Nuclear physics input for the r-process

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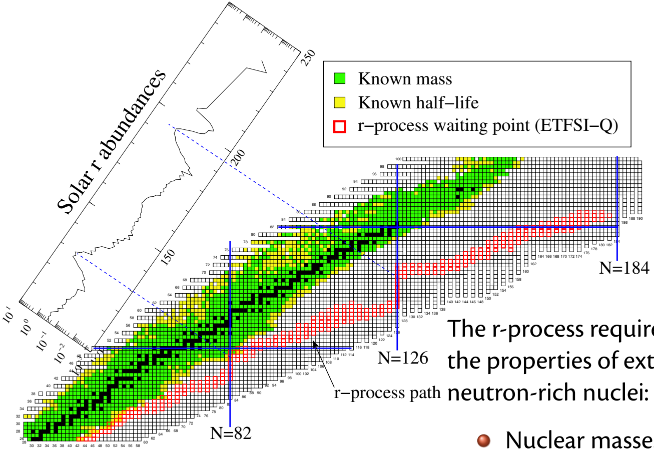
Outline

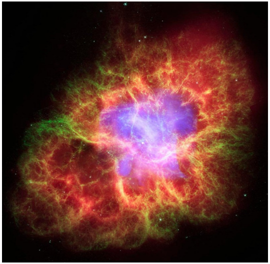
Making Gold in Nature: r-process nucleosynthesis



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

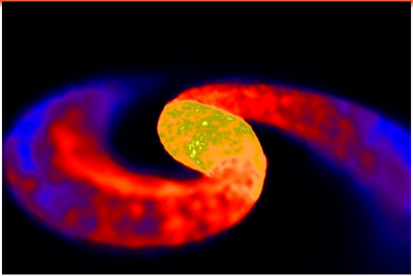
- Nuclear masses.
- Beta-decay half-lives.
- Neutron capture rates.
- Fission rates and yields.

r-process Astrophysical sites



Core-collapse supernova

- Neutrino-winds from protoneutron stars.
- Aspherical explosions, Jets, Magnetorotational Supernova, … [Winteler *et al*, ApJ **750**, L22 (2012); Mösta *et al*, arXiv:1403.1230]



Neutron star mergers

- Matter ejected ($\sim 0.01\ M_\odot$) dynamically during merger.
- Electromagnetic emission from radioactive decay of r-process nuclei [KiloNova, Metzger *et al* (2010), Roberts *et al* (2011), Bauswein *et al* (2013)]
- What is the additional contribution from the accretion disk?

Role of weak interactions

Main processes:

$$\nu_e + n \rightleftarrows p + e^-$$
$$\bar{\nu}_e + p \rightleftarrows n + e^+$$

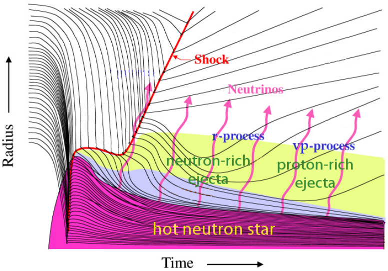
Neutrino interactions determine the proton to neutron ratio.

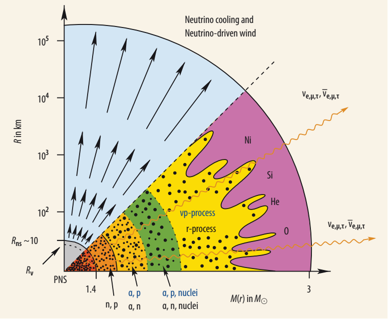
Neutron-rich ejecta:

$$\langle E_{\bar{\nu}_e}\rangle - \langle E_{\nu_e}\rangle > 4\Delta_{np} - \left[\frac{L_{\bar{\nu}_e}}{L_{\nu_e}} - 1\right]\left[\langle E_{\bar{\nu}_e}\rangle - 2\Delta_{np}\right]$$

