Neutron-capture cross section for $^i$ process bottleneck $^{75}$Ga: $^{75}$Ga$(d, p\gamma)^{76}$Ga

69th Meeting of the INTC
February 9th

Spokeperson: Francesco Pogliano, PhD candidate
University of Oslo, Oslo, Norway
Aims

- Aim: Finding the nuclear level density (NLD) and gamma strength function (GSF) of $^{76}\text{Ga}$
Aims

Neutron capture rates important for nucleosynthesis
Aims

Neutron capture rates important for nucleosynthesis

i and r process involve neutron-rich nuclei
Aims

Neutron capture rates important for nucleosynthesis

i and r process involve neutron-rich nuclei

We rely on theoretical models

Experiments -> constrain uncertainty
Motivation 1

The case of Ga-75

Different abundance patterns for s and r process
Motivation 1

The case of Ga-75

Different abundance patterns for s and r process

Abundance in stars: combination of r and s process abundance patterns
Motivation 1

The case of Ga-75

Different abundance patterns for s and r process

Abundance in stars: combination of $r$ and $s$ process abundance patterns

Sometimes not enough
Observation of As in carbon-poor, metal-poor star HD94028
Not able to explain its relative abundance by r and s processes alone

Motivation 1

The impact of \((n,\gamma)\) reaction rate uncertainties on the predicted abundances of \(i\)-process elements with \(32 \leq Z \leq 48\) in the metal-poor star HD94028

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Accepted 2019 November 21. Received 2019 November 18; in original form 2019 September 13

ABSTRACT
Several anomalous elemental abundance ratios have been observed in the metal-poor star HD94028. We assume that its high [As/Ge] ratio is a product of a weak intermediate \((i)\) neutron-capture process. Given that observational errors are usually smaller than predicted nuclear physics uncertainties, we have first set up a benchmark one-zone \(i\)-process nucleosynthesis simulation results of which provide the best fit to the observed abundances. We have then performed Monte Carlo simulations in which 113 relevant \((n,\gamma)\) reaction rates of unstable species were randomly varied within Hansen–Feshbach model uncertainty ranges for each reaction to estimate the impact on the predicted stellar abundances. One of the interesting results of these simulations is a double-peaked distribution of the As abundance, which is caused by the variation of the \(^{76}\)Ga \((n,\gamma)\) cross-section. This variation strongly anticorrelates with the predicted As abundance, confirming the necessity for improved theoretical or experimental bounds on this cross-section. The \(^{58}\)Ni \((n,\gamma)\) reaction is found to behave as a major bottleneck for the \(i\)-process nucleosynthesis. Our analysis finds the Pearson product–moment correlation coefficient \(r_p > 0.2\) for all of the \(i\)-process elements with \(32 \leq Z \leq 42\), with significant changes in their predicted abundances showing up when the rate of this reaction is reduced to its theoretically constrained lower bound. Our results are applicable to any other stellar nucleosynthesis site with the similar \(i\)-process conditions, such as Sakurai’s object \((V4334\ Sagittarii)\) or rapidly accreting white dwarfs.

Key words: nuclear reactions, nucleosynthesis, abundances—stars: abundances—stars: AGB and post-AGB.

Observation of As in carbon-poor, metal-poor star HD94028
Not able to explain its relative abundance by \(r\) and \(s\) processes alone
\(i\) process might explain this
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$i$ process might explain this but only if $^{75}\text{Ga}(n,\gamma)$ rate is low
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Observation of As in carbon-poor, metal-poor star HD94028

Not able to explain its relative abundance by r and s processes alone

$i$ process might explain this but only if $^{75}$Ga(n,$\gamma$) rate is low

Uncertainties too large conclude
Motivation 1

Measuring indirectly the neutron-capture rate
-> constrain the uncertainty
Motivation 1

Measuring indirectly the neutron-capture rate
-> constrain the uncertainty

Either clearer picture of the i process, or uncovering the need of a new, yet unknown theory
Motivation 2

Providing useful experimental data, useful for the $i$ process and for the $r$ process.
Experiment

Steps:

A beam of $^{75}\text{Ga}$ is impinged onto a $\text{CD}_2$ target.
Experiment

Steps:

