Sub- and Near- Coulomb $\alpha$-transfer reactions for nuclear astrophysics

Grigory Rogachev
Acknowledgements


* Present affiliation Davidson College
** Present affiliation Argonne National Laboratory
α capture reactions play important role in astrophysics.
Direct measurements at Gamow energies are difficult 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.
A 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 α-transfer using the known widths of the 1⁻ state in ²⁰Ne.

Benchmark experiment

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

Known total width of the $1^-$ state at 5.79 MeV is $28(3)$ eV.

Partial $\alpha$ width of the $1^-$ state determined from ANC is $29(6)$ eV.

\[
\Gamma_\alpha = P_l(kR) \frac{W^2_{-\eta,l+1/2}(2kR)}{\mu R} \left(C_{\alpha^{16}C}^{12}C\right)^2,
\]

\[
\frac{d\sigma}{d\Omega} \text{ (nb/steradian)}
\]
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.

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

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

<table>
<thead>
<tr>
<th>$\left(C_{a^{12}\text{C}}^{16}\text{O}(0^+)\right)^2$ (10^6 fm^{-1})</th>
<th>$\left(C_{a^{12}\text{C}}^{16}\text{O}(3^-)\right)^2$ (10^4 fm^{-1})</th>
<th>$\left(C_{a^{12}\text{C}}^{16}\text{O}(2^+)\right)^2$ (10^{10} fm^{-1})</th>
<th>$\left(C_{a^{12}\text{C}}^{16}\text{O}(1^-)\right)^2$ (10^{28} fm^{-1})</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>...</td>
<td>...</td>
<td>2.07 ± 0.80</td>
<td>4.00 ± 1.38</td>
<td>[1]</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>1.29 ± 0.23</td>
<td>4.33 ± 0.84</td>
<td>[2]</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>1.96^{+1.41}_{-1.27}</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>
</tr>
</tbody>
</table>


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 - it is constructive for $0^+$ (R. deBoer, et al., RMP (2017)).
ANC for $^{16}\text{O}$ G.S.

- $^{16}\text{O}$ g.s. ANC is one of the few remaining uncertainties in $^{12}\text{C}(\alpha,\gamma)$ - R. deBoer, et al., RMP (2017)

- Sub-Coulomb ($^6\text{Li},d$) approach cannot be used to determine ANC of the deeply bound states

- One can use the ($^{20}\text{Ne},^{16}\text{O}$) - $^{20}\text{Ne}$ g.s. is an $\alpha$-cluster state which is bound by 4.7 MeV

- $^{12}\text{C}(^{20}\text{Ne},^{16}\text{O})$ is promising

- ANC of $^{20}\text{Ne}$ g.s. is not known…
$^{12}\text{C}(^{20}\text{Ne},^{16}\text{O})$ and $^{16}\text{O}(^{20}\text{Ne},^{16}\text{O})^{20}\text{Ne}(1-)$

- At truly sub-Coulomb energies (30 MeV), cross section is VERY small
- At Nearly sub-Coulomb energies (35 MeV) reaction has some model dependance, but it can be removed by correlating with the backward angle elastic scattering!
The $K^\pi = 0^+$ cluster band in $^{16}\text{O}$

- $0^+$ at 6.05 MeV; 40% of $\alpha$-SP limit ($\gamma_\alpha = 0.48 \text{ MeV}^{1/2}$)
- $2^+$ 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 reduced width is calculated directly from ANC and compared to the $\alpha$-SP limit.

The $\gamma_\alpha$ used in [1] for the $0^+$ at 6.05 MeV was $0.01 \text{ MeV}^{1/2}$.

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

The $^{13}$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.

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

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


$^{13}$C($\alpha,\alpha$)

$^{16}$O(n,n)

$^{13}$C($\alpha,n$)

$^{13}$C($\alpha,\alpha$)
The $1/2^+$ state new energy and width

- From the complete R-matrix fit the 6.356 MeV state is actually at 6.376 +/- 6 MeV. The threshold is at 6.359 MeV - it is not sub-threshold

T. Faestermann, et al.
PRC 92, (2015)

$^{19}$F($d,\alpha)^{17}$O

6.363 +/- 3 MeV
$\Gamma = 136$ keV
The $1/2^+$ state new energy and width

**s-factor due to $1/2^+$**

<table>
<thead>
<tr>
<th>Energy</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.356 MeV</td>
<td>124 keV</td>
</tr>
<tr>
<td>6.363 MeV</td>
<td>124 keV</td>
</tr>
<tr>
<td>6.363 MeV</td>
<td>136 keV</td>
</tr>
</tbody>
</table>

The s-factors are calculated using the same sub-Coulomb alpha-transfer data.

If $1/2^+$ is at 6.363 MeV its $\Gamma_\alpha = 2.4 \times 10^{-137}$ MeV
The s-factor for the $^{13}\text{C}(\alpha,n)$ reaction

The Gamow window is shown.

