Measurement of the $^{62,63}\text{Ni}(n,\gamma)$ cross section at n_TOF/CERN

Claudia Lederer
University of Vienna

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ERAWAST II, Zürich
Nucleosynthesis of heavy elements

Claudia Lederer  
ERAWAST II, Zürich, 01.09.2011
Nucleosynthesis of heavy elements

**rapid neutron capture**
- explosive scenarios (supernovae)
- $\tau_{n,\gamma} (10^{-3}s) < t_{1/2}$
- $N_n \sim 10^{21} \text{ cm}^{-3}$

**s-process**

**slow neutron capture**
- AGB stars, massive stars
- $\tau_{n,\gamma} (\sim 100 \text{ yr}) > t_{1/2}$
- $N_n \sim 10^{8} \text{ cm}^{-3}$
s-process: Local approximation

- repeated neutron bursts
- temperature and neutron density constant

\[ s\text{-process abundance} \times \text{cross section} = N_s \langle \sigma \rangle = \text{constant} \]

Maxwellian averaged cross section (MACS):

\[
\langle \sigma \rangle_{kT} = \frac{2}{\sqrt{\pi}} \frac{\int \sigma(E_n) E_n \exp(-E_n / kT) dE_n}{\int E_n \exp(-E_n / kT) dE_n}
\]
s-process: Local approximation

- repeated neutron bursts
- temperature and neutron density constant

\[ \text{s-process abundance} \times \text{cross section} = N_s <\sigma> = \text{constant} \]

A<90 weak s-process
A>90 main s-process

F. Käppeler, Prog. Part. Nucl. Phys. 43 (1999)
s-process: stellar sites

<table>
<thead>
<tr>
<th>weak component:</th>
<th>main component:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Massive stars (&gt;8M(_\odot))</td>
<td>AGB stars (1-3M(_\odot))</td>
</tr>
<tr>
<td>He core burning</td>
<td>C shell burning</td>
</tr>
<tr>
<td>(^{22})Ne((\alpha,n))</td>
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</tr>
<tr>
<td>kT(\sim)25 keV</td>
<td>kT(\sim)90 keV</td>
</tr>
<tr>
<td>T(\sim)3-3.5\times10^8 K</td>
<td>T(\sim)10^9 K</td>
</tr>
<tr>
<td>(N_n = 10^6) cm(^{-3})</td>
<td>(N_n = 10^{11}-10^{12}) cm(^{-3})</td>
</tr>
<tr>
<td>N(_\sigma) not const (\rightarrow) Propagation effects !!</td>
<td></td>
</tr>
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<td>kT(\sim)8 keV</td>
<td>kT(\sim)25 keV</td>
</tr>
<tr>
<td>T(\sim)0.9\times10^8 K</td>
<td>T(\sim)3-3.5\times10^8 K</td>
</tr>
<tr>
<td>(N_n = 10^7-10^8) cm(^{-3})</td>
<td>(N_n = 10^{10}-10^{11}) cm(^{-3})</td>
</tr>
</tbody>
</table>
How to measure MACS?

• activation technique

create quasi Maxwellian spectrum in laboratory

measure spectrum averaged CS:

\[ <\sigma>_\text{EXP} = \frac{N_P}{N_T} \frac{1}{\Phi} \]

needs radioactive reaction product

include direct component

need to know: CS dependence and neutron spectrum

• time of flight technique
The time-of-flight technique

- Neutron production target
- Pulsed charged particle beam
- Pulsed neutron beam
- Flight length $L$
- Reaction product detector
- Sample
- $E_n = mc^2(\gamma - 1)$ with $\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$

$tof = t_{reaction} - t_{production}$

$v = \frac{L}{tof}$
The time-of-flight technique

- Extract cross-section by determining reaction-yield $Y_R (E_n)$:

$$Y_R = \frac{C - B}{\varepsilon \cdot f \cdot \phi}$$

C.....count rate
B.....background
$\varepsilon$.....efficiency
f.....corrections for sample size
$\phi$.....neutron flux

Courtesy F. Gunsing
The time-of-flight technique

• Excitation Energy: \[ E_c = \sum E_\gamma = E_n + S_n \]

- detection of full \( \gamma \) cascade
  \( \varepsilon_c \approx 100 \% \)
  4\( \pi \) detector array

- detection of single \( \gamma \)'s
  e.g. apply pulse height weighting technique:
  pulse height dependent weight on signals to achieve
  \[ \varepsilon_\gamma = k \cdot E_\gamma \]
  so that:
  \[ \varepsilon_c = k \cdot (E_n + S_n) \]

Courtesy F. Gunsing
spallation neutron source
- 20 GeV/c protons on Pb-target
- water as moderator and coolant
- pulse width: 7 ns
- intensity: $7 \times 10^{12}$ protons per pulse
  $\rightarrow 1.2 \times 10^6$ neutrons/pulse @ 185 m
- flight path: 185 m
- neutron energy: $10^{-3}$-$10^{10}$ eV
- beam size at capture setup: Ø~4 cm
- energy resolution $\Delta E/E$:
  $3 \times 10^{-4}$ @ 1 eV – $4.2 \times 10^{-3}$ @ 1 MeV

www.cern.ch/ntof
2 setups for capture measurements:

