The first experimental \((a, xn)\) compound reaction in inverse kinematics study using neutron-rich nuclei

Sunghoon(Tony) Ahn for HabaNERO collaboration
CNR 2018
September 27\textsuperscript{th}, 2018
[Acknowledgements]

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\textbf{34 collaborators from 11 Institutes}
• All elements in the Universe are outcome of nuclear reactions occurring in stars.
• Nucleosynthesis process can explain the observation.

→ **Nuclear structure information is important!**
→ mass, Q-value, $T_{1/2}$, $P_n$, level densities and **reaction rates**

Schematic overview of the nuclear processes on nuclear chart

H. Schatz, 2016
Understanding the Origin of Elements

- All elements in the Universe are outcome of nuclear reactions occurring in stars.
- Nucleosynthesis process can explain the observation.

→ **Nuclear structure information is important!**
→ mass, Q-value, \( T_{1/2} \), \( P_n \), level densities and **reaction rates**

Abundances of the elements in the solar system. 
*Lodders, K., Palme H., & Gail, H.P. 2009*

Schematic overview of the nuclear processes on nuclear chart 
*H. Schatz, 2016*
Abundance Pattern of Old Stars

- Abundance patterns of old stars (metal poor halo stars) formed by a few events?
- These stars are old and preserve in their photospheres the abundance composition at the location and time of their formation?
- Many surprises found in the observations!
  → Another nucleosynthesis needed! Weak r-process?

\[ \text{solar r-process}\]

\[ \text{HD 122563}\]
Weak r-process and $(\alpha,xn)$ reactions

- In the neutrino driven wind at CCSN with $T \sim 4$ GK, charge particle reactions fall out of NSE.
- Low neutron to seed ratio for $(n,\gamma)$ reactions.
- $(\alpha,xn)$ reactions with Iron seeds provide enough abundances for low Z (<50) elements.

A Nucleosynthesis simulation in the weak r-process considering dominant $(\alpha,xn)$ reactions
Agreement between model and measurement

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A Nucleosynthesis simulation in the weak r-process considering dominant $(\alpha,xn)$ reactions

$^{75}\text{Ga} + \alpha \rightarrow ^{78}\text{As} + n$

Weak r-process abundances considering dominant $(\alpha,n)$ reactions
Bliss et al, arXiv:1612.02435v2

HD122563
No Experimental data for \((\alpha, xn)\) cross sections

Experimental data for \((\alpha, xn)\) reaction cross section

Compiled by Z. Meisel

<table>
<thead>
<tr>
<th>Product</th>
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No experimental knowledge of \((\alpha, xn)\) cross sections for n-rich nuclei [except around Z~50]

List of Sensitive \((\alpha, xn)\) reactions
Bliss et al, in preparation

β-stable
CS for \(E_\alpha < 6.1\) MeV
No CS data for \(E_\alpha < 6.1\) MeV & \(E_{\alpha,\text{thresh}} < 6.1\) MeV

EXFOR database, as of 5 March 2018
Uncertain \((\alpha, n)\) cross sections for neutron-rich nuclei

- How accurate the \((\alpha, n)\) cross sections for the weak r-process model?
- Theoretical \((\alpha, n)\) cross sections have large spread of predictions.
- \((\alpha, n)\) reaction rates largely depend on reaction codes and input parameters.

\[ ^{86}\text{Se}(\alpha,n) \] reaction rate ratio w/ various HF code
J. Pereira and F. Montes, Phys Rev C 93, 034611 (2016)

\[ ^{85}\text{Se}(\alpha,n)^{88}\text{Kr} \] reaction rate ratios w/ various alpha OMP
J. Pereira and F. Montes, Phys Rev C 93, 034611 (2016)
• Goal: total cross section measurement
• Beam: neutron rich nuclei (a few facilities)
• Target: \(^4\)He gas target (gas cell with thin window foils, gas chamber or gas jet)
• Detector: neutrons, recoils (*high efficiency*, clean separation from background)

\( (\alpha,n) \) reaction in inverse kinematics

Kinematics diagram for \( A(\alpha,n)B \) reaction in inverse kinematics

- Plastic scintillator
- Moderator and Proportional counter
- Ion chamber
- Time Projection Chamber
- Recoil Separator
• Needs for a high efficient neutron detector for neutron energy up to 20 MeV

Simulated kinematics curves for $^{75}\text{Ga}(\alpha,n)^{78}\text{As}$ reaction in inverse kinematics

→ a long counter system, modified to be efficient for high energies and with flat efficiency curve as energy is not measured.