A beam of $^{75}$Ga is impinged onto a CD$_2$ target

Detect p-$\gamma$ coincidences with MINIBALL, Oslo’s LaBr3 and T-REX
Experiment

Steps:
A beam of $^{75}\text{Ga}$ is impinged onto a $\text{CD}_2$ target
Detect $p$-$\gamma$ coincidences with MINIBALL, Oslo’s LaBr3 and T-REX
Calculate excitation energy of $^{76}\text{Ga}$ via kinematics
Experiment

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Calculate excitation energy of $^{76}\text{Ga}$ via kinematics

Make “raw” matrix
Experiment

Oslo method (in inverse kinematics)

Unfolding

First generation

Data for $^{127}$Sb at OCL
Experiment

Oslo method (in inverse kinematics)

Unfolding

First generation

Fermi’s golden rule:

\[ P(E_\gamma, E_x) \propto \rho(E_x - E_\gamma) \mathcal{T}(E_\gamma) \]

GSF:

\[ \mathcal{T}(E_\gamma) = \frac{f(E_\gamma)}{2\pi E_\gamma^3} \]
From the NLD and the GSF it is possible to retrieve the \((n,\gamma)\) cross section using the HF formalism.
From the NLD and the GSF it is possible to retrieve the \((n,\gamma)\) cross section using the HF formalism MACS and capture rate for A-1 nucleus (Calculations with reaction code TALYS).
First application of the Oslo method in inverse kinematics

Nuclear level densities and $\gamma$-ray strength functions of $^{80}$Kr

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Received: 12 July 2010; Accepted: 14 January 2011. Published online: 26 February 2010. © The Author(s) 2010. Communicated by A. Miletich.

Abstract The $\gamma$-ray strength function ($\gamma$SR) and nucleus level density (NLD) have been extracted for the first time from inverse kinematics reactions with the Oslo method. This novel technique allows measurements of their properties over a wide range of previously inaccessible excitation energies. Proton-$\gamma$ coincidence events from the $^{80}$Kr reactions were measured at Thulins LAB and the $\gamma$SR NLD of $^{80}$Kr was obtained. The low-energy region of the $\gamma$SR compared to shell-model calculations, while the high-energy region is dominated by M3 strength. The $\gamma$SR

This has been done many times before, also in inverse kinematics.
Setup

Closely modelled to experiment IS559 on $^{67}$Ni

<table>
<thead>
<tr>
<th>Previous experiment (IS559)</th>
<th>Present case</th>
</tr>
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<tbody>
<tr>
<td>$^{66}$Ni + CD$_2$ → $^{67}$Ni + p</td>
<td>$^{75}$Ga + CD$_2$ → $^{76}$Ga + p</td>
</tr>
<tr>
<td>E($^{66}$Ni) = 300 MeV (4.5 MeV/A)</td>
<td>E($^{75}$Ga) = 350 MeV (4.6 MeV/A)</td>
</tr>
<tr>
<td>$I_{beam} = 4 \times 10^6$ pps at MINIBALL</td>
<td>$I_{beam} = 2.5 \times 10^6$ pps at MINIBALL</td>
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<tr>
<td>$d_{target} = 0.6$ mg/cm$^2$</td>
<td>$d_{target} = 1.0$ mg/cm$^2$</td>
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<tr>
<td>6 days of beamtime</td>
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<tr>
<td>6 LaBr3 detectors from Oslo were far from target position</td>
<td>6 LaBr3 detectors 5 cm closer to target position</td>
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<td>C-REX with only forward CD detector covering 25° to 49°</td>
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1.5M good coincidences
Setup

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2.5e6 beam of 2005 might not be replicated

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2.5e6 beam of 2005 might not be replicated

Can the experiment be carried out?

