r-process nucleosynthesis: An Introduction

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March 6th, 2024

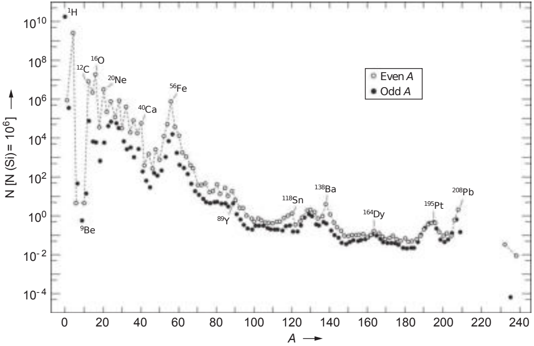
19th Russbach School on Nuclear Astrophysics

March 3 – 9, 2024

Rußbach am Paß Gschütt (Austria)

Solar system elements: where do they come from?

credit: Palme, Lodders and Jones (2014)



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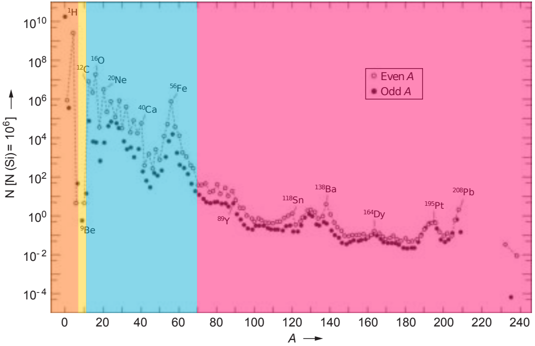
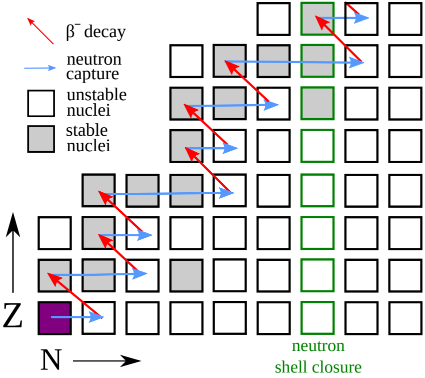


- H, He and (some) Li: Big-Bang nucleosynthesis.
- (some) Li, Be and B: Galactic cosmic rays on interstellar medium.
- Nuclei up to Fe peak: Stellar evolution and explosions.
- Beyond Fe peak: p nuclei, and (s- and r-)**neutron capture processes**.

The s process

B^{2}FH, Rev. Mod. Phys. 29, 547 (1957) ; A. Cameron, Report CRL-41 (1957)

s(low neutron capture) process: $\tau_{(n,\gamma)} > \tau_{\beta-}$, $n_n = 10^{10-12}$ cm^{-3}

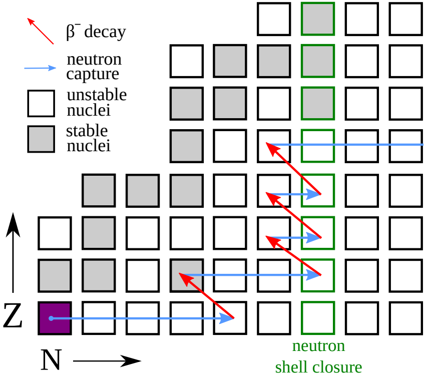


- The path to heavier nuclei stays close to stability.
- Astrophysical site: 0.8-8 $M_\odot$ stars.

The r process

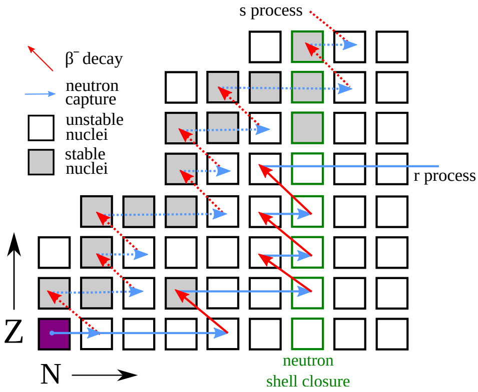
B[2]FH, Rev. Mod. Phys. 29, 547 (1957) ; A. Cameron, Report CRL-41 (1957)

r(apid neutron capture) process: $\tau_{(n,\gamma)} \ll \tau_{\beta-}$, $n_n > 10^{26}$ cm^{-3}



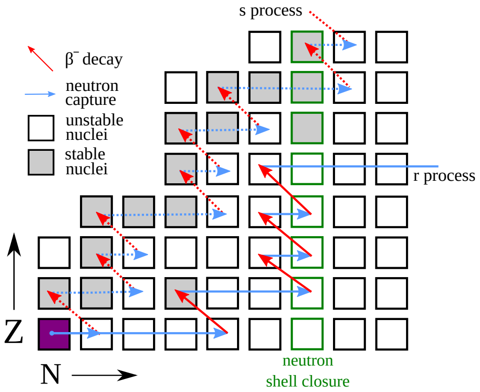
- The path to heavier nuclei goes through neutron-rich nuclei.
- Astrophysical site with high neutron fluxes → transient object.

