Nuclear astrophysics at FRANZ
(neutron-induced reactions for nuclear astrophysics)

René Reifarth
GSI Darmstadt/University of Frankfurt

International Summer School
"Nuclear Theory and Astrophysical Applications"
Dubna, Russia, July 24 - August 2
solar abundance distribution

- H, He
- C, O
- Fe
- Ba
- Pb

- big bang nucleosynthesis
- fusion of charged particles
- thermal equilibrium
- neutron induced reactions

Abundance distribution: $\text{Si} = 10^6$
Nucleosynthesis of the elements

Heavy elements (A>56) are produced by the s-process (~50%) and the r-process (~50%)

Fusion up to iron

Proton number

Neutron number
the s-process

- $^{80}$Br, $t_{1/2}=17$ min, 92% ($\beta^-$), 8% ($\beta^+$)
- $^{64}$Cu, $t_{1/2}=12$ h, 40% ($\beta^-$), 60% ($\beta^+$)
- $^{80}$Se, $t_{1/2}=65$ ka, 92% ($\beta^-$), 8% ($\beta^+$)
- $^{85}$Kr, $t_{1/2}=11$ a

- p-process
- s-only
- r-only
s-process in AGB stars

convective envelope

H - burning

He - burning

He – intershell

C-O - core

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

\[ ^{22}\text{Ne}(\alpha,\text{n}) \]
s-process nucleosynthesis

Two components were identified and connected to stellar sites:

**Main s-process 90<A<210**
- TP-AGB stars 1-3 $M_\odot$

<table>
<thead>
<tr>
<th>Component</th>
<th>Temperature</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell H-burning</td>
<td>$0.9 \times 10^8$ K</td>
<td>$10^7 - 10^8$ cm$^{-3}$</td>
</tr>
<tr>
<td>He-flash</td>
<td>$3-3.5 \times 10^8$ K</td>
<td>$10^{10} - 10^{11}$ cm$^{-3}$</td>
</tr>
<tr>
<td>$13C(\alpha,\eta)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{22}Ne(\alpha,\eta)$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Weak s-process A<90**
- Massive stars > 8 $M_\odot$

<table>
<thead>
<tr>
<th>Component</th>
<th>Temperature</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core He-burning</td>
<td>$3-3.5 \times 10^8$ K</td>
<td>$10^6$ cm$^{-3}$</td>
</tr>
<tr>
<td>Shell C-burning</td>
<td>$\sim 1 \times 10^9$ K</td>
<td>$10^{11} - 10^{12}$ cm$^{-3}$</td>
</tr>
<tr>
<td>$^{22}Ne(\alpha,\eta)$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

René Reifarth (Goethe University Frankfurt)
What’s needed?

- Reaction rates
  - Neutron induced (1-200 keV)
  - Charged particles
- Half-lives

\[
\langle \sigma \rangle_{kT} = \frac{\langle \sigma \cdot v \rangle}{v_T} = \frac{2}{\sqrt{\pi}} \int_0^\infty \sigma(E) \cdot E \cdot e^{\frac{E}{kT}} \cdot dE
\]
René Reifarth (Goethe University Frankfurt)

Stellar model vs. experiment

Modern s-process models (AGB stars)

Classical s-process

new n-facilities (FRANZ, SARAF)

DANCE, n_TOF

Life Times for Unstable Isotopes, $\rho_n = 10^{11}$ cm$^{-3}$

- Neutron capture
- $\beta$-decay

$^{95}$Zr

$^{93}$Zr
Neutron Captures – time-of-flight technique

**Experiment**

- Pulsed proton beam
- Time pick off
- Neutron production target
- Flight path length
- Time-of-flight
- Low Energy
  - $E_n = 1$ MeV
  - $\Delta E = 7$ keV
  - $\Delta E = 0.2$ keV
  - $\Delta E = 0.01$ meV
- High energy
  - $E_n = 100$ keV
  - $\Delta E = 32$ keV
  - $\Delta E = 1$ keV
- $\gamma$-Rays
  - $E_n = 1$ MeV
  - $\Delta E = 1.6$ MeV
  - $\Delta E = 1$ meV
  - $\Delta E = 5$ eV

**Example:**

- $L = 20$ m
- $\text{TOF}_g = 67$ ns
- $\Delta \text{TOF} = 5$ ns
- $\Delta \text{TOF} = 0.7$ µs
- $\Delta \text{TOF} = 1$ ms

- $E_n = 1$ MeV
- $\text{TOF}_n = 1.5$ µs
- $\Delta E = 7$ keV
- $\Delta E = 1.6$ MeV
- $E > 2$ eV

