Theory for nuclear processes in stars and nucleosynthesis

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Nuclear Astrophysics in Germany
November 15-16, 2016

Nuclear Astrophysics Virtual Institute

HELMHOLTZ GEMEINSCHAFT

SFB 1245

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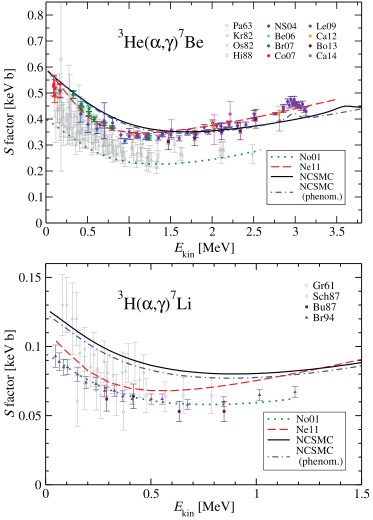
Bundesministerium für Bildung und Forschung

Outline

Ab-initio description of nuclear reactions

- Extending ab-initio approaches for a proper treatment of continuum.
- Cluster phenomena in light nuclei (Hoyle state)
- Different approaches available.
  - Fermion Molecular Dynamics
  - No-Core Shell Model with Continuum
  - Nuclear Lattice



Dohet-Eraly, *et al*, PLB **757**, 430 (2016)

Stellar electron capture and beta-decay

We need to account for a broad range of conditions

- Stellar evolution and accretion phases. Sensitive to relatively few reactions: URCA pairs ^{23}Na-^{23}Ne, ^{25}Mg-^{25}Na,…for white dwarfs and heavier nuclei neutron star crust. Accurate modeling of individual transitions, important screening corrections.
- Explosive phases. Type Ia supernova, Oxygen deflagration in ONe cores. Competition between many electron capture and beta-decay processes.
- Core-collapse: core evolution sensitive to electron capture on exotic neutron rich nuclei.

Range of nuclei for Oxygen deflagration

many of the relevant rates are based on simple analytical estimates (ANA).

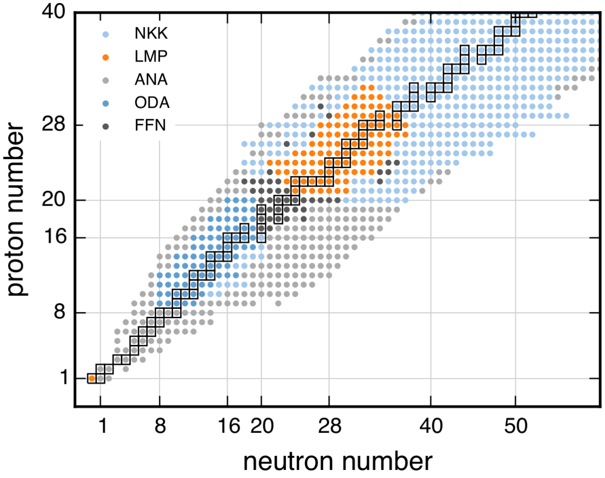
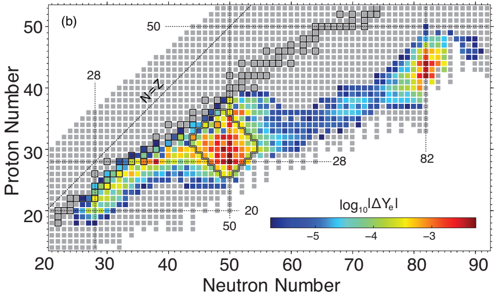


Figure from Sam Jones

Electron captures during collapse

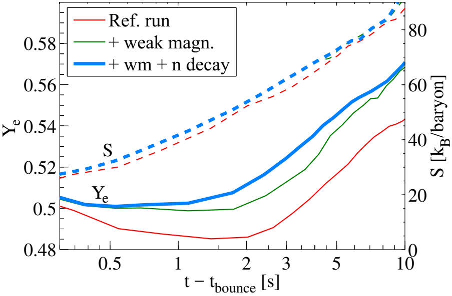
Most relevant electron capture nuclei during collapse



Sullivan *et al.*, ApJ **816**, 44 (2015)

- Mainly nuclei around $N = 50$ and $N = 82$. Sensitive to shell structure far from stability.
- Theoretical challenge: description of correlations across shell closures.
- Many of the relevant nuclei are becoming experimentally accessible.

