^{\pi}=0^+$ and $0^-$ bands in $^{16}$O have their analogous $1/2^-$ and $1/2^+$ bands in $^{17}$O.

**SF from:**


<table>
<thead>
<tr>
<th>$^{16}$O</th>
<th>$^{17}$O</th>
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<tbody>
<tr>
<td>$0^+$ at 6.05 MeV (40%)</td>
<td>1/2$^-$ at 3.06 MeV (30%)</td>
</tr>
<tr>
<td>$1/2^-$ at 6.36 MeV (50%)</td>
<td>SF from:</td>
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<tr>
<td>$1/2^+$ at 7.20 MeV (50%)</td>
<td></td>
</tr>
<tr>
<td>$3/2^+$ at 7.40 MeV (50%)</td>
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<tr>
<td>$7/2^+$ at 9.70 MeV ???</td>
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<tr>
<th>$^{16}$O</th>
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<td>$1^-$ at 9.5 MeV (100%)</td>
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<th>$^{17}$O</th>
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<td>$3^-$ at 11.6 MeV (100%)</td>
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Summary

✓ Sub-Coulomb α-transfer reaction provides a model independent way to constrain the astrophysical reaction rates.

✓ The method was benchmarked against known width of 1− state at 5.79 MeV in $^{20}$Ne.

✓ Cascade transitions (CT) s-factor for $^{12}$C(α,γ) reaction have been constrained. The combined CT contribution does not exceed 4% of the total cross section.

✓ Uncertainties of the neutron source for the s-process reaction $^{13}$C(α,n) have been dramatically reduced.

✓ The first three members of the highly clustered rotational band $K^\pi=1/2^+$ are firmly established in $^{17}$O.
THANK YOU!