- neutron-rich ejecta: r-process
- proton-rich ejecta: νp-process

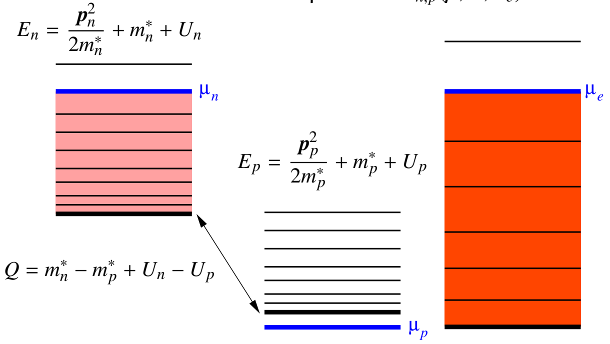
We need accurate knowledge of ν_e and $\bar{\nu}_e$ spectra





Neutrino interactions at high densities

Most of Equations of State treat neutrons and protons as "non-interacting" (quasi)particles that move in a mean-field potential $U_{n,p}(\rho, T, Y_e)$.



$$E_n = \frac{\boldsymbol{p}_n^2}{2m_n^*} + m_n^* + U_n$$

$$E_p = \frac{\boldsymbol{p}_p^2}{2m_p^*} + m_p^* + U_p$$

$$Q = m_n^* - m_p^* + U_n - U_p$$

- ν_e absorption opacity affected by final state electron blocking

$$\chi(E_\nu) \propto (E_\nu + \Delta m^* + \Delta U)^2 \exp\left(\frac{E_\nu + \Delta m^* + \Delta U - \mu_e}{kT}\right), \quad \Delta U = U_n - U_p$$

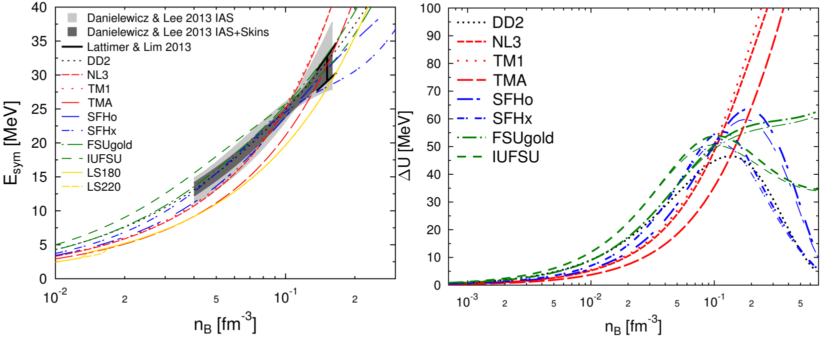
- $\bar{\nu}_e$ absorption affected by energy threshold (ΔU).

$$\chi(E_\nu) \propto (E_\nu - \Delta m^* - \Delta U)^2 \quad E_\nu > \Delta m^* + \Delta U$$

- larger symmetry energy (larger ΔU) implies: i) the larger the energy difference between ν_e and $\bar{\nu}_e$; ii) smaller electron flavor luminosities.

Constrains in the symmetry energy

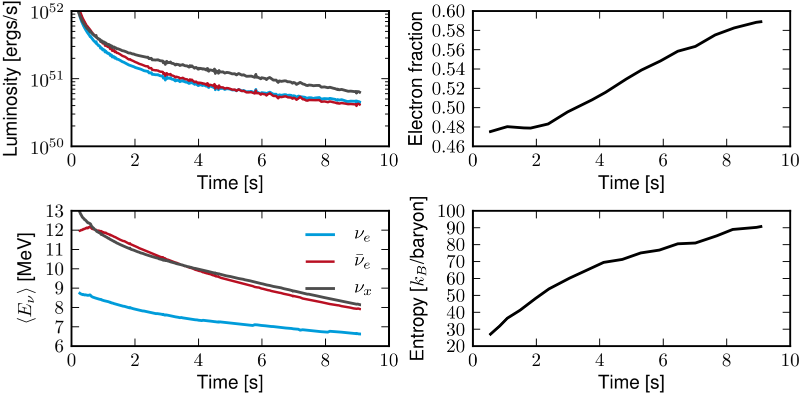
- Combination nuclear physics experiments and astronomical observations (Lattimer & Lim 2013)
- Isobaric Analog States (Danielewicz & Lee 2013)



Figures from Matthias Hempel (Basel)