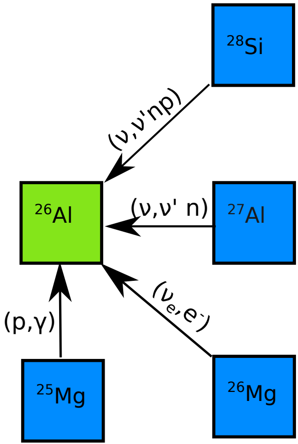
Neutrino-matter interactions in supernova



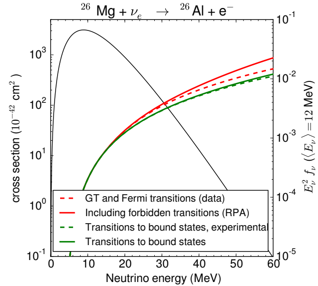
- Many different processes contributing during different phases: explosion, neutron star deleptonization.
- Consistent treatment with underlying experimentally constrained EoS.
- Code implementations often introduce errors of order the claimed accuracy.
- What is their role in mergers?

Neutrino nucleus reactions

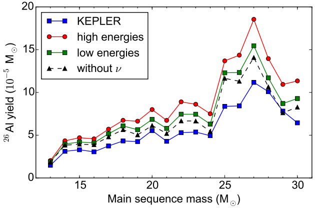
Having accurate neutrino spectra is also important for the production of several nuclei (^{7}Li, ^{11}B, ^{19}F, including ^{26}Al).



GT: (^{3}He, t), Zegers+ 2006; Forbidden: RPA

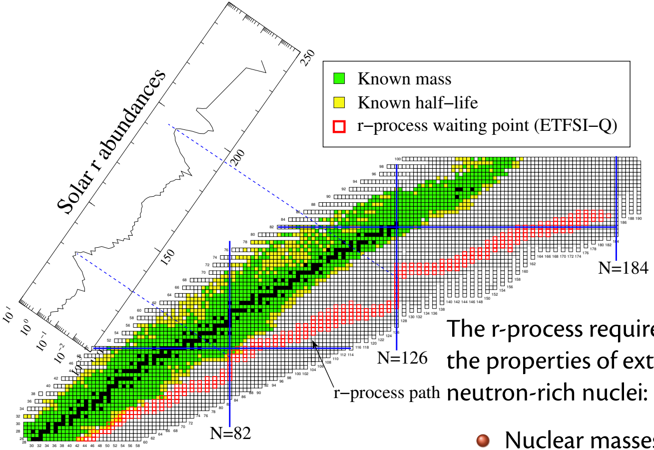


low: $\langle E_{\nu_e} \rangle = 8.8$ MeV, $\langle E_{\bar{\nu}_e} \rangle = \langle E_{\nu_{\mu,\tau}} \rangle = 12.6$ MeV
high: $\langle E_{\nu_e} \rangle = \langle E_{\bar{\nu}_e} \rangle = 12.6$ MeV, $\langle E_{\nu_{\mu,\tau}} \rangle = 18.9$ MeV



A. Sieverding

Making Gold in Nature: r-process nucleosynthesis

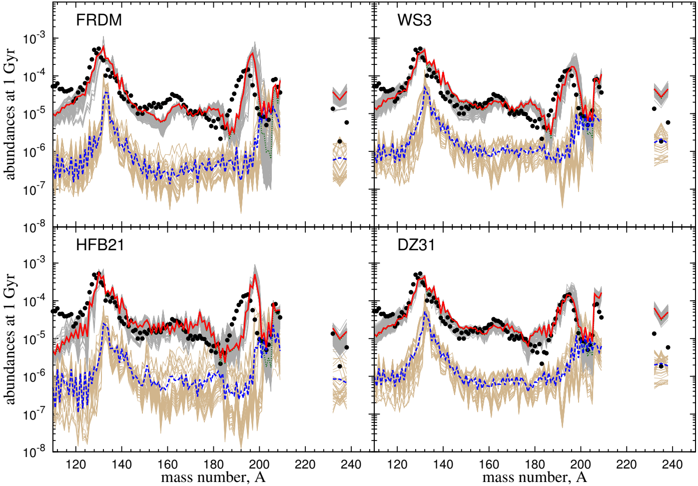


The r-process requires the knowledge of the properties of extremely neutron-rich nuclei:

- Nuclear masses.
- Beta-decay half-lives.
- Neutron capture rates.
- Fission rates and yields.