- $E_n = 100$ keV
- $\text{TOF}_n = 4.6$ µs
- $\Delta E = 0.2$ keV
- $\Delta E = 1$ keV
- $E > 2$ eV

- $E_n = 10$ keV
- $\text{TOF}_n = 15$ µs
- $\Delta E = 7$ eV
- $E > 2$ eV

- $E_n = 1$ eV
- $\text{TOF}_n = 1.5$ ms
- $\Delta E = 0.01$ meV
- $\Delta E = 1$ meV
- $\Delta E = 5$ eV

**Astrophysics**
branch point in the s-process path

\[
\begin{align*}
  & \sim t_{1/2}^{-1} \\
  & s\text{-process path} \\
  & \sim \sigma_{\text{capture}} \Phi_n
\end{align*}
\]

\[
\begin{align*}
  f_\beta &= \frac{\lambda_\beta}{\lambda_\beta + \lambda_n} \\
  &\approx \frac{\langle \sigma \rangle_A N_A}{\langle \sigma \rangle_{A+1} N_{A+1}}
\end{align*}
\]
(n,g) experiments with unstable isotopes and fundamental stellar physics evaluations

<table>
<thead>
<tr>
<th>Branch Isotope</th>
<th>Half-Life</th>
<th>Facility</th>
<th>Observable</th>
<th>Stellar Physics</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{151}\text{Sm}$</td>
<td>93 yr</td>
<td>FZK, n_TOF, DANCE</td>
<td>$^{152}\text{Gd}$ in solar distribution $^{151}\text{Eu}/^{153}\text{Eu}$ ratio hyperfine line split</td>
<td>Timescale of hot Helium-shell flash s-process in very old stars</td>
<td>done</td>
</tr>
<tr>
<td>$^{134}\text{Cs}$</td>
<td>2 yr</td>
<td>DANCE, FRANZ</td>
<td>Ba isotope ratios from presolar grains</td>
<td>Sets $^{12}\text{C}$ abundance of He-shell flash</td>
<td>current uncertainty: ± 30%</td>
</tr>
<tr>
<td>$^{135}\text{Cs}$</td>
<td>2 Myr</td>
<td></td>
<td>Ba isotope ratios</td>
<td>Amount of rotation</td>
<td>± 10%</td>
</tr>
<tr>
<td>$^{95}\text{Zr}$</td>
<td>64 d</td>
<td>FRANZ/FAIR</td>
<td>$^{96}/\text{Zr}/^{94}\text{Zr}$ ratio presolar grains</td>
<td>Temperature at bottom of He-shell flash region</td>
<td>Current uncertainty: 20 - 80 mb</td>
</tr>
</tbody>
</table>

René Reifarth (Goethe University Frankfurt)
Experimental problems

\[ f_\beta = \frac{\lambda_\beta}{\lambda_\beta + \lambda_n} \approx \frac{\langle \sigma \rangle_A N_A}{\langle \sigma \rangle_{A+1} N_{A+1}} \]

\[ \lambda_n \sim \sigma_{\text{capture}} \phi_n \]

**Unstable isotope**
- sample preparation
- very small amounts
- radioactive background

**High precision**
- neutron induced background
- isotopic impurities
- statistics

**Activation technique**

**TOF technique**

**Calorimetric technique**
Red Giants – easy to spot

Orion

Betelgeuze

Bootes

Arkturus
Red Giants become White Dwarfs

Ring nebula illuminated by the White Dwarf in the center.
branch point at $^{128}$I

- $^{127}$I
  - $^{126}$Te
    - $^{128}$Xe
      - 2 s-only isotopes
      - temperature and electron density dependent
      - no dependency on neutron flux

$\Rightarrow$ stellar thermometer
**Meteorites – hints from the sky**

Meteorites contain presolar grains!