Impact on neutrino luminosities and Y_e evolution

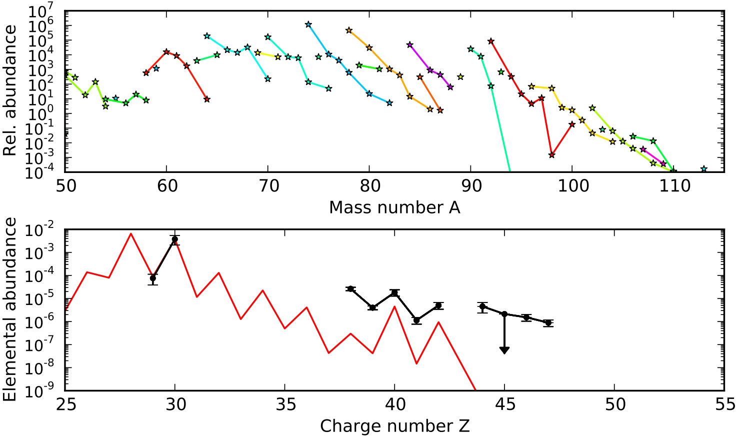
1D Boltzmann transport radiation simulations (artificially induced explosion) for a 11.2 $M_\odot$ progenitor based on the DD2 EoS (Stefan Typel and Matthias Hempel).



Y_e is moderately neutron-rich at early times and later becomes proton-rich.

GMP, Fischer, Huther, J. Phys. G **41**, 044008 (2014).

Nucleosynthesis



- Elements between Zn and Mo, including ^{92}Mo, are produced
- Mainly neutron-deficient isotopes are produced
- No elements heavier than Mo ($Z = 42$) are produced.

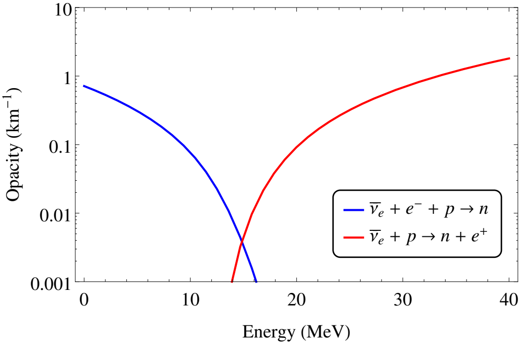
Neutron decay

The neutron-proton energy difference in the medium could be of the order of several 10s MeV. Neutron decay is an important source of low energy neutrinos.

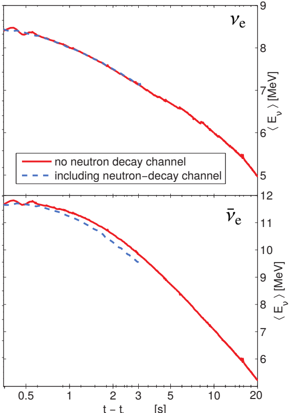
$$n \rightleftarrows p + e^- + \bar{\nu}_e$$

$$e^+ + n \rightleftarrows p + \bar{\nu}_e$$

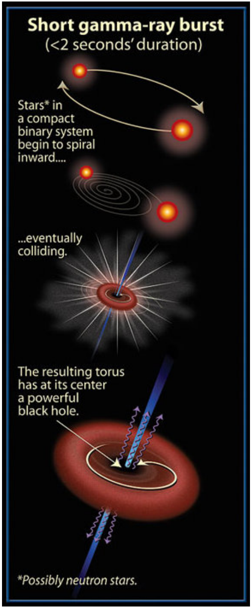
This is part of the direct URCA process in neutron stars [Lattimer *et al*, (1991)]