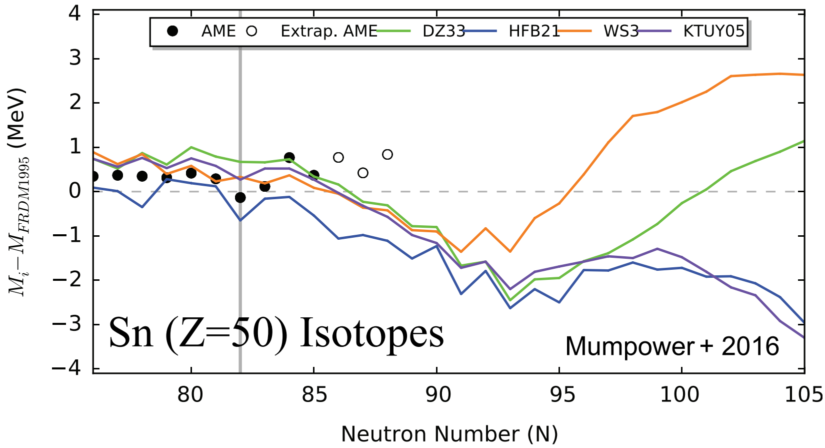
r process in dynamical ejecta from mergers

Ejection of very neutron-rich material in mergers results in abundance distributions insensitive to variations of astrophysical conditions. Sensitivity to nuclear physics input remains.



Theoretical masses far from stability

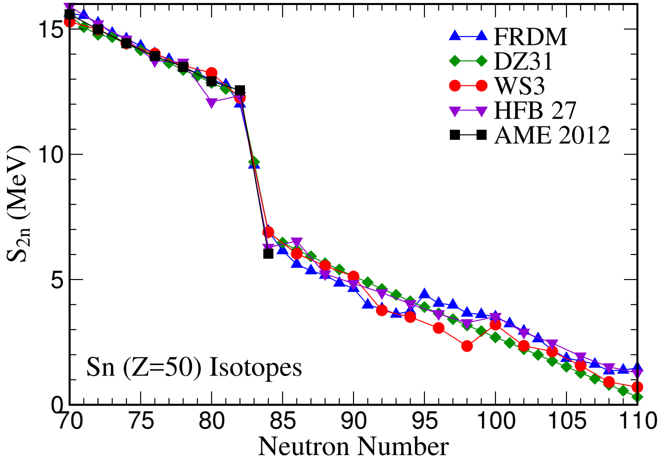
Theoretical models do rather well far from stability!



Spread due to small differences in symmetry energy (~ 0.5 MeV, smaller experimental range 29.0-32.7).

Comparison S_{2n}

Very similar predictions for Q-values (relevant quantity).

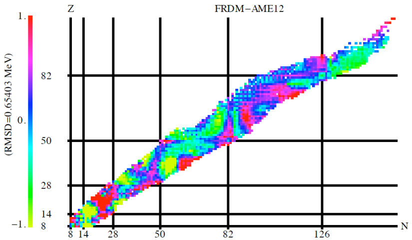


Variations in localized regions responsible for different abundances predictions.

Outlook: addressing systematic diff. between mass models

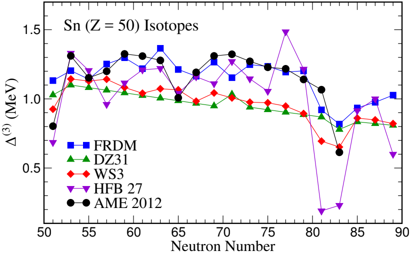
Most of the differences between mass models originate due to:

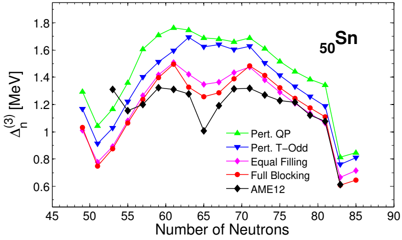
- Treatment of transitional nuclei (shape coexistence). Requires beyond mean field techniques (Rodríguez+ 2015)
- Proper description odd and odd-odd nuclei.



