In-beam studies of the astrophysical p-process

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The $p$ nuclei

- Po (Z=84)
- Se (Z=34)

- about 35 heavy p-rich nuclei (74<A<196)
- low isotopic abundance
The \( p \)-process network

**Reaction network:**
- mainly \((\gamma,n), (\gamma,p), \) and \((\gamma,\alpha)\) reactions
- about 2000 nuclei and 20000 reactions

**Possible astrophysical site:**
- temperature about 2-3 GK
- time scale 1-10 s

\( \Rightarrow \) O/Ne layers during SN II
Impact of reaction rate measurements

- Measurement of reaction rates in the laboratory
- Calculation of stellar rates (statistical model)

Reliable stellar reaction rates

- Abundance of p nuclei

Constraints for stellar models
Abundance of $p$ nuclei: prediction vs. observation

Error bars only due to nuclear physics input

S. Goriely et al., Astronomy & Astrophysics 444 (2005) L1
Nuclear Physics input for the network calculations

- Ground state masses
- Properties of excited states
- Level densities
- Photoresponse ($\gamma, \gamma'$), ($\gamma, n$), ($\gamma, \alpha$), ($\gamma, p$)
- Optical potentials (p, n, $\alpha$ – nucleus)
Measurement of $\alpha$-nucleus optical potentials

Po (Z=84)

Se (Z=34)

Gamow window lies below Coulomb barrier
($6 \text{ MeV} < E_{\text{Gamow}} < 12 \text{ MeV}$)

$\Rightarrow \sigma \approx 0.1 \mu b \text{ bis } 100 \mu b$

Only nine $\alpha$– induced reactions have been published within the Gamow window!
A very sensitive tool: Activation analysis

I. Irradiation

\[ \alpha \]

projectile \rightarrow target

\[ \gamma, n, p \]
ejectile

II. Counting

HPGe detector

shielding \rightarrow target

György‘s talk

At IKP Cologne:

Two 120% Clover plus addback, shielded by BGO and passive shielding
Limitations of the activation technique

- Stable reaction products
- Very long half live of reaction products
- Weak $\gamma$ intensities of radioactive decays

($\alpha,\gamma$) reaction not accessible by activation

In-beam ($\alpha,\gamma$) and ($p,\gamma$) studies
In-beam experiments using HPGe detectors

HORUS @ IKP Köln:

• 14 HPGe detectors in close geometry
• Photopeak efficiency at 1332 keV: up to 5%

• High energy resolution to observe single transitions
• Adequate efficiency to study low cross sections
• Determination of angular distributions possible
• Coincidence technique to suppress background
Deexcitation of compound state
Transitions to ground state
Transitions to 1st excited state

$^{92}\text{Mo}(p,\gamma)^{93}\text{Tc}$

$E_p = 3300$ keV
$Q = 4087$ keV

First in-beam ($p,\gamma$) experiment on $^{92}\text{Mo}$
Radiative proton capture on $^{92}\text{Mo}$
Radiative proton capture on $^{92}$Mo

Total cross section

Experiment: In-beam (Cologne) by

$\sigma$ [$\mu$b]

Proton energy [keV]
Radiative proton capture on $^{92}$Mo

**Total cross section**

<table>
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<th>Experiment:</th>
<th>In-beam (Cologne)</th>
<th>Activation (Cologne)</th>
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<td>Optical model potential by</td>
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<td>Koning et al. (TALYS)</td>
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**Test of OMP**

**Proton energy [keV]**

- **σ [μb]**
  - $10^2$
  - $10$
  - $5$
  - $2$
  - $1$
$^{92}\text{Mo}(p,\gamma)$: Partial cross sections

\[ E_p = 3300 \text{ keV} \]

**Gamma-strength function by:**
- Experiment
- Kopecky-Uhl
- Brink-Axel
- Goriely (Hartree-Fock BCS)
- Goriely (Hartree-Fock Bogolyubov)

**Levels:**
- 01
- 392
- 681
- 1503
- 1788
- 1801

**Graph:**
- $\sigma_{\text{Level}} / \sigma_{\text{Total}}$ axis
- Level energy [keV] axis

**Note:** Preliminary
$^{92}\text{Mo}(p,\gamma)$: Production of excited states

Information about $\gamma$-ray strength function
Radiative $\alpha$ capture: $^{92}\text{Mo}(\alpha,\gamma)$

$E_\alpha = 9300$ keV
$Q = 1692$ keV

$\sigma(\text{experiment}) = 382 \pm 100$ µb
$\sigma(\text{TALYS}) = 422$ µb

Background reduction necessary for smaller cross sections!
Background reduction using $\gamma$-$\gamma$ coincidence techniques

$^{92}\text{Mo}(\alpha,\gamma)^{96}\text{Ru}$

No coincidence

Counts vs $E$ [keV]

Coincidence with $E_\gamma=833$ keV

Counts vs $E$ [keV]

$685\,	ext{keV}$

$833\,	ext{keV}$

$1098\,	ext{keV}$

$1316\,	ext{keV}$
Accelerator Mass Spectrometry – an option to measure small reaction cross sections

CologneAMS

- Tandetron with 6 MV terminal voltage
- Standard isotopes: $^{10}$Be, $^{14}$C, $^{26}$Al, $^{36}$Cl, $^{129}$I (geosciences, prehistory, protohistory)
- Ample beam time for development
CologneAMS – a new option to measure small reaction cross sections

- Main shipment: May 18th, 2010
- Ready to go: July 10th, 2010
In-beam studies using multi detector γ arrays can allow the determination of many astrophysically relevant observables.

**Fall 2010**: Restart of HORUS@IKP (after 3M€ Tandem renovation)

**Spring 2011**: Start of CologneAMS

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