Nuclear Physics and Astrophysics Uncertainties in Nucleosynthesis of p-Nuclei in the $\gamma$-Process

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Monte Carlo approach to quantify final abundance uncertainties

- *Simultaneous* variation of all rates in network (above Fe)
- Individual, asymmetric, *T-dependent* uncertainty for each rate
  » Constructed from considering experimental data + thermal enhancement
- Determination of *key rates* through correlations in abundance variations

Application to production of p-nuclei in the \( \gamma \)-process

- Massive stars (ccSN)
  » Combined uncertainties on final yields
  » Model uncertainties
- SN Ia (thermonuclear SN)
  » Uncertainties in single-degenerate 2D model
  » More general considerations (density dependence of results)

Galactic Chemical Evolution

- Relative importance of ccSN and SN Ia when contributing to solar p-abundances
- Relative importance of nuclear and model uncertainties in this context
Nuclear Physics Impact/Uncertainties in Nucleosynthesis Calculations

1. Impact of uncertainties in:
   • Nuclear properties required for cross section calculations
     • model, model input
   • Reaction cross sections
     • model, model input (=nuclear properties)
   • Astrophysical reaction rates
     • (stellar) cross section input
   • Astrophysical models
     • “Scenarios”, models, further physics, numerics

2. Experimental constraint of rates through a measurement
   • Stellar rate only partly constrained in explosive nucleosynthesis
   • Inclusion of experimental error in rate uncertainty

3. Impact of rate uncertainties on predicted abundances
   • SYSTEMATIC variation of rates or nuclear input
   • Identification of major flows, Monte Carlo variation
Nuclear Physics Impact/Uncertainties in Nucleosynthesis Calculations

1. Determine rate uncertainties
2. Choose model, obtain trajectories
3. Perform MC runs
4. Analyze results (uncertainty distrib., key rates)
“PizBuin” Monte Carlo Framework

- Parallelized Monte Carlo driver + efficient, fast reaction network + analysis tools
- Hertfordshire-Basel-Keele-… collaboration (with N. Nishimura, R. Hirschi), within ERC and STFC projects and the BRIDGCE consortium (UK)
- ability to vary 10000s of reactions simultaneously in post-processing
- Goal: large scale study of nuclear uncertainties in various nucleosynthesis processes, mainly in massive stars but also SNIa, X-ray bursts
- Current focus on nucleosynthesis beyond Fe: (weak) s-process, p/γ-process, vp-process, (ν-driven winds, r-process, rp-process), …

Advantages of MC:

- Allows systematic, simultaneous variation of large number of rates
- Allows quantification of combined uncertainties
- Allows to study complex flow patterns, automatic identification of key reactions!
Impact of rate uncertainties

Abundance change when changing a rate:
- Negative slope: Destruction rate
- Positive slope: Production rate

Dependence can be non-linear.
Impact of rate uncertainties

Slope determines sensitivity to rate change:
- Steep slope: Strong dependence
- Shallow slope: Weak dependence

Variation of individual rate tests slope, NOT importance of rate!
Impact of rate uncertainties

A rate to which abundance is less sensitive can nevertheless dominate the abundance uncertainty!

Importance of rates determined by:
1. Dependence of abundance on rate
2. Uncertainty in rate
3. Competition with other rates

Individual rate variation does not account for all factors → need simultaneous variation within individual rate uncertainties!
Identifying key reactions through correlations

➢ Pearson correlation coefficient
**Thermally excited target nuclei**

Ratio of nuclei in a thermally populated excited state to nuclei in the ground state is given by the Saha Equation:

\[
\frac{n_{ex}}{n_{gs}} = \frac{g_{ex}}{g_{gs}} e^{-\frac{E_x}{kT}}
\]

\[g = (2J + 1)\]

Ratios of order 1 for \(E_x \sim kT\)