A. Arzhanov, Gogny functional

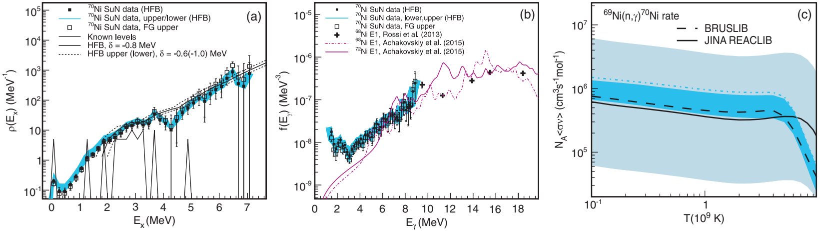
$$\Delta^{(3)}(N) = (S_n(N+1) - S_n(N))/2$$





Constraining neutron capture rates

Liddick, et al., Phys. Rev. Lett. 116, 242502 (2016)

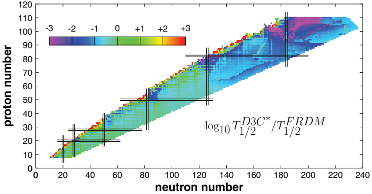


- Experimental constrains in gamma-strength far from stability.
- Understanding low energy upbend and behaviour with neutron excess.
- Extending reaction model beyond statistical treatment.

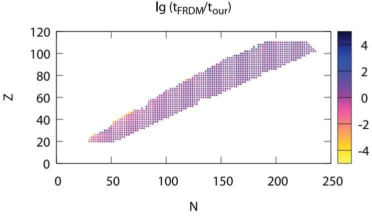
Global beta-decay calculations

- Beta-decay rates determine the speed of matter flow from light to heavy nuclei.
- r-process path determined by neutron separation energies
- nuclei with largest impact are those with larger instantaneous half-lives.
- Despite tremendous progress at RIB facilities (RIBF at RIKEN) most of the half-lives are based on theoretical calculations.
- Two microscopic calculations (GT+FF) have become available:
  - Covariant density functional theory + QRPA (Marketin+ 2016)
  - Skyrme finite-amplitude method (Mustonen & Engel 2016)

Marketin & GMP 2016



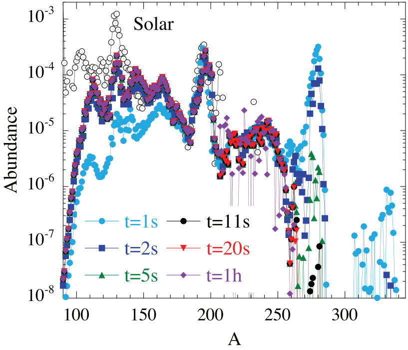
Mustonen & Engel 2016



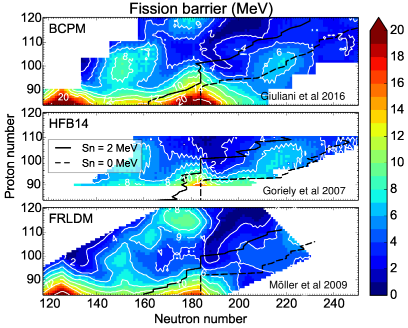
Fission barriers

The impact of different fission barriers and yields has not been sufficiently explored.

Goriely & GMP 2015

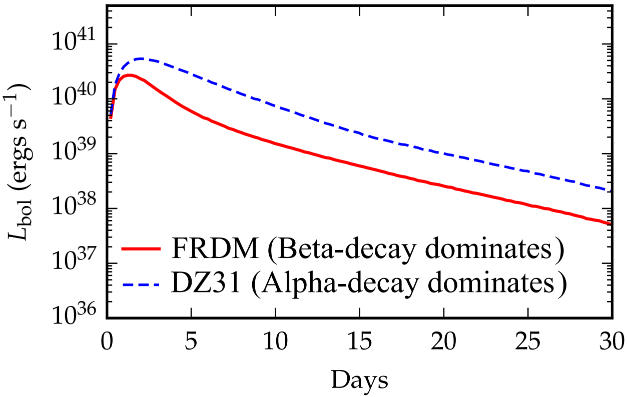


S. Giuliali



Kilonova light curve

Understanding the nuclear physics signatures in kilonova light curves



Ratio of luminosities at peak value and at late times can be used to constrain the produced amount of nuclei between Pb and U.

Barnes, Kasen, Wu, GMP, ApJ 829, 110 (2016).