See lecture by Ernst Zinner!
evidence for neutron capture:  

**DIRECT**

\[ ^{AX} + n \rightarrow ^{A+1X} + Q \]

\[ Q = \sum \gamma_i \]

\( \Rightarrow \) “monoenergetic” if 100 % efficiency
The $^7\text{Li}(p,n)$ reaction

- Negative Q-value (-1.644 MeV)
  - Neutron spectrum close to threshold depends strongly on proton energy
  - Q-value in reach for small accelerators
- Huge cross section close to threshold
**neutrons:**

- $^7\text{Li} (p, n)$
- 1 .. 200 keV
- $10^4$ n / s cm$^2$
- 80 cm flight path

**$\gamma$-Detector:**

- 41 BaF$_2$ crystals
- 15 cm length
- $\varepsilon_\gamma \approx 90\%$
- $\varepsilon_{\text{casc}} \approx 98\%$

---

**René Reifarth (Goethe University Frankfurt)**
Schematic TOF spectrum

- 80 cm flight path
- 10 cm inner detector radius
- $E_{\text{max}} = 200$ keV
- $E_{\text{min}} = 1$ keV

Prompt flash

$(n,\gamma)$ on sample

Other reactions
• isotopically enriched $^{128}$, $^{129}$, $^{130}$Xe
• 0.5 .. 1 g per sample
• filled in Ti-spheres ($R_{\text{in}} = 4.8 \text{ mm}$, $R_{\text{out}} = 5 \text{ mm}$)
• $p = 60 \text{ bar}$
sum spectra

- Peak at neutron-binding energy
- $\varepsilon_{\text{casc}} = 96 \ldots 98 \%$
- energy threshold: 1.6 MeV
- relative to $^{197}\text{Au}(n,\gamma)$
multiplicity

discrimination of natural background

\[(n, \gamma)\]:
90% multiplicity \( \geq 3 \)

natural background:
multiplicity \( \leq 2 \).
sample dependent background

\[(n,\gamma) + (n,n)\]

\[\text{COUNTS PER CHANNEL}\]

\[\text{GAMMA-ENERGIE (MeV)}\]

\[\text{128Xe}\]

\[\text{C}\]

\[\text{128Xe}\]

\[\text{134,136 Ba}\]

\[\text{133,135 Ba}\]
time of flight

- background due to scattered neutrons delayed
- $\sigma_{\text{tot}} / \sigma_\gamma(^{128}\text{Xe}) = 25$. 
128, 129, 130Xe(n,γ)-cross sections

NEUTRON ENERGY (keV)

CAPTURE CROSS SECTION (mb)

129Xe(n,γ)

128Xe(n,γ)

130Xe(n,γ)
Spallation neutron sources

• Need to increase neutrons/proton
• n/p = $10^{-6}$ for $^7$Li(p,n)
• Idea: high energy protons use most of their energy to knock out neutrons from a heavy nucleus - spallation
• Now n/p between 20 (LANSCE,SNS) and 250 (n_TOF)
FP 14 views the second-tier coupled water moderator.
Neutron spectrum at spallation sources

Neutron flux at FP14 Lujan Center (DANCE)

Conditions at LANSCE: $\Delta t=0.1 \, \mu s$, $E_p = 800 \, \text{MeV}$, $I_p = 100 \, \mu A$ (80 kW)
s-process nucleosynthesis in the region between iron and tin with the important branching at $^{63}\text{Ni}$. 

The s-process around $^{63}\text{Ni}$
Nuclear data needs for the weak s-process

Problems:
- small cross sections
- resonance dominated
- contributions from direct capture
- propagation effects
Detector for Advanced Neutron Capture Experiments

neutrons:
- spallation source
- thermal .. 500 keV
- 20 m flight path
- $3 \times 10^5$ n/s/cm$^2$/decade

$\gamma$-Detector:
- 160 BaF$_2$ crystals
- 4 different shapes
- $R_i=17$ cm, $R_a=32$ cm
- 7 cm $^6$LiH inside
- $\varepsilon_\gamma \approx 90\%$
- $\varepsilon_{\text{casc}} \approx 98\%$

René Reifarth (Goethe University Frankfurt)
Background due to \((n,n)\)

Reduction due to \(^6\text{LiH}\) shell
\((R_i = 10.5 \text{ cm}, R_a = 16.5 \text{ cm})\)

\[
\begin{align*}
\text{Pb w/o LiH} & \quad \text{Pb with LiH} \\
\text{Sb}(n,\gamma) \text{ from impurities in Pb} & \quad \text{Only Sb}(n,\gamma) \text{ from impurities in Pb}
\end{align*}
\]
Simulated effect of the $^6\text{LiH}$ absorber

- **no LiH**
  - $\text{Au(n,n)}$
  - $\text{Au(n,\gamma)}$

- **6 cm LiH**
  - $\text{Au(n,n)}$
  - $\text{Au(n,\gamma)}$

$10 < \frac{E_n}{\text{keV}} < 100$
New high-resolution campaign has been performed at n_TOF

