Using non-predictive theories to predict the nucleosynthesis of heavy elements.

Attempting an uncertainty evaluation...


Friday, March 10, 2017
R-PROCESS – IMPACT OF NEUTRON CAPTURE UNCERTAINTIES

Mumpower et al., Prog. in Part. and Nucl. Phys. 86, 86, (2016)
How could we estimate uncertainty?

- **Statistical:**
  Are the model parameters defined with enough precision? Are there correlations?
  Monte Carlo of parameters around a central value using some distribution,
  see e.g. Bertolli et al, arXiv:1310.4578 [astro-ph.SR]
How could we estimate uncertainty?

- **Statistical:**
  Are the model parameters defined with enough precision? Are there correlations?
  Monte Carlo of parameters around a central value using some distribution,
  see e.g. Bertolli et al, arXiv:1310.4578 [astro-ph.SR]

- **Systematic:**
  *Is the model correct?*
  Usual approach: Use various appropriate models and compare results.
  Problem: Perhaps the distribution is not well-sampled (e.g. Are all the models (equally) appropriate?)
"Let many flowers bloom"

**HOW MUCH UNCERTAINTY TO EXPECT?**


<table>
<thead>
<tr>
<th>Nuclear Level Density</th>
<th>γ ray Strength Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant Temperature matched</td>
<td>Kopecky-Uhl generalized Lorentzian (KU) [9]</td>
</tr>
<tr>
<td>to the Fermi Gas model (CT+BSFG)</td>
<td>[11]</td>
</tr>
<tr>
<td>Back-shifted Fermi Gas model</td>
<td>Hartree-Fock BCS + QRPA (HF-BCS+QRPA) [13]</td>
</tr>
<tr>
<td>(BSFG) [11],[12]</td>
<td></td>
</tr>
<tr>
<td>Generalized Super fluid model</td>
<td>Hartree-Fock-Bogolyubov + QRPA (HFB+QRPA) [16]</td>
</tr>
<tr>
<td>(GSM) [14],[15]</td>
<td>Modified Lorentzian (Gor-ML) [18]</td>
</tr>
<tr>
<td>Hartree Fock using Skyrme force</td>
<td></td>
</tr>
<tr>
<td>(HFS) [17]</td>
<td></td>
</tr>
<tr>
<td>Hartree-Fock-Bogoliubov (Skyrme</td>
<td></td>
</tr>
<tr>
<td>force) + combinatorial method</td>
<td></td>
</tr>
<tr>
<td>(HFBS-C) [19]</td>
<td></td>
</tr>
</tbody>
</table>

---

![Diagram showing neutron and proton numbers with different color codes indicating the stability of nuclei.](image)
HOW MUCH UNCERTAINTY TO EXPECT?

Reaction rates for Europium-165

~1 order of magnitude

$T_9 = 1.5$ GK
NUCLEAR LEVEL DENSITY

$^{^{165}}$Eu + n

$\text{Nuclear Level Density (MeV$^{-1}$)}$

$^{166}$Eu excitation energy, (MeV)

- Constant Temperature + Backshifted Fermi Gas
- Back-shifted Fermi Gas
- Generalized Superfluid
- Hartree-Fock using Skyrme force
- Hartree-Fock-Bogoliubov using Skyrme force

$T_g < 1.5\text{GK}$
GAMMA RAY STRENGTH FUNCTION

$^{165}$Eu + n

![Graph showing gamma ray strength function with different theoretical models and a temperature limit $T_g < 1.5$ GeV.](image)
What about the Optical Potential Uncertainty?

Reaction rates for Eu isotopes at 1.0 GK

![Graph showing reaction rates for Eu isotopes at 1.0 GK with data from Koning-Delaroche and JLM.]

S. Nikas et al., PRC, *in preparation*
The isovector imaginary neutron potential: A key ingredient for the r-process nucleosynthesis

S. Goriely\textsuperscript{a}, J.-P. Delaroche\textsuperscript{b}
\textsuperscript{a} Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, Campus de la Plaine, CP 226, 1050 Bruxelles, Belgium
\textsuperscript{b} DPTA/Service de Physique Nucléaire, CEA/DAM Ile de France, BP 12, 91680 Bruyères-le-Châtel, France

JLM semi-microscopic Optical Potential,

For n+ X(A,Z,N):

\[ U(E) = \lambda V\(E\)\[V_0(E) + \lambda V_1(E)\alpha V_1(E)\] \\
\quad + i\lambda W(E)\[W_0(E) + \lambda W_1(E)\alpha W_1(E)\]

gray region: thorough checks with (p,p), (n,n) and (p,n) data, 1.5-10% uncertainty

(Bauge, Delaroche, Girod, PRC63, (2001), 024607)
\[ U(E) = \lambda V(E) [V_0(E) + \lambda V_1(E) \alpha V_1(E)] \\
\quad + i \lambda W(E) [W_0(E) + \lambda W_1(E) \alpha W_1(E)] \]

**Case 1:** 30% higher \( \lambda_{w1} \) @ 100keV

**Case 2:** 50% higher \( \lambda_{w1} \) @ 100keV

**Case 3:** 50% higher \( \lambda_w \) @ 100keV

(Goriely and Delaroche, PLB653, (2007), 178)
(Goriely and Delaroche, PLB653, 2007, 178)
Is it important for astrophysics?
Is it important for astrophysics?

Yes, terrifying!
Proposed experiment @ Ohio U accelerator

- $E_{\text{beam}} < 5\text{MeV/u}$
- Experimental setup for particle evaporation measurements
- Region with experimentally constrained level densities

$^{11}\text{B} + ^{48}\text{Ca} \rightarrow ^{59}\text{Mn}^*$ \quad \rightarrow \quad \text{Measure evaporated particle yields}
Conclusions-Wishlist

▶ Need microscopic theory to (at a minimum) understand trends in statistical properties of nuclei and eliminate models.
▶ A fully microscopic effective interaction useful for finite nuclei would be nice.
▶ Theoretical support is critical for experimental techniques applicable away from stability, e.g. beta-Oslo (measurements of level densities and $\gamma$ ray strengths), Surrogate technique (indirect neutron cross section measurements).