Reaction Cross Sections for the \( r \), \( s \), and \( p \) Process

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- s process: impact of \((n, \gamma)\) reactions for the description of He burning scenarios
- explosive nucleosynthesis in the \( r \) and \( p \) processes: large reaction networks of unstable isotopes
components of the solar abundance distribution

- stellar burning
- NSE
- weak
- main s process
- r process
- p process

neutron reactions
\[
s\text{-, } r\text{-, and } p\text{-process mechanisms}
\]

\[
s\text{-process abundance } \times \text{ cross section } = \sigma N_s = \text{constant}
\]
Maxwellian averaged cross sections

- measure $\sigma(E_n)$ by time of flight, $0.3 < E_n < 300$ keV, determine average for stellar spectrum correct for SEF

- produce thermal spectrum in laboratory, measure stellar average directly by activation correct for SEF
classical approach: $\sigma N$ - curve

repeated neutron bursts
$T = \text{const}$
$n_n = \text{const}$

two processes:
$A<90$: not saturated
$A>90$: flow equilibrium

different scenarios:
- massive stars
- low-mass stars

$n$-magic isotopes are bottlenecks

branchings provide $n_n, T, \rho$
$r$-process residuals

$N_r = N_\odot - N_s$

commonly used for comparison with $r$-process calculations
the $s$ process in TP-AGB stars

$^{13}\text{C}(\alpha,n)$ source operates during H-burning phase $kT=8$ keV

final abundance patterns via $^{22}\text{Ne}(\alpha,n)$ during He shell flash $kT=23$ keV
Search for an abundance signature in AGB stars

Classical s process

AGB model

Stellar model

New Nd cross sections

Old Nd cross sections
success of the main s process in TP-AGB stars of 1-3 $M_{\odot}$

main s process limited to mass region from Zr to Bi
## weak s process – conditions at stellar site

**stellar site:** massive stars with $M > 8 M_\odot$

<table>
<thead>
<tr>
<th></th>
<th>core He-burning</th>
<th>shell C-burning</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>temperature</strong></td>
<td>$3-3.5 \cdot 10^8$ K</td>
<td>$\sim 1 \cdot 10^9$ K</td>
</tr>
<tr>
<td><strong>neutron density</strong></td>
<td>$10^6$ cm$^{-3}$</td>
<td>$10^{11}-10^{12}$ cm$^{-3}$</td>
</tr>
<tr>
<td><strong>neutron source</strong></td>
<td>$^{22}$Ne($\alpha$,n)</td>
<td>$^{22}$Ne($\alpha$,n), $^{13}$C($\alpha$,n)$^{16}$O</td>
</tr>
</tbody>
</table>

**important:** reaction flow NOT in equilibrium
reaction flow not in equilibrium
propagation waves

accurate \((n,\gamma)\) measurements for all stable Fe and Ni isotopes under way at CERN by the \textit{n\_TOF} collaboration
n_TOF first results: $^{62}\text{Ni}(n,\gamma)$

previous TOF measurements
(courtesy I. Dillmann)
what about theory?

$^{176}\text{Hf}, ~^{178}\text{Hf}, ~^{180}\text{Hf}$: MACS uncertainties 1 - 2%

exercise joined by 6 leading groups:
calculate MACS of $^{174}\text{Hf}$ and $^{182}\text{Hf}$ prior to measurement

but theory indispensable for stellar corrections
thermal population of nuclear states

\[ P(E_k) = \frac{(2J_k + 1)e^{-E_k/kT}}{\sum_m (2J_m + 1)e^{-E_m/kT}} \]

in \(^{187}\text{Os}\) at \(kT = 30\ \text{keV}\):

- \(P(\text{gs}) = 33\%\)
- \(P(1\text{st}) = 47\%\)
- \(P(\text{all others}) = 20\%\)

stellar enhancement factor

\[ \text{SEF} = \sigma^* / \sigma_{\text{exp}} = 1.2 \]
MACS data @ kT = 30 keV

data from www.kadonis.org

I Dillmann, R Plag
needed: cross sections with uncertainties between $1\%$ and $5\%$
for complete set of isotopes from $^{12}\text{C}$ to $^{210}\text{Po}$,
including unstable samples
quests for s-process data

weak s process
- propagation effects, extended network branchings at $^{63}$Ni, $^{79}$Se, $^{85}$Kr (n$_n$, T)

main s process
- s-only isotopes for overall distribution
- unstable branch point isotopes (n$_n$,T, $\rho$)
- presolar grains involving 75 isotopes
- bottle neck reactions; neutron poisons
- neutron source reactions ($^{13}$C and $^{22}$Ne)
- thermally excited states: scattering data
decomposition of solar abundances

s-, r-, p-nuclidian composition
(Anders and Grevesse 1989)
- SN shock front heating O-Ne layers to $T_9 = 1 - 3$
- time scale 1 s
- network of $\gamma$-induced reactions
$\rho$-process network