A. M. ALPIZAR-VICENTE et al., PRC 77, 015806 (2008)
Propagation effects in the weak s-process

\[ ^{62}\text{Ni}(n,\gamma)^{63}\text{Ni} \]

previous: 12.5 mb
new: 28.4 mb

$^{63}\text{Ni}(n,g)$ performed at DANCE

No experimental data exist so far (only transmission measurements)
Evidence for neutron capture: 

**INDIRECT**

\[ ^A X + n \rightleftharpoons ^{A+1} X \]

\[ ^{A+1} X \rightleftharpoons ^{A+1} Y + \gamma + \ldots \]

Produced Activity:

\[ A \propto \frac{A N \cdot \Phi_n \cdot \sigma}{t_{1/2}} \cdot t_a \]
Neutron Capture on $^{14}$C

- Verification of Coulomb Dissociation (CD) as an indirect method for determining $(n,\gamma)$ rates
- Big Bang Nucleosynthesis
- Neutron-induced CNO cycles – s-process
- Neutrino-driven winds – r-process
14C - sample

- 283 mg $^{14}\text{C}$ ($t_{1/2} = 5.7$ ka), determined from decay heat
- carrier: $^{\text{nat}}\text{C}$, activated Ni-container
- active impurities:
  - $^{44}\text{Ti}$ ($t_{1/2} = 44$ y)
- 21x12 mm$^2$ diameter

activation only (presently) feasible method
Activation Method

$^{14}\text{C}(n,\gamma)^{15}\text{C}$ reaction
detected via $^{15}\text{C}(\beta^-)^{15}\text{N}$ decay
($t_{1/2}=2.5$ s)

Determination of neutron flux via $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$

Neutron source: $^{7}\text{Li}(p,n)^{7}\text{Be}$

$^{14}\text{C}$ sample irradiated for 10 s, then activity counted for 10 s ("cyclic activation")

R. Reifarth et. al, PRC C 77, 015804 (2008)
A standard neutron spectrum – working horse!

$E_p = 1912$ keV, neutron cone fully covered

Quasi-Maxwellian averaged distribution:

- $kT = 25$ keV
- $E_{\text{max}} = 110$ keV
Other neutron spectra

\(E_p = 1912\) keV

\(E_p = 2000\) keV

\(E_p = 2290\) keV

\(E_p = 2530\) keV
$^{15}$C – $\gamma$-spectra

- Measured activity of the 5.3 MeV line
- Fit: $e^{-t/2.449k} + \text{background}$

- 5.3 MeV - FE
- 4.8 MeV - SE
- 4.3 MeV - DE

René Reifarth (Goethe University Frankfurt)
Description and Deconvolution

- p-wave capture
- good agreement with exp. data

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>7.1 ± 5</td>
<td>6.5 ± 0.4</td>
<td>0.92 ± 0.08</td>
</tr>
<tr>
<td>150</td>
<td>10.7 ± 1.2</td>
<td>11.7 ± 0.6</td>
<td>1.09 ± 0.12</td>
</tr>
<tr>
<td>500</td>
<td>17.0 ± 1.5</td>
<td>16.5 ± 0.8</td>
<td>0.97 ± 0.10</td>
</tr>
<tr>
<td>800</td>
<td>15.8 ± 1.6</td>
<td>17.5 ± 0.9</td>
<td>1.11 ± 0.11</td>
</tr>
</tbody>
</table>
Comparison with other rate estimates

- Descouvemont (2000)
- Timofeyuk et al. (2006)
- This work
- Timofeyuk et al. (2006)
- Horváth et al. (2000)
- Wiescher et al. (1990)
Comparison with CD
Future developments

- Ever more neutrons
- Indirect methods
The Frankfurt neutron source at the Stern-Gerlach-Zentrum (FRANZ)

Neutron beam for activation
neutron flux: $10^{12}$ s$^{-1}$

W$_b$ = 120 keV
P$_b$ = 24 kW

W$_b$ = 700 keV
P$_b$ = 3.5 kW

W$_b$ = 2,0±0.2 MeV
P$_b$ = 10 kW

2 mA proton beam
250 kHz
< 1ns pulse width
neutron flux: $10^7$ s$^{-1}$ cm$^{-2}$

Flight path: 80 cm
The Frankfurt neutron source will provide the highest neutron flux for a nuclear astrophysics program in relevant keV region (1 – 500 keV) worldwide.

### Neutron capture measurements of small cross sections:
- Big Bang nucleosynthesis: $^1\text{H}(n,\gamma)$
- Neutron poisons for the s-process: $^{12}\text{C}(n,\gamma)$, $^{16}\text{O}(n,\gamma)$, $^{22}\text{Ne}(n,\gamma)$.
- ToF measurements of medium mass nuclei for the weak s-process.