• BaF$_2$ total absorption calorimeter
  40 crystals in $4\pi$ geometry

• two C$_6$D$_6$ detectors
  optimized for low neutron sensitivity
  ($\varepsilon_n/\varepsilon_\gamma < 4 \cdot 10^{-5}$)
  detection of at most one $\gamma$ ray per cascade
  $\Rightarrow$ PHWT
• sample independent background → measurement of empty holder
• neutron induced background → measurement of dummy sample (e.g. Carbon)
• $\gamma$-induced background (200 eV – 300 keV) → measurement of dummy sample (e.g. Pb)
• measurement with neutron filters

Borated water as moderator: significant reduction of $\gamma$ background!!!
Borated water: 2009 vs. 2010

Iron (45 mm, 2mm) [background subtracted]

Counts/Pulse

$\log_{10}(E_{\nu})$

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Observation of old halo star CS22892-052:
• A>120: scales with solar r-process component
• A<120: abundances systematically lower (Sneden et al.)

solar r-component:

\[ N_r = N_{\odot} - N_s \]

\[ \propto \frac{1}{\langle \sigma \rangle_{n,\gamma}} \]
$^{62}$Ni$(n,\gamma)$: Motivation

High uncertainties of $(n,\gamma)$ cross-sections in medium mass region directly enter into r-process calculations.

Neutron capture cross-section of $^{62}$Ni influences abundance of following isotopes up to $A=90$!
$^{62}\text{Ni}(n,\gamma)$: Motivation

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$^{62}\text{Ni}(n,\gamma)$ MACS at 30 keV

Campaign to measure all stable Fe and Ni isotopes!

(J.L. Tain, M. Heil et al, INTC/P-208, 2006)
$^{62}\text{Ni}(n,\gamma)$: available data

- Tomyo et al., 2005
- Nassar et al., 2005
- Alpizar-Vicente et al., 2008
- Dillmann et al., 2010
- Bao and Kaeppeler, 1987
- Bao et al., 2000
- Rauscher and Guber, 2002

MACS (mb) vs. Neutron Energy (keV)
previous measurements compared to JENDL evaluation
(Courtesy I. Dillmann)

new data from n_TOF
previous measurements compared to JENDL evaluation
(Courtesy I. Dillmann)

new data from n_TOF

Preliminary !!!
$^{63}\text{Ni}(n,\gamma)$: Motivation

- $t_{1/2}(\text{terr})=100.1\;\text{y}$, $t_{1/2}(90\;\text{keV})=0.4\;\text{y}$

Core He burning, $kT=25\;\text{keV}$, $N_n\sim10^6\;\text{cm}^{-3}$

C shell burning, $kT=90\;\text{keV}$, $N_n\sim10^{11}\;\text{cm}^{-3}$
$^{63}\text{Ni}(n,\gamma)$: Motivation

$^{63}\text{Ni}(n,\gamma)$ MACS x2, /2

$^{63}\text{Ni}(n,\gamma)$ at n_TOF

- $t_{1/2}=100.1\text{ yr}$
- no cross section data above thermal energies
- MACS at stellar energies relies on extrapolations or calculations
- MACS at 30 keV:
  - KADoNiS: $31\pm 6\text{ mb}$
  - TENDL(2009): $68.9\text{ mb}$

- Measurement of $^{63}\text{Ni}(n,\gamma)$ at n_TOF (C. Lederer, C. Massimi, et al., INTC/P-283, 2010)
$^{63}\text{Ni}(n,\gamma)$ at n_TOF

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  - TENDL(2009): $68.9 \text{ mb}$
  - this work: $90.8 \text{ mb}$
- this work: generation of artificial set resonances with fixed statistical properties
**63Ni sample**

Original material (TU Munich, G. Korschinek, T. Faestermann):
- $^{62}$Ni sample irradiated in thermal reactor (in 1984 and 1992)
- total mass: 1002 mg
- enrichment in $^{63}$Ni: ~13 % (= 131.8 mg)
- contaminants: ~15.4 mg $^{63}$Cu

After chemical separation at PSI (D. Schumann):
- NiO powder, 1156 mg
- $^{63}$Ni/$^{62}$Ni=0.134 (=108.4 mg)
- Container: PEEK ($C_{20}H_{12}O_3$)
- <0.01 mg $^{63}$Cu
Borated water: 2009 vs. 2011

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$^{63}\text{Ni}(n,\gamma)$ – first results from n_TOF (2011)
$^{63}\text{Ni}(n,\gamma)$ – first results from n_TOF (2011)
• (n,γ) cross sections over wide energy range (few – hundreds keV) are needed as input for s-process studies

• measurement campaign at n_TOF for improving data on Fe/Ni cross sections (54,56,57Fe, 62Ni finished, 58Ni underway)

• measurement of unstable 63Ni(n,γ) at n_TOF sucessfully finished 2011, data analysis underway

• new n_TOF programmes of astrophysical interest coming forward, e.g. (n,p) reactions (see talk by P.J. Woods)
THANK YOU FOR YOUR ATTENTION