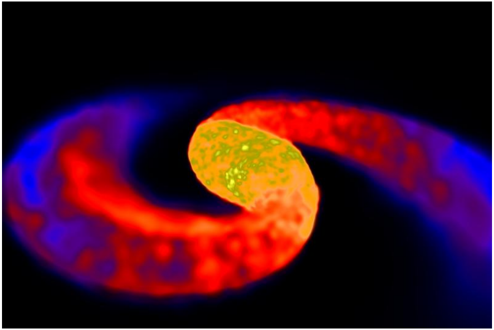


Fischer, Lohs, GMP, Qian, in preparation



Neutron star mergers: Short gamma-ray bursts and r-process

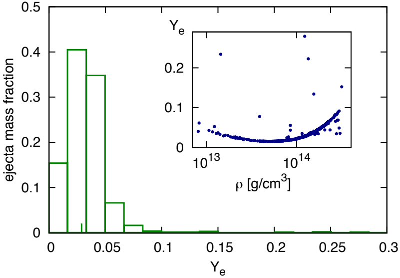


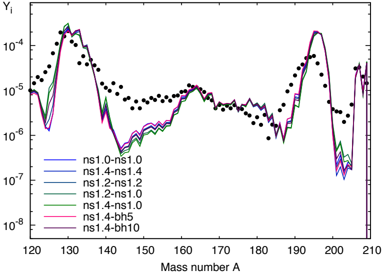


- Mergers are expected to eject around $0.01\ \mathrm{M}_\odot$ of very neutron rich-material ($Y_e \sim 0.01$). A similar amount of less neutron-rich material ($Y_e \sim 0.1$–0.2) is expected from the accretion disk.
- They are also promising sources of gravitational waves.
- Observational signatures of the r-process?

Neutron-star mergers: Astrophysically robust

Korobkin, Rosswog, Arcones, & Winteler, MNRAS **426**, 1940 (2012)





similar results: Bauswein, Goriely, Janka, ApJ **773**, 78 (2013)

General features r-process

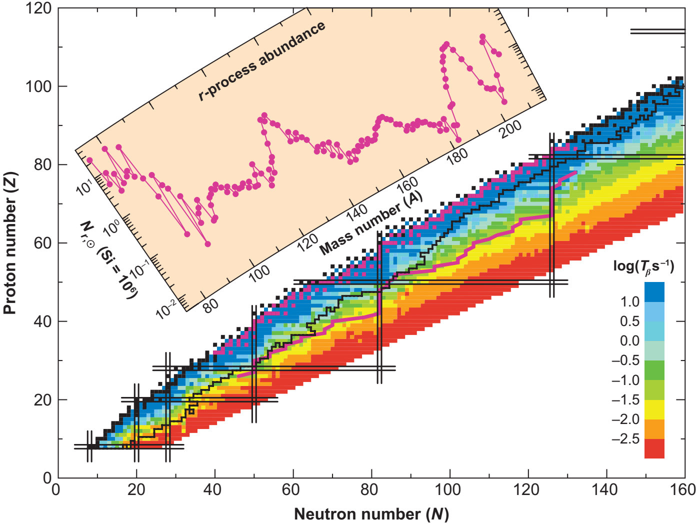
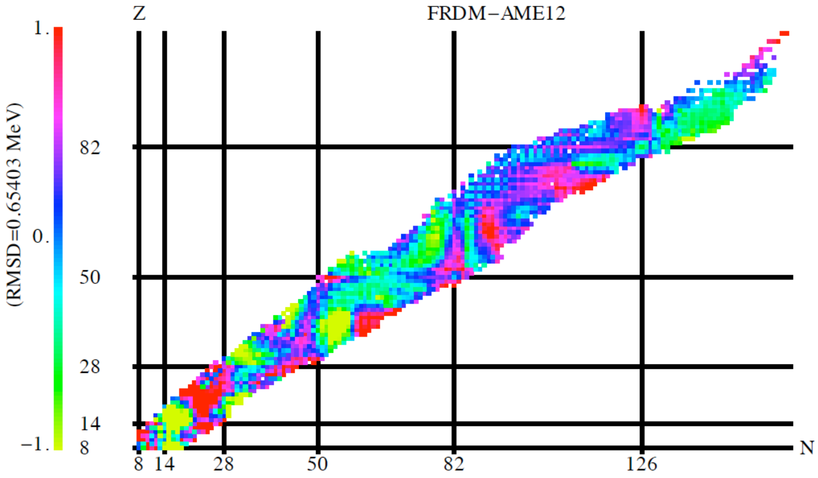


Figure from Peter Möller.

Global mass models vs experiment

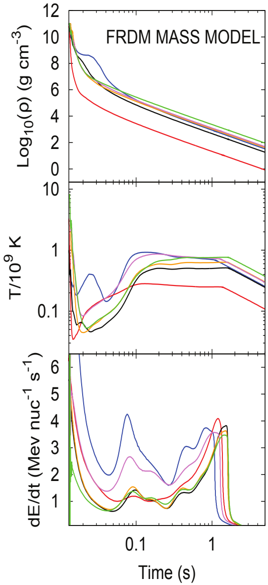


Similar behaviour for all mass models.

Problems in reproducing masses in transitional regions.