→ HABANERO
HABANERO: Heavy ion Accelerated Beam induced (Alpha,Neutron) Emission Ratio Observer

- Ultra High Molecular Weight Polyethylene (UHMWPE, \( \rho=0.945\,\text{g/cm}^3 \)) box
- 36 \(^3\text{He}\) long counter tubes and 44 BF\(_3\) tubes (80 tubes total)

- **First long counter neutron detector used for nuclear reaction studies.**
HabaNERO Commissioning at Ohio University

- 3 neutron energies, 5 steps of polar angle and 5 steps of azimuthal angle.
- For $3.92 \text{ MeV} \leq E_n \leq 14 \text{ MeV}$, $\langle \varepsilon \rangle = 24.4\%$, $\delta \varepsilon = 2\%$.

Detector Setup Photo

Efficiency plot for detector at theta=90 deg

- Preliminary!!
$^{75}\text{Ga}(\alpha,xn)$ reaction cross sections

Experimental data for $(\alpha,xn)$ reaction cross section
Compiled by Z. Meisel
$^{75}\text{Ga}(\alpha, xn)$ reaction experiment at ReA3, NSCL

- $^{75}\text{Ga}$ beam with In-flight separation method and Gas Stopper/Reaccelerator at NSCL
- $E_{\text{beam}} = 2.71 \sim 4.0$ MeV/A (for $T \sim 3.5\sim 5.3$ GK coverage), 5 beam energy steps
Experimental Setup for $^{75}\text{Ga}(\alpha,\text{xn})$ reaction

- $^{75}\text{Ga}$ reaccelerated beams by ReA3, NSCL, bombard $^4\text{He}$ gas target ($T=355\text{ug/cm}^2$) in the middle of the HABANERO.
- Position Sensitive Ionization Chamber (PSIC) provides beam current and PID.

Experimental Setup Design

- $^{75}\text{Ga}$ beam 3 ~ 4 MeV/u
- reactions occurred in He gas cell target
- beam stopping
- $^{78}\text{As}$
- PSIC
- EBIT charge breeder
- LINAC
- Experimental stations
- HABANERO
- Experimental Setup Design
First measurement of $^{75}\text{Ga}(\alpha,n)$ reaction at NSCL

- Purity: $^{75}\text{Ga} = 95\%$, $^{78}\text{Kr} = 4\%$, $^{75}\text{Ge} = 1\%$
- Beam intensity: more than 6000 pps in average
Neutron Multiplicity Analysis Method

- Neutrons were detected in EBIT-HabaNERO correlation spectrum.
- Neutron excess of $^{75}\text{Ga}(\alpha,n)$ reaction from comparison of 4He gas-in and gas-out run.
- Neutron source: room background, beam induced background, $(\alpha,n)$ and $(\alpha,2n)$.
- Using Maximum Likelihood Estimation (MLE) Method.

![Time after EBIT signal (usec)](image)

$$
\begin{pmatrix}
M_1 \\
M_2 \\
M_3 \\
M_4
\end{pmatrix} =
\begin{pmatrix}
P_{11}(\epsilon) & P_{12}(\epsilon) & P_{13}(\epsilon) & P_{14}(\epsilon) \\
P_{21}(\epsilon) & P_{22}(\epsilon) & P_{23}(\epsilon) & P_{24}(\epsilon) \\
P_{31}(\epsilon) & P_{32}(\epsilon) & P_{33}(\epsilon) & P_{34}(\epsilon) \\
P_{41}(\epsilon) & P_{42}(\epsilon) & P_{43}(\epsilon) & P_{44}(\epsilon)
\end{pmatrix}
\begin{pmatrix}
\sigma_{(\alpha,1n)} \\
\sigma_{(\alpha,2n)} \\
\sigma_{BG_{beam}} \\
\sigma_{BG_{room}}
\end{pmatrix}
$$

![Beam Energy vs Ratio (%)](image)

![Beam Energy vs (~a,n) cross section](image)

![Beam Energy vs (~a,2n) cross section](image)
Preliminary Results

- Disagreement between measured and calculated cross sections!!
- \((a,2n)\) cross sections significantly suppressed.