The reaction produces $^{13}\text{C}^{1/2-} + \alpha$ with $L=1$.

The s-factor is given in eV b. The graph shows the energy dependence of the s-factor.
The s-factor for the $^{13}\text{C}(\alpha, n)$ reaction

Gamow window

$1/2^+$  $3/2^+$

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

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

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

- $0^+ \text{ GS}$
  - $4^+ \ 10.35 \text{ MeV}$
  - $3^- \ 11.60 \text{ MeV}$
  - $2^+ \ 6.92 \text{ MeV}$
  - $1^- \ 9.58 \text{ MeV}$
  - $0^+ \ 6.05 \text{ MeV}$
  - $40\% \alpha+^{12}\text{C(gs)}$

- $1/2^-$
  - $3/2^- \ 4.55 \text{ MeV}$
  - $5/2^- \ 3.84 \text{ MeV}$

- $1/2^+$
  - $3/2^+ \ 7.20 \text{ MeV}$
  - $1/2^+ \ 6.376 \text{ MeV}$

- $100\% \alpha+^{12}\text{C(gs)}$

- $50\% \alpha+^{12}\text{C(gs)}$
$^{22}\text{Ne}(\alpha,n)$ reaction

- $^{22}\text{Ne}(\alpha,n)$ is not a well constrained reaction.

Gamow window in C.M. energies
\(~ 400 \text{ - } 800 \text{ keV}\)

Gamow window in excitation energies of $^{26}\text{Mg}$ 10.9 \text{ - } 11.4 \text{ MeV}

$^{22}\text{Ne}(^6\text{Li},d)$

Experiment

$^{22}\text{Ne} + ^6\text{Li} + \alpha + \text{d}$

$1.0\text{ MeV/u} \rightarrow ^{26}\text{Mg} + \alpha$
Multipole-Dipole-Multipole (MDM) Setup

Slit in the target chamber to select particles for a certain angular range

*Ph.D thesis, A. Spiridon*

D. M. Pringle et al. / The oxford MDM-2 magnetic spectrometer
The excitation energy range of $^{26}$Mg was probed using $^6$Li($^{22}$Ne,d) and $^7$Li($^{22}$Ne,t) reactions.

d spectrum
$^6$Li($^{22}$Ne,d)$^{26}$Mg$^*$

Excitation energy

Counts

Excitation energy [MeV]

10.7  10.8  10.9  11   11.1  11.2  11.3  11.4

20

18

16

14

12

10

8

6

4

2

0

Excitation energy using t [MeV]

Counts

Excitation energy

10.7  10.8  10.9  11   11.1  11.2  11.3  11.4

20

18

16

14

12

10

8

6

4

2

0
Comparison with direct measurements

Direct measurements of $^{22}$Ne(α,n)

[M. Jaeger, PRL 87(2001)]
Comparison with direct \((^6\text{Li},d)\) measurements

82.3 MeV \(^6\text{Li}\)


32 MeV \(^6\text{Li}\)


- Talwar et al. identifies two very strong 1\(^-\) states having very large \(\alpha\)-spectroscopic factor at 11.17 MeV and 11.32 MeV.
What can we say about the $J^\pi$ of the 11.3 MeV state?

$T = \text{Talwar (2016)}$

$G = \text{Giesen (1993)}$

$^{22}\text{Ne}(^6\text{Li},d)^{26}\text{Mg}$

$11.3 \text{ MeV}$ [T]

$10.95 \text{ MeV}$ [G], [T]

$11.3 \text{ MeV}$ [G]

Cross Section (mb/sr)

Transferred Angular Momentum (L)
Resonance strengths previously measured are quite different from one another.

Almost by a factor of 3!
$^{22}\text{Ne}(\alpha,n)$ Reaction rate comparisons

$$N_A < \sigma \nu > = 1.54 \times 10^5 \times (\mu T_9)^{-3/2} \times \sum_i (\omega \gamma)_i \exp\left( - \frac{11.605 \times E_{cm}^i}{T_9} \right)$$

$\sigma \nu$ - Reaction rate
$\mu$ - Reduced mass
$E_{cm}^i$ - Resonance energy in CM
$\omega \gamma$ - Resonance strength (meV)
$T_9$ - Temperature (GK)
Effect on Isotope Abundances for s-process only isotopes

The production factor of s-process only isotopes as a ratio to Kaeppler et al.

Star model = 5.0 Solar mass & solar metallicity
**Summary**

- Sub-Coulomb $\alpha$-transfer reaction provides a (almost) model independent way to constrain the astrophysical reaction rates.

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

- The near $\alpha$ - threshold states ANCs can be firmly established using ($^6\text{Li},d$) and ($^7\text{Li},t$).