General features evolution in mergers

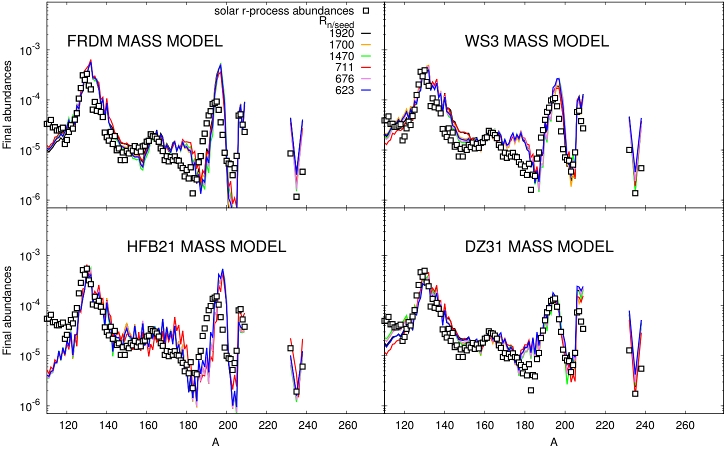
- r-process stars once electron fermi energy drops below ~ 10 MeV to allow for beta-decays ($\rho \sim 10^{11}$ g cm^{-3}).
- Important role of nuclear energy production.
- Increases temperature to values that allow for an $(n, \gamma) \rightleftarrows (\gamma, n)$ equilibrium.
- r-process operates at moderate high entropies, $s \sim 50$–100 k/nuc.



Trajectories from simmulation A. Bauswein and H.-T. Janka.

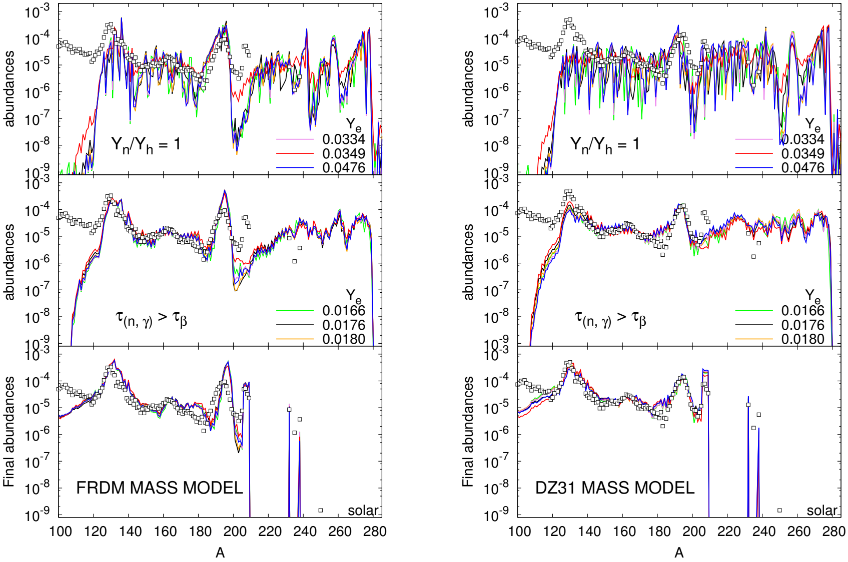
Final abundances different mass models

neutron captures computed consistently for each mass model.

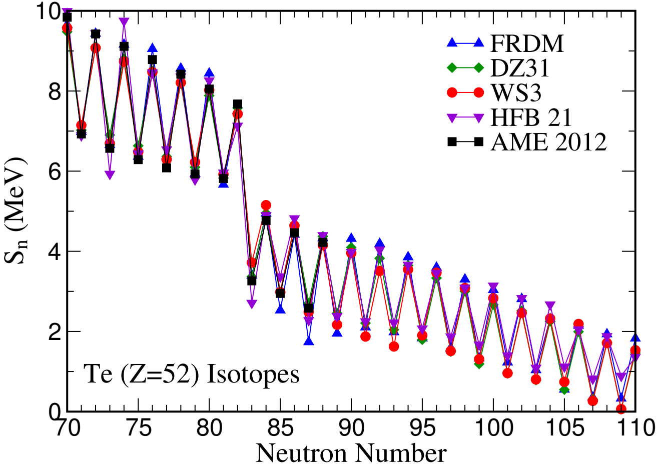


J. Mendoza-Temis, G. Martinez-Pinedo, K. Langanke, A. Bauswein, H.-Th. Janka, in preparation.

Temporal evolution (selected phases)