**75Ga\((a,xn)\)As cross sections**
(\alpha,xn) reaction studies with FRIB

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NSCL PAC41 Approved!

Bliss, Arcones, Montes & Pereira, in prep.

Relevant (\alpha,^*n) reactions

Nuclear chart with relevant (\alpha,xn) reactions
There’s plenty to do... and we’re working on it!

Detectors for (α,xn) reaction studies

HabaNERO@NSCL

S. Ahn et al.

TexAT@TAMU

G. Rogachev et al.

MUSIC@ANL

R. Talwar et al. PRC 2018

Z. Meisel et al.
Summary

- Disagreements on the very metal poor halo stars for elements between Z=37 and 47.
- One proposal for the issue is a failed r-process to make ($\alpha, xn$) reactions happen to build up higher Z elements earlier than the r-process.
- ($\alpha, xn$) reaction rates are very uncertain and no experimental data exists.
  → Experimental ($\alpha, xn$) measurements are necessary to reduce the uncertainties.

- $^{75}\text{Ga} (\alpha, xn)$ reaction in inverse kinematics experiment performed at ReA3, NSCL.
- Neutron energy can go up to 20 MeV from the kinematics calculations.
- HABANERO is completed for the development and commissioned at Ohio University.
- RIB ($^{75}\text{Ga}^{26+}$) beam searching for neutrons from 4He gas cell target.
- Neutrons were seen in the EBIT-HabaNERO correlation spectrum.
- Data Analysis is close to completion.
  → Measured $^{75}\text{Ga} (\alpha, xn)$ cross sections show large deviations from the theoretical calculations!

- Outlook: More opportunities of ($\alpha, xn$) reaction studies will be provided by FRIB.
[Back up Slides]
Incomplete r-process

Metal-poor star HD122563

Nuclear reaction time scales

Time scale [s]
• Good agreement on abundance pattern of $Z<47$.
• The abundances are sensitive to the $(\alpha,n)$ reaction rates.
• $(\alpha,n)$ reactions are very uncertain and no experimental data exists.

**Metal-poor star**

**HD122563**

**$r$-process abundances considering dominant $(\alpha,n)$ reactions**

Bliss *et al.*, *In preparation*

**$(\alpha,n)$ reaction rate ratio w/ various HF code**

F. Montes, J. Pereira, and A. Arcones, *In preparation*
Charged particle (α) capture process

- Good agreement on abundance pattern of Z<47.
- The abundances are sensitive to the (α,n) reaction rates.
- (α,n) reactions are very uncertain and no experimental data exists.

![Graph showing abundance pattern of Z<47](image)

- Metal-poor star HD122563

r-process abundances considering dominant (α,n) reactions
Bliss et al., In preparation

![Graph showing (α,n) reaction rate ratios](image)

(α,n) reaction rate ratios w/ various alpha OMP
F. Montes, J. Pereira, and A. Arcones, In preparation
Angular dependency of efficiency on (α,2n) kinematics

1. As you lower the energy of neutron, it seems the angular dependency of the efficiency gets smaller.
Angular dependency of efficiency on ($\alpha,2n$) kinematics

1. $E_{\text{beam}} = 3.74$ MeV/A in inverse kinematics
Angular dependency of efficiency down to 0.1keV

1. As you lower the energy of neutron, it seems the angular dependency of the efficiency gets smaller.

\[ \theta_{\text{hole}} = 3.58 \]
\[ \theta_{3\text{He}} = 19.74 \]
\[ \theta_{\text{BF}_3} = 39.46 \]
HabaNERO designed for high and flat efficiency

- HABANERO: Heavy ion Accelerated Beam induced (Alpha,Neutron) Emission Ratio Observer
- Properties:
  1) Relatively high and flat efficiency for large energy range
  2) For $0.1 \text{ MeV} \leq E_n \leq 20 \text{ MeV}$, $\langle \varepsilon \rangle = 22\%$, $\varepsilon_{\text{max}} = 27\%$, $\varepsilon_{\text{min}} = 17\%$, $\delta \varepsilon = 5\%$.