- **Only small correction for:**
  - light nuclei (level spacing several MeV)
  - Gamow window at low energy: at low \(T\)
- **LARGE correction, when**
  - low lying (~100 keV) excited state(s) exist(s) in the target nucleus
  - temperatures are high (explosive nucleosynthesis)
  - the populated state has a very different rate

The correction for this effect has to be calculated.
Ground state contribution to stellar rate

\[ X = \frac{R_0}{R^* G_0} = \frac{\int \sigma^{\text{lab}}(E) \Phi_{\text{MB}}(E,T) dE}{\int \sigma^{\text{eff}}(E) \Phi_{\text{MB}}(E,T) dE} \]

- **g.s. contribution (X)**
  - gives g.s. contribution to stellar rate
  - =1 at \( T=0 \)
  - confined to \( 0 \leq X \leq 1 \)
  - monotonically decreasing to 0
  - Uncertainty scales with \( G_0 \) and is related to \( X \):
    - \( u = (1-X)u' \)

Traditional Stellar Enhancement Factor is different:

\[ f_{\text{SEF}} = \frac{R^*}{R_0} \]

(SEF does not give exc. state contribution!)

\[ U_{\text{new}}^* = U_{\text{exp}} + (U^* - U_{\text{exp}})(1 - X_0) \]

g.s. contributions for p-nucleosynthesis
(\(\gamma\)-process)

\(\text{(n,}\gamma\text{)} @ 2.5 \text{ GK}\)

\(\text{(p,}\gamma\text{)} @ 3 \text{ GK}\)

\(\text{(\(\alpha\),}\gamma\text{)} @ 2 \text{ GK}\)
Examples of uncertainty limits assigned to reaction rates; “standard” rates are g.s. rates taken from compilations.

\[ U_{\text{new}}^* = U_{\text{exp}} + (U^* - U_{\text{exp}})(1 - X_0) \]

\( U^* \) is temperature-dependent!
Rate variation factors

- Derived/motivated by systematic uncertainties in relevant nuclear properties (dominating reaction widths)
  - just using different options in a code is not a systematic variation

- Experimental and theoretical uncertainties have to be combined
  - $T$-dependent uncertainties! (based on g.s. contrib. to stellar rates)
  - Asymmetric uncertainty factors.

- Variation factors (applied to forward and inverse rate):
  - $(n,\gamma)$: $T$-dependent, ranging from few % (exp KADoNiS) to $*/2$
  - $(p,\gamma)$, $(p,n)$: effectively $*2$, $/3$ (except for few exp. rates with large g.s. contributions)
  - $(\alpha,\gamma)$, $(\alpha,n)$, $(\alpha,p)$: effectively $*2$, $/10$
  - $\beta$-decays: $T$-dependent, from 30% to $*/10$
The $\gamma$-Process

Photodisintegration of seed nuclei (produced in situ or inherited from prestellar cloud). NOT total disintegration, of course! (just the right amount)

Explosive burning in O/Ne shell in core-collapse SN

Woosley & Howard 1978; Prantzos et al 1990; Rayet et al 1995
Uncertainty distribution functions for final p-production

\[ \log_{10}(2) \approx 0.3 \]
\[ \log_{10}(5) \approx 0.7 \]

KEPLER 25 Msun

KEPLER 15 Msun

Rauscher et al.,
MNRAS 463 (2016) 4153
p-Nucleus Production/Destruction per Zone

About 100 zones (trajectories), with about 1500 nuclides in network (with all connecting reactions), each MC run includes 10000 iterations per zone.

KEPLER 25Msun

KEPLER 15Msun
Determination of key rates (mostly contributing to uncertainty)
- Level 1 key rate: strong correlation with abundance change
- Level 2: strong correlation with remaining abundance after level 1 key rates kept fixed (level 1 rates covered their contribution before)
- Level 3: strong corr. after level 1 and 2 kept fixed

Independent of initial magnitude of uncertainty!

