The origin of the proton rare isotopes in nature

Status and Uncertainties of Nuclear-Reaction Rates

Wolfgang Rapp
Out-line

• Overview Nucleosynthesis
• Observed Abundances
• Scenarios for p-Process
• Experimental Status
• Reaction Network
• Influence of Rates on the p-Abundances
• Conclusions
Overview Nucleosynthesis

s-process

r-process

Fe-seed

r-process

s-process
Observed Abundances

mass number

s-process
r-process
p-process

abundances (Si=10^6)
Isotopic anomalies

**HL-Xe vs. solar Xe**

Isotope anomaly [%] vs. mass number
Scenarios for p-Process

Conditions
- Very hot environments $T_9 = 2 - 3$
- Short time scale

Where?
- Explosive massive stars (SN type II)
- Binary systems (nova, x-ray burster, SN type I)
- Accretion discs on compact objects (black holes)
- Othere scenarios: pre-type II SN production, PCSN, SSAD.
Reaction Energy and Gamov Peak

Rate:
\[
\langle \sigma \cdot v \rangle = \left( \frac{8}{\pi \cdot \mu} \right)^{1/2} \cdot \frac{1}{(k \cdot T)^{3/2}} \cdot \int_0^\infty \sigma(E) \cdot \exp\left( -\frac{E}{k \cdot T} \right) \cdot dE
\]

- Penetrability
- Maxwell Boltzmann distribution

\[ ^{92}\text{Zr}(\alpha,\gamma)^{96}\text{Mo} \quad T_9=2 \]

\[ ^{112}\text{Sn}(p,\gamma)^{113}\text{Sb} \quad T_9=2 \]
Status of \((p,\gamma)\)-Experiments
Status of (α,γ)-Experiments

• Few experimental data on α-induced reactions.

• Measurements of $^{144}\text{Sm}(\alpha,\gamma)$-cross section showed a big difference to theory.

• Exp (n,α) rates for different isotopes shows:
  - $^{143}\text{Nd}$: exp. = NONSMOKER/2.7
  - $^{147}\text{Sm}$: exp. = NONSMOKER/3.3

• α-induced reactions on $^{96}\text{Ru}$ result in exp. = theo./2
\textbf{\textsuperscript{95}Mo(n,\alpha)-Experiment}

- Oak Ridge National Laboratory
- 150 MeV e\textsuperscript{-}-accelerator, 525 Hz, 8 ns, (\gamma,n)-reactions on Ta
- Energy calibration: time of flight method
- \alpha\textsuperscript{-}-particles were detected using a CIC.
The $^{95}\text{Mo}(n,\alpha)$-cross section
NON-SMOKER/Holmes

![Graph showing the ratio of reaction rates against mass number. The y-axis is logarithmic (10^0 to 10^1). The x-axis represents mass number ranging from 40 to 180.]
Activation-Experiments

- **8 Mo & 7 Sn activations at the PTB (Germany)**
  - \( E_\alpha = 8 - 11 \text{ MeV} \)
  - \( I_\alpha = 5 - 7 \mu\text{A} \)
  - \( t_{\text{Mo}} = 25 \text{ min} - 9 \text{ h}; \Delta t = 30 \text{ s} \)
  - \( t_{\text{Sn}} = 45 \text{ min} - 4 \text{ h}; \Delta t = 30 \text{ s} \)

![Diagram of activation-experiment setup]

- **Isolators**
- **Cooling**
- **Target**
- **α-beam**
- **Diaphragm**
- **μ A**
Results:

$^{112}\text{Sn}(\alpha,\gamma)^{116}\text{Te}$

$^{92}\text{Mo}(\alpha,n)^{97}\text{Ru}$

$^{94}\text{Mo}(\alpha,n)^{95}\text{Ru}$
Potential parameters

Using SMOKER code and a $\chi^2$-test

Wood-Saxon potential:

$$V(r) = -\frac{V_0}{1 + \exp\left(\frac{r - r_r A^{1/3}}{a_r}\right)} - i \frac{W_0}{1 + \exp\left(\frac{r - r_v A^{1/3}}{a_v}\right)}$$

<table>
<thead>
<tr>
<th>parameter</th>
<th>$V_0$</th>
<th>$r_r$</th>
<th>$a_r$</th>
<th>$W_0$</th>
<th>$r_v$</th>
<th>$a_v$</th>
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<tr>
<td>value</td>
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<td>1.40 fm</td>
<td>0.52 fm</td>
<td>25.0 MeV</td>
<td>1.40 fm</td>
<td>0.52 fm</td>
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<tr>
<th>reaction $\chi^2$</th>
<th>$^{94}$Mo($\alpha$,n)</th>
<th>$^{92}$Mo($\alpha$,n)</th>
<th>$^{112}$Sn($\alpha$,\gamma)</th>
<th>$^{95}$Mo(n,$\alpha$)</th>
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<tbody>
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<tbody>
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<td>1.31 fm</td>
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<tr>
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<td>4.0</td>
<td>9.1</td>
<td>4.9</td>
<td>29.4</td>
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New Potential Parameters

\[ ^{95}\text{Mo}(n,\alpha)^{92}\text{Zr} \]

\[ ^{112}\text{Sn}(\alpha,\gamma)^{116}\text{Te} \]

\[ ^{92}\text{Mo}(\alpha,n)^{95}\text{Ru} \]

\[ ^{94}\text{Mo}(\alpha,n)^{97}\text{Ru} \]
Independent experiments

- $^{70}$Ge($\alpha,\gamma$)$^{74}$Sr
- $^{96}$Ru($\alpha,\gamma$)$^{100}$Pd
- $^{143}$Nd(n,$\alpha$)$^{140}$Ce
- $^{144}$Sm($\alpha,\gamma$)$^{148}$Gd

CROSS SECTION (BARN)

ENERGY (MeV)
Network

Extended a MSU network was used for x-ray burst.
Simulated explosive O/Ne burning in a SN Type II.

Now:
- 1814 nuclei
- \( \sim 15000 \) rates
- 10 layers
Network $T_{9_{\text{max}}} = 3.1$
Network $T_{9_{\text{max}}} = 2.4$
Some Definitions

- **Overabundance factor**
  \[ F_i = \frac{X_i}{X_{i\text{-Solar}}} \]

- **Produced mass of isotope i**
  \[ m_i(M) = \sum_{n \geq 1} \frac{1}{2} \times (X_{i,n} + X_{i,(n-1)}) \times (M_n - M_{n-1}) \]

- **Averaged overproduction factor for a isotope i.**
  \[ \langle F_i \rangle = m_i(M) / (M_p(M) \times X_{i\text{-Solar}}) \]

- **Normalized overproduction factor**
  \[ F_0 = \sum_i \langle F_i \rangle / 35 \]
Normalized Overabundances

![Graph showing normalized overabundances vs mass number with various elements plotted on the graph.](image-url)
Influence of Rate Types

(i) neutron-rates
(ii) proton-rates
(iii) $\alpha$-rates

![Graphs showing influence of rate types on mass number](image-url)
Conclusions

• More experimental data are needed for $\alpha$-induced rates ($A>147$).

• The ($\gamma,p$)-rates on p-nuclei ($A<96$) should be measured.

• The Mo and Ru problem is not a problem of rate uncertainty ($n,p,\alpha$ on $A>56$)

• Convection should be considered in the model.
interesting publications:
