Nuclear physics input for r-process studies

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Outline

• Introduction.

• Nuclear masses.

• Beta decay half-lives.

• Summary and outlook.
What is the **origin of the elements?**

- **HOW?** Different nucleosynthesis processes.

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**Motivation**

- What is the **origin of the elements?**
  - **HOW?** Different nucleosynthesis processes.
What is the origin of the elements?

- WHERE? Different astrophysical scenarios.

Big Bang

Stars

Supernovae

Neutron star mergers

X-ray bursts

Credit: Daniel Price (U/Exeter) and Stephan Rosswog (Int. U/Bremen)

http://apod.nasa.gov/apod/image/9912/
What is the **origin of the elements**?

- **HOW?** Different nucleosynthesis processes.
- **WHERE?** Different astrophysical scenarios.
- **Observables**: Elementary abundance pattern in stars.
  Light curves in explosive events.

Fingerprints of **nuclear structure** and stability features **in the solar system abundances**.

**Nuclear physics input:**
- Masses
- $\beta$-Half lives
- Reaction rates
- Fission
- Neutrino reactions

*Taken from experiments and... theory!!*
• Nuclear masses determine in r-process nucleosynthesis:
  ▸ Neutron capture rates/photo-disintegration.
  ▸ Beta decay Q-values.

Final abundances depend on the mass model used (for the same astrophysical conditions)

S. Goriely et al.  A. Arcones and G. Martínez-Pinedo, PRC 83, 045809 (2011)

Impact of nuclear masses on r-process simulations

• Nuclear masses determine in r-process nucleosynthesis:
  ▶ Neutron capture rates/photo-disintegration.
  ▶ Beta decay Q-values.

• Changes in the final r-process abundances produced by a 25% variation of the separation energies have been studied globally.

• Most sensitive nuclei are those near to the neutron magic numbers.


Fig. 3. Comparison of the sensitivity to mass values determined by eq. (2). The separation energies far from stability were generated by the FRDM [25], Dufo-Zuker [26], and HFB-21 [27]. The scale is from white to dark red, indicating regions with a small change to a substantial change in the resulting abundances. For reference, stable nuclei have been included as black crosses and the magic numbers have been indicated by thin lines. Superimposed on the sensitivity results are the limits of accessibility by CARIBU [28] and the proposed FRIB intensities [29]. In both cases, we have plotted the conservative limits of what can be produced and measured in mass measurements.
Masses@GSI/FAIR and the r-process path

New masses around $^{132}$Sn

- JYFLTRAP@JYVÄSKYLÄ (J. Hakala et al., Phys. Rev. Lett. 109, 032501 (2012))

Effect on r-process simulations

Neutron separation energies were overestimated in the mass models with respect to the experimental data, inhibiting ($\gamma$,n) reactions which would push material to longer-lived isotopes.

Drastic transition from $^{133}$Sb to $^{137}$Sb in HFB-21 mass model not observed in the data including the new masses measured at CPT-CARIBU.

• Experimental masses where available: ~2300 (Audi et al. Chinese Phys. C 36, 1287 (2012)).

• Theoretical global nuclear mass models widely used in nucleosynthesis calculations:
  ➡ Finite Range Droplet Model (FRDM). (Möller et. al 1995, Möller et. al 2012)
  ➡ Extended Thomas-Fermi plus Strutinsky Integral (ETFSI). (Aboussir et al. 1995)
  ➡ Weizsäcker-Skyrme (WS). (N. Wang et al. 2010)
  ➡ Duflo-Zuker (DZ) functional based on Shell Model. (Duflo and Zuker 1995)
  ➡ Self-consistent mean field models based on Hartree-Fock-Bogoliubov approximations:
    ▶ Skyrme HFB-* (Goriely et al 2013)
    ▶ Gogny D1M (Goriely et al. 2009)

  Typical r.m.s. deviation from the experimental data ~0.6 MeV
Nuclear binding energies have been computed recently for heavier nuclei using chiral effective field theory interactions

**Ab-initio methods are far from being useful for nucleosynthesis simulations:**
- Limited to magic or semi-magic nuclei.
- Limited accuracy so far (too much overbinding).
- Good results in some regions while in other regions are very bad.
- Missing many body forces, uncertainties in the three body coupling constants, etc.
Microscopic mass models with effective interactions

- Self-consistent mean field approximations provide a very good description of known data.
- There are still some problems in transitional regions and local uncertainties:
  - Numerical noise.
  - Some physics missing: Restoration of broken symmetries and configuration mixing.
  - Nuclei with odd number of protons/neutrons are not treated in equal footing as the even-even ones.

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Self-consistent (beyond) mean field description

Selected applications

- Shell closures far from the stability
- Multiple shape coexistence
- Shape transitions

Nuclear matrix elements for double-beta decay

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Microscopic mass models. Beyond mean field effects

- BMF effects correct the under binding at the MF level but produces excess of binding energy → refit of the force

- BMF effects reduces the spread of the data, specially in the light nuclei

- Shell effects are present both at MF and BMF levels


See also M. Bender et al, PRC 73, 034322 (2006)
Impact of beta-decay half-lives on r-process simulations

- Beta decay half-lives determine the time scale in r-process nucleosynthesis

Changing the half-life of a single element produces significant changes in the final abundances obtained in r-process simulations

M. Quinn et al, PRC 85, 035807 (2012)
Experimental beta-decay half-lives of neutron rich nuclei

- Beta decay half-lives@RIKEN/RIBF

S. Nishimura et al, PRL 106, 052502 (2011)

Z. Y Xu et al, PRL 113, 032505 (2014)
Experimental beta-decay half-lives of neutron rich nuclei

- Beta decay half-lives@NSCL/MSU

F. Montes et al, PRC 76, 035801 (2006)
Experimental beta-decay half-lives of neutron rich nuclei

- Beta decay half-lives@RISING/GSI

A. I. Morales et al, PRL 113, 022702 (2014)
• Beta decay half-lives have been computed on FRDM model so far and the calculations show several problems:
  
  ‣ Inconsistent treatment of first-forbidden transitions.
  ‣ Overestimation of half-lives.
  ‣ Strong odd-even effects.

• Recent microscopic calculations including Gamow-Teller and first forbidden transitions:
  
  ‣ Shell Model for $N = 50, 82, 126$.
  ‣ Non-relativistic DFT+QRPA
  ‣ Global calculations within the Covariant Density Functional Theory, using the spherical QRPA method.
Shell Model calculations including first forbidden transitions for $N = 50, 82, 126$.

Very good agreement with the available experimental data

Less significant odd-even effects than in FRDM model

Global calculations using spherical covariant DFT+pnQRPA calculations.

Good agreement with the experimental data, particularly in short-lived nuclei.

T. Marketin et al., in preparation
Beta-decay half-lives.
First forbidden contribution

For $N=50$, first forbidden contributions increase above $Z=28$ for CDFT calculations while they are negligible for SM.

For $N=82$, first forbidden contributions remain small both for CDFT and SM calculations.

For $N=126$, first forbidden contributions increase with proton number in SM while remain constant for CDFT.

For FRDM, a less smooth result is obtained.

Systematics of the first forbidden contributions can be performed within the CDFT framework.
Electron capture in Core-collapse supernova

The r-process

Summary

Impact on r-process abundances

120 140 160 180 200

Mass Number

log(Abundance)

FRDM
DDME1*

Solar r-process abundances

Beta-decay half-lives.
Impact on r-process nucleosynthesis

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Beta-decay half-lives
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T. Marketin et al., in preparation

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Experiments for nuclear masses, beta decay half-lives, beta delayed neutron emission, etc:
THE MORE THE BETTER

However, not all nuclei belonging to the r-process path will be experimentally accessible:
THEORETICAL UNCERTAINTIES

• *Ab-initio methods* are still far away from being usable in astrophysical applications.
• *Shell model* cannot be applied extensively either.
• We have to rely upon mic/mac approaches and/or *energy density functional* methods (also for *fission* studies).
Summary and outlook

Improving energy density functional methods for nuclear astrophysics applications:

- Study of **odd-systems** on the same footing as the even-even ones (masses and beta-decays).
- Development of **parametrizations** of the interaction fitted with BMF functionals (now becoming available thanks to the new computational resources).
- Including all possible **degrees of freedom** within the theoretical framework (multipoles, single particle excitations, ...).
- Solving technical problems such as providing reliable **extrapolation** schemes to infinite working basis.

Further improvements are (will be) possible thanks to the combined experimental and theoretical efforts.
Best is (hopefully) yet to come...

Thank you for your attention!!