### Neutron capture measurements with small sample masses:
- Radio-isotopes for $\gamma$-ray astronomy $^{59}\text{Fe}(n,\gamma)$ and $^{60}\text{Fe}(n,\gamma)$
- Branch point nuclei, e.g. $^{85}\text{Kr}(n,\gamma)$, $^{95}\text{Zr}(n,\gamma)$, $^{147}\text{Pm}(n,\gamma)$, $^{154}\text{Eu}(n,\gamma)$, $^{155}\text{Eu}(n,\gamma)$, $^{153}\text{Gd}(n,\gamma)$, $^{185}\text{W}(n,\gamma)$
Setup with very short flight path

Li-target 34 cm sample

Challenge: Neutrons bouncing around in the detector
**TOF spectrum - very short flight path**

- 4 cm flight path
- 17 cm inner detector radius
- $E_{\text{max}} = 100$ keV
- $E_{\text{min}} = 1$ keV

Prominent reactions:
- $(n,\gamma)$ on sample
- Other reactions

TOF (ns)

100 5.5

$E_n$ (keV)
Motivation – $^{60}\text{Fe}$ in the universe

Detection of $\gamma$-ray lines from interstellar $^{60}\text{Fe}$ with SPI (INTEGRAL)

$E_\gamma = 1173$ and $1333$ keV

$^{60}\text{Fe}/^{26}\text{Al} = 0.11 \pm 0.03$

ongoing production in massive stars and distribution by subsequent supernovae

tests stellar model and SN rate

Motivation – $^{60}$Fe on earth

- can be found in deep sea manganese crusts
- Gives hints about a nearby supernova
- 2.8 Ma ago

• Weak s-process component
• During C-shell burning in massive stars
Production and Destruction of $^{60}$Fe

$^{60}$Fe($\beta^-$) : done

$^{59}$Fe(n,$\gamma$) : Extremely difficult

$^{60}$Fe($\gamma$,n) : Coulomb dissociation, scheduled

$^{60}$Fe(n,$\gamma$) : Cyclic activation @ 25 keV, Needs to be improved to meet requirements at kT= 90 keV
Double neutron capture

- produce the sample “on the fly”
- $10^{12} \text{n/s/cm}^2 @ 25 \text{keV} \sim 5 \times 10^3 \text{n/cm}^3$
$^{59}\text{Fe}(n,\gamma)$ at FRANZ ($t_{1/2}=45$ d)

- activate $^{58}\text{Fe}$, wait for 2$^{nd}$ neutron capture
- measure $^{60}\text{Fe}/^{58}\text{Fe}$ ratio via AMS

$10^{12}$ neutrons/s/cm$^2$

**Graph:**
- **Y-axis:** Abundance relative to $^{58}\text{Fe}$
- **X-axis:** Activation time (d)
- **Red Line:** $10^{-8} \times ^{59}\text{Fe}/^{58}\text{Fe}$ ratio
- **Black Line:** $^{60}\text{Fe}/^{58}\text{Fe}$ ratio
Coulomb dissociation

• Method for radioactive beams:
  – Inverse kinematics
  – “virtual photon field” as result of relativistic interaction with high-Z target (lead)
  – Produce beam of radioactive ions
  – In-beam experiment
  – Detect ALL prompt products
    • Gammas
    • Ions
Astrophysically relevant energy window: $E_\gamma \approx S_n + kT/2 = 8 - 12$ MeV, width $\sim 1$ MeV

**Coulomb dissociation in inverse kinematics:**

- Virtual photons produced by a high-Z target (Pb)
- Projectile at $\sim 500$ MeV/u
- Large impact parameter $b$
- $E_{\text{max}}$ of the virtual photon spectrum $\sim 20$ MeV
- C and empty target measurements (to subtract nuclear contribution and background)
Fragmentation in FRS target
Stable beam from SIS
degraded
separated fragment beam
LAND/ALADIN in Cave C

SIS
FRS
ESR

Layout of the experimental facilities at GSI
R³B - Reactions with Relativistic Radioactive Beams

TARGET
(CH₂, LH₂, Pb...)

~100 – ~1000 AMeV
From: R³B
Technical Report
Summary

• n-induced reactions are important for nucleosynthesis beyond iron
• s-process can be used as a tool to constrain stellar parameters, if the corresponding reaction rates are known
• we are now close to measure n-induced cross section at stellar energies on radioactive nuclei on a routinely basis
• So far almost all measurements are done on stable nuclei