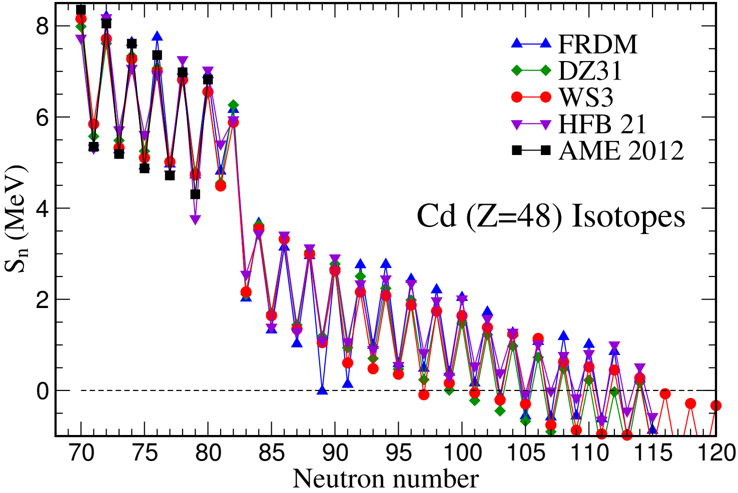


Role of $N \sim 90$ (Telurium isotopes)



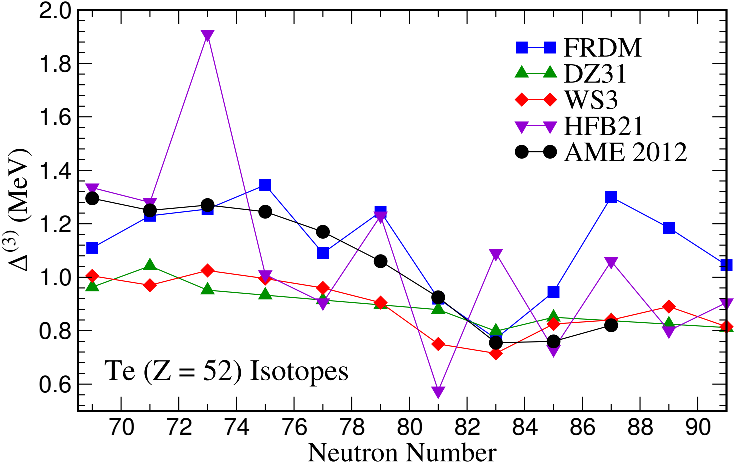
Hakala *et al*, PRL **109**, 032501 (2012)
Van Schelt, *et al*, PRC **85**, 045805 (2012)

Neutron Separation energies Cd isotopes



FRDM mass model predicts rather low neutron separation energies approaching $N \sim 90$ for $Z \sim 50$.

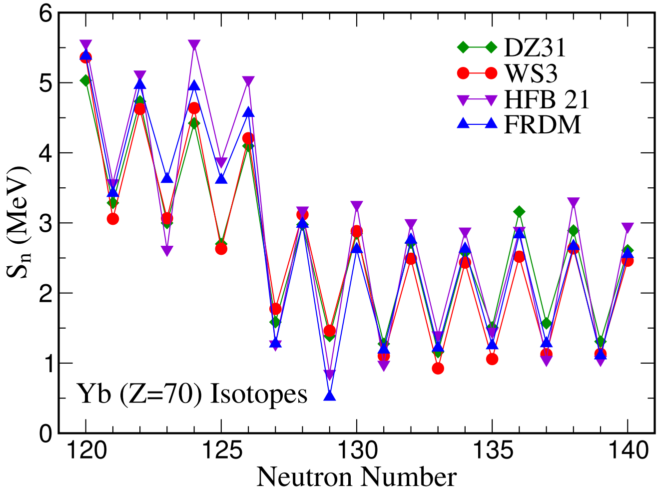
Odd-even effects (Te isotopes)



$$\Delta^{(3)} = (-1)^N \left[2B_e(Z,N) - B_e(Z,N+1) - B_e(Z,N-1)\right]/2$$

All mass models have problems reproducing odd-even effects

The role of $N \sim 130$



Both FRDM and HFB models predict a sudden drop in neutron separation energies approaching $N \sim 130$ for $Z \sim 70$.