Neutron detection efficiency by MCNP simulation for neutrons having various theta angle
HabaNERO Commissioning at OU

- Mono-energetic beam at EAL, Ohio University
- $E_n = 3.92, 6.51$ MeV by D(d,n) and 13.3 MeV by T(d,n)
Neutron Detector for (α,n) reaction

- HABANERO: Heavy ion Accelerated Beam induced (Alpha,Neutron) Emission Ratio Observer

- Properties:
  1) Relatively high and flat efficiency for large energy range
  2) For $0.1 \text{ MeV} \leq E_{n_{\text{isotr}}} \leq 20 \text{ MeV}$, $\langle \varepsilon \rangle = 22 \%$, $\delta \varepsilon = 5 \%$, $\varepsilon_{\text{max}} = 27 \%$, $\varepsilon_{E=0.1} = 20 \%$, $\varepsilon_{E=20} = 17 \%$. 

Neutron detection efficiency by MCNP simulation for $^{75}\text{Ga}(\alpha,n)$ reaction
Neutron Detector for \((\alpha,n)\) reaction

Calculated \((\alpha,n)\) and \((\alpha,2n)\) cross sections from TALYS code
- Efficiency vs. Phi angle with $En = 3$ MeV and Theta = 40/90 deg (Left Top) and with $En = 4$ MeV and Theta = 40/90 deg (Right Top)
Differences on Efficiency vs. Polar angle at a fixed En and theta angle between two quads and four quads

MCNP simulation result
MCNP simulation result

- Particle Tracks for neutrons bouncing back to another side of quads (18 neutrons out of 76 generated at (theta, phi) = (90, 90)
- Particle Tracks for neutrons bouncing back to another side of quads (22 neutrons out of 97 generated at (theta,phi) = (90,45)
1. By varying populations of final states of $^{78}$As/$^{77}$As, we can perform the sensitivity study of the efficiency.

1) For (a,n) reaction: $19.8\% \leq \langle \epsilon \rangle \leq 24.5\%$ and $0.2\% \leq \delta \epsilon \leq 2.04\%$

2) For (a,2n) reaction:
   - The 1$^{\text{st}}$ neutron: $18.58\% \leq \langle \epsilon_{n1} \rangle \leq 20.83\%$ and $0.02\% \leq \delta \epsilon_{n1} \leq 0.82\%$
   - The 2$^{\text{nd}}$ neutron: $10.25\% \leq \langle \epsilon_{n2} \rangle \leq 15.4\%$ and $0.08\% \leq \delta \epsilon_{n2} \leq 6.07\%$