Consider g.s. contribution to judge experimental possibility for improvement.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$r_{corr,0}$</th>
<th>$r_{corr,1}$</th>
<th>$r_{corr,2}$</th>
<th>Key rate Level 1</th>
<th>Key rate Level 2</th>
<th>Key rate Level 3</th>
<th>$X_0$ (2 GK) capture</th>
<th>$X_0$ (3 GK) capture</th>
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<tbody>
<tr>
<td>$^{78}$Kr</td>
<td>-0.77</td>
<td>0.38</td>
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<td>4.44 × 10^{-2}</td>
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<td>0.67</td>
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<td>$^{92}$Mo + α ↔ γ + $^{96}$Ru</td>
<td>$^{166}$Yb + α ↔ γ + $^{170}$Hf</td>
<td>1.28 × 10^{-1}</td>
<td>7.94 × 10^{-2}</td>
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<tr>
<td>$^{94}$Mo</td>
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<td>0.78</td>
<td>0.67</td>
<td>$^{95}$Mo + n ↔ γ + $^{96}$Mo</td>
<td>$^{145}$Eu + p ↔ γ + $^{146}$Gd</td>
<td>$^{179}$Ta + n ↔ γ + $^{180}$Ta</td>
<td>8.88 × 10^{-1}</td>
<td>8.24 × 10^{-1}</td>
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<td>1.00</td>
<td>9.86 × 10^{-1}</td>
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<td></td>
<td></td>
<td>5.62 × 10^{-1}</td>
<td>3.97 × 10^{-1}</td>
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<tr>
<td>$^{136}$Ce</td>
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<td>0.66</td>
<td></td>
<td></td>
<td></td>
<td>7.79 × 10^{-1}</td>
<td>6.73 × 10^{-1}</td>
</tr>
<tr>
<td>$^{138}$Ce</td>
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<td>0.64</td>
<td>0.66</td>
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<td>4.16 × 10^{-1}</td>
<td>2.54 × 10^{-1}</td>
</tr>
<tr>
<td>$^{138}$La</td>
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<td>0.66</td>
<td>$^{138}$La + n ↔ γ + $^{139}$La</td>
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<td></td>
<td>8.71 × 10^{-1}</td>
<td>6.43 × 10^{-1}</td>
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<tr>
<td>$^{144}$Sm</td>
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<td>0.79</td>
<td>0.66</td>
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<td>$^{164}$Yb + α ↔ γ + $^{168}$Hf</td>
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<td>6.18 × 10^{-1}</td>
<td>4.92 × 10^{-1}</td>
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<tr>
<td>$^{164}$Er</td>
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<tr>
<td>$^{168}$Yb</td>
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<td>0.66</td>
<td>$^{164}$Yb + α ↔ γ + $^{168}$Hf</td>
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<td></td>
<td>2.13 × 10^{-1}</td>
<td>1.24 × 10^{-1}</td>
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<tr>
<td>$^{180}$Ta</td>
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<td>0.09</td>
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<td>2.12 × 10^{-1}</td>
<td>1.26 × 10^{-1}</td>
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<td>1.80 × 10^{-1}</td>
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<tr>
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<td>0.09</td>
<td>0.66</td>
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<td></td>
<td>7.09 × 10^{-2}</td>
<td>3.96 × 10^{-2}</td>
</tr>
<tr>
<td>$^{196}$Hg</td>
<td>-0.86</td>
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<td>0.66</td>
<td>$^{195}$Pb + n ↔ γ + $^{196}$Pb</td>
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<td></td>
<td>2.37 × 10^{-1}</td>
<td>1.46 × 10^{-1}</td>
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<tr>
<td>$^{158}$Ce</td>
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<td>0.66</td>
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<td>1.04 × 10^{-1}</td>
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<tr>
<td>$^{158}$Os</td>
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<td>0.20</td>
<td>0.66</td>
<td></td>
<td></td>
<td></td>
<td>3.58 × 10^{-1}</td>
<td>1.58 × 10^{-1}</td>
</tr>
<tr>
<td>$^{196}$Pt</td>
<td>-0.86</td>
<td>0.17</td>
<td>0.66</td>
<td></td>
<td></td>
<td></td>
<td>2.97 × 10^{-1}</td>
<td>1.89 × 10^{-1}</td>
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<tr>
<td>$^{158}$Pb</td>
<td>-0.81</td>
<td>0.20</td>
<td>0.66</td>
<td></td>
<td></td>
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<td>3.28 × 10^{-1}</td>
<td>2.39 × 10^{-1}</td>
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<tr>
<td>$^{92}$Nb</td>
<td>0.75</td>
<td>0.75</td>
<td>0.66</td>
<td>$^{92}$Zr + p ↔ γ + $^{93}$Nb</td>
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<td></td>
<td>9.91 × 10^{-1}</td>
<td>9.76 × 10^{-1}</td>
</tr>
<tr>
<td>$^{98}$Tc</td>
<td>0.89</td>
<td>0.89</td>
<td>0.66</td>
<td>$^{96}$Mo + p ↔ γ + $^{97}$Tc</td>
<td></td>
<td></td>
<td>9.50 × 10^{-1}</td>
<td>8.56 × 10^{-1}</td>
</tr>
<tr>
<td>$^{146}$Sm</td>
<td>-0.65</td>
<td>0.65</td>
<td>0.66</td>
<td>$^{144}$Sm + α ↔ γ + $^{148}$Gd</td>
<td></td>
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<td>9.99 × 10^{-1}</td>
<td>9.65 × 10^{-1}</td>
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<tr>
<td>$^{146}$Gd</td>
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<td>$^{147}$Gd + n ↔ γ + $^{148}$Gd</td>
<td></td>
<td></td>
<td>9.92 × 10^{-1}</td>
<td>9.28 × 10^{-1}</td>
</tr>
</tbody>
</table>
Uncertainty distribution functions for final $p$-production