- For the deeply bound states ($^{20}\text{Ne},^{16}\text{O}$) can be used.
THANK YOU!
Constraining cascade transitions in $^{12}\text{C}(\alpha,\gamma)$ 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]

Resonance Strengths

Spin-parity assignments are unknown for these states.

Assumed $J^\pi$ values of 0$^+$, 1$^-$ and 2$^+$.

Energies for the peaks from our fit:
- 11.30 (9) MeV
- 11.09 (9) MeV
- 10.95 (9) MeV
- 10.83 (9) MeV

Energies for the peaks previously observed:
- 11.319 (2) MeV$^1$
- 11.09 MeV$^2$
- 10.953 (25) MeV$^2$
- 10.808 (20) MeV$^2$

$^2$Physical Review C 76 (2007) 025802
Outline

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

Importance of $\alpha$-capture reactions

- $\alpha$-capture reactions play a crucial role in nuclear astrophysics.

- The *slow neutron capture process (s-process)* taking place in *Asymptotic Giant Branch (AGB)* stars is responsible for the formation of about half of the elements beyond $^{56}\text{Fe}$.

- The main neutron source reactions for the s-process:

\[ ^{13}\text{C}(\alpha,n)^{16}\text{O} \]
\[ ^{22}\text{Ne}(\alpha,n)^{25}\text{Mg} \]
Slow neutron capture process

- “Main” component - produces nuclei with masses $A > 90$
  - AGB stars ($M < 10 \ M_{\text{sun}}$)
- “Weak” component - produces nuclei with masses $A < 90$
  - Massive stars ($M > 10 \ M_{\text{sun}}$)

Adapted from Smith, Schatz, Timmes, Wiescher, Greife (2005)
Slow neutron capture process

s-process follows the path of stability for $\beta$-decay

The time separation between two neutron captures is very long (~10 years)

Gamow window for astrophysics

Energy range in which nuclear reactions occur in stellar environments.

\[ E_0 = 0.122\left(Z_1^2 Z_2^2 \mu T_9^2 \right)^{1/3} \]
\[ \Delta E = 0.236\left(Z_1^2 Z_2^2 \mu T_9^5 \right)^{1/6} \]
Sub-Coulomb $\alpha$-transfer technique

- Perform direct $\alpha$-transfer reactions at sub-Coulomb energies (Ex: $^{6}$Li,d)).
- Extract Asymptotic Normalization Coefficients (ANC) instead of the spectroscopic factors.

Sub-Coulomb energies significantly reduce the dependence of results on optical model parameters of the DWBA calculations.

What is Asymptotic Normalization Coefficient (ANC) and Spectroscopic Factor (SF)?

**Spectroscopic Factor :**

\[ F \rightarrow A + x \]

\[ SF = \frac{(C_{Ax}^F)^2}{b^2} \]

**Single Particle ANC**

\[ \left( \frac{d\sigma}{d\Omega} \right)_{Exp} = \frac{(C_{22}^{26}Mg_{Ne,\alpha})^2}{b_{26}^2 Mg} \frac{(C_{d,\alpha}^{6}Li)^2}{b_{6}^2 Li} \left( \frac{d\sigma}{d\Omega} \right)_{DWBA} \]
Previous measurements

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

Calculated the \( \Gamma_\alpha \) of the well known \( 1^- \) state at 5.79 MeV of \( ^{20}\text{Ne} \).

Calculated - 29(6) eV
Known - 28(3) eV

\[ ^{13}\text{C}(\alpha,n) \]

Calculated the \( \alpha \)-ANC of \( 1/2^+ \) state at 6.376 MeV in \( ^{17}\text{O} \)

Constrained the Cascade Transitions of \( ^{12}\text{C}(\alpha,\gamma) \)

Modified Oxford Detector

- 4 Proportional Counter wires
- Chamber filled with isobutane gas
CsI modification

- 7 CsI(Tl) detectors
- 5 x 5 cm² active area for each
- Detector resolution <5%

Drawing of the CsI(Tl) array

SCIONIX CsI photodiode detector
Micromegas plate

A - PCB board
B - Anode pads
C - pillars
D - Mesh

Ph.D Thesis, A. Spiridon
$^{26}\text{Mg}$ Level Scheme
Sub-Coulomb $\alpha$-transfer reactions provide a powerful method to constrain astrophysical reaction rates, and has been proved to be very successful in studying many reactions.

**Summary**

There is an evident difference between the $^{22}\text{Ne}(^6\text{Li},d)$ measurements done at the Coulomb barrier vs. higher energy measurements.

Extraction of ANC s and predictions for the $^{22}\text{Ne}(\alpha,n)$ reaction and its role in isotope abundances are currently underway.

The $1^-$ spin-parity assignment for the 11.3 MeV state can be obtained via a study of previous ($^6\text{Li},d$) measurements.