1.5M good coincidences
Normalization

The lower the beam yield, the higher the uncertainty -> risk of the experiment being inconclusive
Normalization

Data for $^{127}$Sb at OCL

The lower the beam yield, the higher the uncertainty -> risk of the experiment being inconclusive

Oslo method: technically ok with only ~100k coincidences for non-exotic nuclei
Normalization

The lower the beam yield, the higher the uncertainty -> risk of the experiment being inconclusive

Oslo method: technically ok with only ~100k coincidences for non-exotic nuclei

Require low energy states for normalization
Convert Proposal to Lol

We need a (more) complete level scheme

$^{76}$Ga is odd-odd: many levels, high statistics needed
**ADOPTED LEVELS, GAMMAS for $^{76}$Ga**

**Author:** Balraj Singh  
**Citation:** Nucl. Data Sheets 74, 63 (1995)  
**Cutoff date:** 22-Dec-1994  
**Full ENDF file**  
$Q(\beta^-) = 4916.3$ keV  
$S(n) = 5903$ keV  
$S(p) = 11027$ keV  
$Q(a) = -8938.6$ keV  
**References:**  
A $^{72}$Zn $\beta^-$ decay (5.7 S)

<table>
<thead>
<tr>
<th>$E(\text{level})$ (keV)</th>
<th>XREF</th>
<th>$Jm(\text{level})$</th>
<th>$T_{1/2}(\text{level})$</th>
<th>$E(y)$ (keV)</th>
<th>$I(y)$</th>
<th>$M(y)$</th>
<th>Final level</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>A</td>
<td>$(2+,3\pi)$</td>
<td>32.6 ± 6</td>
<td>100</td>
<td>D</td>
<td>8.8</td>
<td>(2+,3\pi)</td>
</tr>
<tr>
<td>172.29</td>
<td>A</td>
<td>$(1+,2+,3\pi)$</td>
<td></td>
<td>100</td>
<td>D</td>
<td>8.8</td>
<td>(2+,3\pi)</td>
</tr>
<tr>
<td>199.50</td>
<td>A</td>
<td>1</td>
<td></td>
<td>100</td>
<td>D</td>
<td>8.8</td>
<td>(2+,3\pi)</td>
</tr>
<tr>
<td>275.28</td>
<td>A</td>
<td>1</td>
<td></td>
<td>100</td>
<td>5.3</td>
<td>16</td>
<td>(1+,2+,3\pi)</td>
</tr>
<tr>
<td>281.57</td>
<td>A</td>
<td>(LE 3)</td>
<td></td>
<td>98.6</td>
<td>100</td>
<td>8.8</td>
<td>(2+,3\pi)</td>
</tr>
<tr>
<td>369.81</td>
<td>A</td>
<td>(LE 3)</td>
<td></td>
<td>33.12</td>
<td>100</td>
<td>8.8</td>
<td>(2+,3\pi)</td>
</tr>
<tr>
<td>560.53</td>
<td>A</td>
<td>1</td>
<td></td>
<td>12.2</td>
<td>108</td>
<td>100</td>
<td>(2+,3\pi)</td>
</tr>
<tr>
<td>680.83</td>
<td>A</td>
<td>(LE 3)</td>
<td></td>
<td>10.3</td>
<td>48</td>
<td>100</td>
<td>(2+,3\pi)</td>
</tr>
<tr>
<td>781.55</td>
<td>A</td>
<td>(LE 3)</td>
<td></td>
<td>69.29</td>
<td>100</td>
<td>8.8</td>
<td>(2+,3\pi)</td>
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<tr>
<td>1030.38</td>
<td>A</td>
<td>1</td>
<td></td>
<td>78.8</td>
<td>100</td>
<td>8.8</td>
<td>(2+,3\pi)</td>
</tr>
<tr>
<td>1106.03</td>
<td>A</td>
<td></td>
<td></td>
<td>100</td>
<td>8.8</td>
<td>(2+,3\pi)</td>
<td></td>
</tr>
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</table>

We need a more complete level scheme for $^{76}$Ga is odd-odd: many levels, high statistics needed. Might be inconclusive for less than 750k coincidences (corresponding to ~1.2e6 pps @ MINIBALL under the same conditions).
Updated estimates on the production of $^{75}$Ga may be needed to guarantee useful statistics.
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May convert this Proposal to a Letter of Intent until beam yields are clarified.
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Thank you
Questions
Angle distribution

\[ d(^{75}\text{Ga},p)^{76}\text{Ga} \]

\[ T_{\text{inc}} = 345.0 \text{ MeV} \]