$\log_{10}(2) \approx 0.3$
$\log_{10}(5) \approx 0.7$

KEPLER 25 Msun

KEPLER 15 Msun
Uncertainty distribution functions after determining key reactions

\[ \log_{10}(2) \approx 0.3 \]
\[ \log_{10}(5) \approx 0.7 \]
Uncertainty distribution functions for final $p$-production in two different stellar model codes

Hashimoto (1990)

$\log_{10}(2) \approx 0.3$

$\log_{10}(1.6) \approx 0.2$

Kepler 25M$\odot$
p-Nucleus Production/Destruction per Zone in two different model approaches

Resolution of Hashimoto (1990) zones too crude, especially for light nuclei and some heavy species

Cannot follow detailed temperature evolution, overemphasizes certain temperatures/reactions
p-Synthesis in single-degenerate SN Ia (thermonuclear SN)

1. White Dwarf (WD) accretes matter from companion star
2. H/He-burning in accreted matter on surface
3. Temperature-increase leads to explosive C-burning
4. Nuclear burning front disrupts WD

Difficult to model internal heating, ignition, and burning front propagation; requires 2D and 3D treatment.

p-nucleosynthesis may occur in some layers if strong seed enhancement by s-process in H/He-surface!
p-Nuclei from SN Ia (thermonuclear SN)

- Alternative to ccSN: $\gamma$-process in outer layers of exploding White Dwarf.
- Seed nuclei produced in accreted material from companion AGB star.
- Selected 4624 tracer particles (trajectories) out of 15000 from 2D model by Roepke et al.
- Postprocessing required HPC resources: DiRAC facility in the UK (about 700k CPUhrs)

Tracer peak temperatures + densities
Nuclear uncertainties in p-nucleus production of SN Ia model

Only one key rate found:

\[ ^{145}\text{Eu} + p \leftrightarrow \gamma + ^{146}\text{Gd} \]
(affects \(^{146}\text{Sm}\) abundance)

(Also some radioactive isotopes included in our studies.)