<table>
<thead>
<tr>
<th>Ebeam (MeV/A)</th>
<th>$&lt;\text{Eff}&gt;_{M1}$ (%)</th>
<th>dEff_M1 (%)</th>
<th>$&lt;\text{Eff}&gt;_{M1_n1}$ (%)</th>
<th>dEff_M1_n1 (%)</th>
<th>$&lt;\text{Eff}&gt;_{M1_n2}$ (%)</th>
<th>dEff_M1_n2 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.41</td>
<td>20.97</td>
<td>±1.94</td>
<td>18.58</td>
<td>±0.02</td>
<td>11.36</td>
<td>±0.08</td>
</tr>
<tr>
<td>2.64</td>
<td>19.32</td>
<td>±2.52</td>
<td>20.02</td>
<td>±0.35</td>
<td>10.25</td>
<td>±3.16</td>
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<tr>
<td>2.87</td>
<td>20.63</td>
<td>±2.14</td>
<td>20.64</td>
<td>±0.81</td>
<td>10.53</td>
<td>±5.59</td>
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<tr>
<td>3.1</td>
<td>23.42</td>
<td>±1.39</td>
<td>19.65</td>
<td>±0.11</td>
<td>12.59</td>
<td>±3.67</td>
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<tr>
<td>3.32</td>
<td>21.91</td>
<td>±1.3</td>
<td>20.4</td>
<td>±0.5</td>
<td>12.29</td>
<td>±6.07</td>
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<tr>
<td>3.53</td>
<td>22.24</td>
<td>±1.03</td>
<td>20.67</td>
<td>±0.76</td>
<td>13.18</td>
<td>±5.64</td>
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<td>3.74</td>
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<td>±0.23</td>
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<td>±0.82</td>
<td>15.36</td>
<td>±4.69</td>
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Level Diagrams of $^{75}\text{Ga}(\alpha, xn)$ reaction

![Diagram showing discrete and continuum levels](image-url)
Angular Distribution of $^75\text{Ga}(\alpha,n)$ reaction in inverse kinematics

- $d\sigma/d\Omega$ vs. Angle (Discrete Levels) – Inverse Kinematics, LAB Frame
- An assumption of isotropic differential cross section in CoM frame from compound reaction
Abundance Patterns

• “How and where were all of the elements created in the universe?”
• “How do stars burn and explode?”
• Abundance pattern = historical evidences of element formation

Observed \( n \)-capture abundances in CS 22892-02
C. Sneden et al.
Preliminary Result of HabaNERO Commissioning

- For $3.92 \text{ MeV} \leq E_n \leq 13.3 \text{ MeV}$, $<\varepsilon> = 24.4 \%$, $\varepsilon_{\text{max}} = 26.5 \%$, $\varepsilon_{\text{min}} = 21.7 \%$, $\delta \varepsilon = 2 \%$.

![Scaled efficiency of MCNP6 simulation by measured data points](image)
ReA3 Nuclear Astrophysics Experimental Devices

ANASEN (LSU, FSU, TAMU, MSU)
(p,p), (p,α), (α,p), (d,p), (d,n), (α,n) for rp/weak-r

SuN (MSU, ND)
(p,γ) for p-process

Gas Target JENSA (CSM, MSU, ND, ORNL)
(α,p), (p,γ) for rp/ap-process

SECAR
(ANL, CSM, MSU, LSU, ND, ORNL, OU, LBNL, PNNL, Indiana)
(p,γ) for rp-process

AT-TPC
(MSU, WMU, ND)
(3He,d), (d,p) for rp-process

HabaNERO
(MSU, ND, OU, CMU, LSU, FIU, UT)
(α,n) for weak r-process

Heavy Ion Beams
Rapid Neutron Capture Process (r-process)
He gas cell target

- 2um thickness Ti window foil
- large gas volume

Projection of the He gas cell target design
Correlated neutron spectrum with the EBIT signal to compare between gas-in and out run

Preliminary result of neutron yield over $^{75}$Ga beam energy for the rate of 4000ps.

- Correlation between EBIT signal and neutron signal (from HabaNERO)
- Neutron excess from comparison of 4He gas-in and gas-out run to remove systematic fluctuation effect.
- Neutron excess were found in EBIT-HabaNERO correlation spectrum.

Relative $^{75}$Ga($\alpha$,n) Yield (Online Analysis)

- Measured M1 wt Avg
- Talys v1.4 M1 Default
- M1_STDEV_Unc

Preliminary!
Preliminary Results

- Neutron were detected in EBIT-HabaNERO correlation spectrum.
- Neutron excess of $^{75}$Ga(a,n) reaction from comparison of 4He gas-in and gas-out run.

![PID plot in the PSIC](image)

![Correlated neutron time spectrum ($E_{beam}$ = 3.58 MeV/u)](image)
Particle Tracks in TexAT

A picture for TexAT and Micromega Plate

Sample particle tracks

Sample vertex identification by energy loss

Finding track lines using Hough Transformation