- complex network
  - $\gamma$-induced reactions
  - reverse reactions
  - freeze out

$\text{Sm-Bi}$

$\text{Cd-Pm}$

$\text{Ga-Ag}$

- >2000 isotopes
- >20000 reactions

experimental information only for stable isotopes in ground state

- theory absolutely crucial
the $\rho$-process problem with Mo and Ru


Rayet et al., A&A 298 (1995) 517

SN Ia

SN II

MASS NUMBER
Delayed detonation standard

Travaglio et al., NIC XI, July 2010
\( p- \) and \( \alpha- \) induced reactions

Low energy cross section data needed

Gamow window:

\[ E(T, Z) = 5 - 15 \text{ MeV} \]

\( \gamma \)-induced reactions:
- bremsstrahlung + activation
- tagged photons
- Coulomb dissociation

\( p- \) and \( \alpha- \) induced reactions:
- activation
- in-beam \( \gamma \) measurements

So far, all measurements on stable isotopes important for guiding statistical model calculations.
reactions on unstable nuclei at the ESR

measurements of \((p, \gamma)\) or \((\alpha, \gamma)\) rates in inverse kinematics.

- radioactive ions injected, decelerated, and cooled
- reactions studied with internal gas jet target

- applicable to radioactive nuclei and gases
- direct counting of reaction products by in-ring particle detectors (low background, high efficiency)
pilot experiment with stable $^{96}$Ru beam

- measurement with stable beam at $E_p = 9, 10, 11$ AMeV
- $5 \cdot 10^6$ particles per spill,
- target density $1 \cdot 10^{13}$ atoms/cm$^2$, luminosity $2.5 \cdot 10^{25}$
- cross section of 1 mb $\rightarrow \sim 100$ counts/h
preliminary result @ 11 MeV

upper limit for \((p,\gamma)\) (without \((p,n)\) component)

\[\sigma_{p\gamma} < 4.0 \text{ mb}\]

Non-Smoker: 3.5 mb

courtesy M. Heil, GSI
nucleosynthesis in the $r$ process

$r$ process: large network close to drip line, mainly very short-lived radioactive nuclei

 Fusion up to iron

Proton number

Neutron number

vp-process
rp-process
p-process
s-process
r-process
reaction path defined by waiting points at $S_n \sim 2$ MeV

waiting point abundances defined by: $t_{1/2} N_r = \text{const}$

final abundances modified - beta delayed neutron emission - $(n, \gamma)/(\nu, x)$ reactions
The current $r$-process scenario involves the formation of seed nuclei by charged-particle-induced reactions ($\alpha$ process) and the $r$ process path about 15 mass units from stability. This is supported by the $\nu$-driven wind model of core collapse supernovae (SN II) as proposed by Janka et al.
(n,\gamma) cross sections for the r process?

direct (n,\gamma) measurements in or near the r-process path presently out of reach (small \sigma, short \text{t}_{1/2})

but (n,\gamma) data on n-rich light isotopes could contribute to the r-process efficiency in short-dynamic-time-scale models

Terasawa et al. APJ 562, 470, 2001
Coulomb dissociation at LAND

measurements of (γ,n) cross sections proposed on carbon isotopes up to $^{18}$C(γ,n), $^{14,15}$B, and $^{11,12}$Be

Courtesy M. Heil
summary

s process during stellar evolution:
- experimental data for stable isotopes available, but need accuracy
- SEF corrections under control
- challenges for unstable branch points

explosive nucleosynthesis:
- huge networks, mostly unstable nuclei, large SEF corrections
  - theory absolutely crucial
- experimental approaches for $p$ process at RIB facilities
- cross sections for the $r$ process only in exceptional cases