Not key, but weaker correlated to final abundance:

\[ ^{70}\text{Ge} + \alpha \leftrightarrow \gamma + ^{74}\text{Se} \] (for \(^{74}\text{Se}\))
\[ ^{137}\text{Nd} + n \leftrightarrow \gamma + ^{138}\text{Nd} \] (for \(^{138}\text{Ce}\))
\[ ^{145}\text{Eu} + p \leftrightarrow \gamma + ^{146}\text{Gd} \] (for \(^{144}\text{Sm}\))
\[ ^{170}\text{Hf} + \alpha \leftrightarrow \gamma + ^{174}\text{W} \] (for \(^{174}\text{Hf}\))

N. Nishimura et al., MNRAS 474 (2018) 3133
Low-density group only

All tracers

Tracer peak temperatures + densities
Tracer peak temperatures + densities

Low-density group only

High-density group only

Dependence on density conditions; allows for explosion-model-independent analysis
Density dependence of flow paths in SN Ia

Temperature window for nucleosynthesis in $\gamma$-process narrowly defined for given nuclear mass range.

Density can largely vary, depending on site.

Low-density region

Higher density increases capture direction in forward/reverse rate set.

This shifts reaction “boulevard” towards neutron-rich side and alters rate importance and possible competitions.

High-density region
Importance of SN Ia relative to ccSN for Galactic p-production

Modeling:

- GCE model with 3 regions: thick disk, thin disk, halo
- Input stellar models: 2 sets of metallicity-dependent ccSN yields
- Input SN Ia: single-degenerate deflagration model with surface seed enrichment by companion star
- GCE traces galactic enrichment until solar system formation
Importance of SN Ia relative to ccSN for Galactic p-production

Comparison to KEPLER models
Importance of SN Ia relative to ccSN for Galactic p-production

Comparison to NUGRID models
Importance of SN Ia relative to ccSN for Galactic p-production


Modeling:
• GCE model: thick disk, thin disk, halo
• Input stellar models: 2 sets of metallicity-dependent ccSN yields
• Input SN Ia: single-degenerate deflagration model with surface seed enrichment by companion star
• GCE traces galactic enrichment until solar system formation

Conclusions:
• SN Ia produce bulk of p-nuclides
• SN Ia required to explain solar p-abundances
• ccSN negligible, may contribute to:
  • light p-nuclei up to 92Mo, provided there is primary process (α-process, vp-process)
  • 138La, 180Ta: require v-process
  • 184Os, 196Hg, if enough initial abundance in Pb isotopes (yield differences in ccSN models for same mass & metallicity stem from different initial abundance distribution in star)

Uncertainties:
• Nuclear uncertainties comparatively small, don’t change conclusions
• Major uncertainties:
  • Single-degenerate occurrence frequency?!
  • γ-process seed enhancement in accretion from companion star (Battino et al., in prep.)
1. Monte Carlo studies
   - Propagation of rate uncertainties to production factors and abundances, superior over independent variation of individual rates
   - PizBuin Monte Carlo project
     - individual error bar on each reaction, T-dependent uncertainties
     - identification of key reactions through rate-abundance correlations
   - In progress: vp-process in neutrino wind, r-process
   - Future: further processes/sites, e.g., rp-process; improved MC method (rate correlations)
2. γ-process and p-nuclide production
   • ccSN (massive stars): uncertainties below factor of 2, with few exceptions
     • Results mostly independent of model due to reaction “boulevard”, provided sufficient zonal resolution
   • SN Ia (white dwarf): even smaller uncertainties due to even more path alternatives
     • separation of low/high-density contributions allow for more general conclusions

3. Galactic Chemical Evolution (GCE)
   • GCE code tracking p-nucleus production over course of Galactic history
   • Input:
     • Two sets of stellar model (ccSN) yields on grids of mass and metallicity
     • 2D SN Ia model with s-process seed enhancement
   • SN Ia yields dominating over ccSN yields + needed to explain solar ab.
   • BUT: single-degenerate SN Ia occurrence??? Seed enhancement?