Solar system abundances of heavy elements

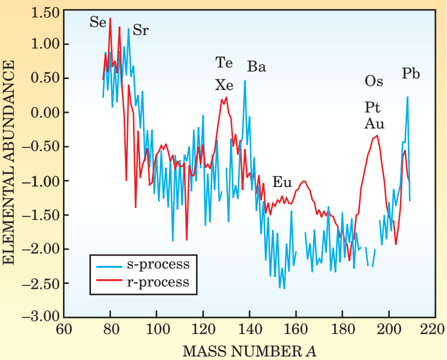


- Accumulation of material at shell closures → peak structure.
- Roughly equal contributions by s and r process.

Solar system abundances of heavy elements



Adapted from Sneden and Cowan, Science 299, 70 (2003)



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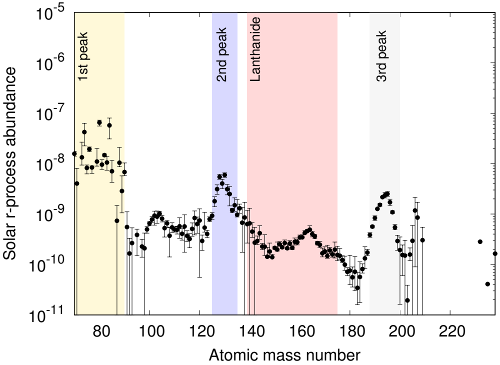
- Roughly equal contributions by s and r process.

Modeling r-process abundances



K. Hotokezaka *et al.*, Int. J. Mod. Phys. D 27, 1842005 (2018)

Astrophysical site

Sets thermodynamic conditions

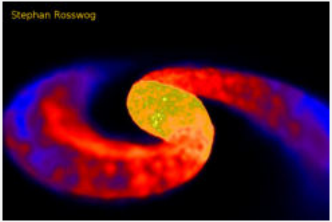
Nuclear physics

Shapes abundances distribution

r-process: astrophysical sites

see poster of Ryota Hatami (#4) and Jan Kuske (#5)

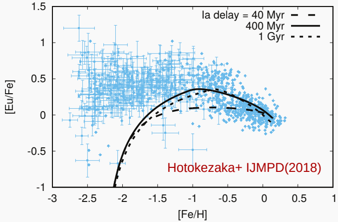
Neutron star mergers



- GW170817 and kilonova:

  lanthanides are produced!
- From simulations:
  - $\sim 10^{-2}$ $M_\odot$ ejected mass.
  - Neutron rich material.
  - Synthesis of nuclei with $A > 90$.

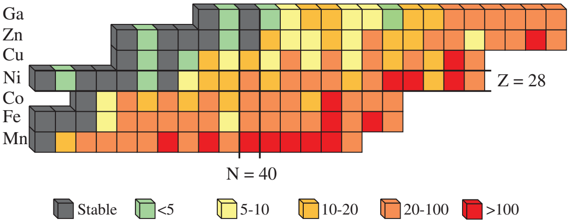
Other sources



- Other scenarios:
  - CCSne (produce first peak).
  - Collapsars
  - Magnetorotational supernovae
  - ...
- Dominating source?

r-process: nuclear physics input

- r process requires the knowledge of the properties of neutron-rich nuclei:
  - Nuclear masses, β-decay rates, neutron-capture rates, fission rates and yields, ...
- Rely on theoretical predictions: impact of uncertainties?



S. N. Liddick *et al.*, PRL **116**, 242502 (2016)

- Nuclei with longest lifetimes have largest impact.

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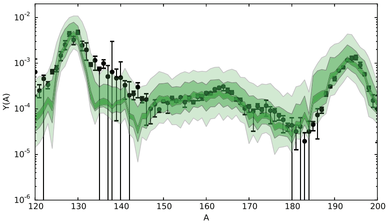

S. N. Liddick *et al.*, PRL **116**, 242502 (2016)

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Composition change

The build-up of elements occur via composition changes through **three main processes**:

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- **Decays**: $a \to b + c$

$$\frac{dn_a}{dt} = -\lambda_a n_a \quad \text{with} \quad \lambda_a = \ln(2)/t_{1/2}(a)$$

The decay rate λ_a can depend on temperature and density.

In order to distinguish between changes in the density (hydrodynamic) from changes in the composition (nuclear reactions), one introduces the **abundance**:

$$Y_i = \frac{n_i}{n} \quad \text{with} \quad n \approx \frac{\rho}{m_u} \equiv \text{number density of nucleons}$$

$$\frac{dY_a}{dt} = -\lambda_a Y_a$$

E.g.: β decay, spontaneous fission

Composition change

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- **Capture processes**: $a + b \rightarrow c + \gamma$

$$\frac{dn_a}{dt} = -n_a n_b \langle \sigma v \rangle_{ab}$$
$$\frac{dY_a}{dt} = -Y_a Y_b \frac{\rho}{m_u} \langle \sigma v \rangle_{ab} \equiv -\lambda_a Y_a$$

being $\lambda_a = (Y_b \rho / m_u) \langle \sigma v \rangle_{ab}$ the destruction rate of target nuclei a by reaction with b.

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- **Photodissociations**: $a + \gamma \to b + c$

$$\frac{dn_a}{dt} = -n_a n_\gamma \langle \sigma c \rangle_{a\gamma}$$
$$\frac{dY_a}{dt} = -Y_a n_\gamma \langle \sigma c \rangle_{a\gamma} \equiv -\lambda_a Y_a$$

  being $\lambda_a = n_\gamma \langle \sigma c \rangle_{a\gamma}$ the photodissociation rate of target nuclei a.

Stellar reaction rates

General reaction between n_a and n_b particles per volume of targets a and projectiles b:

$$a + b \rightarrow c + d$$

The number of reactions per unit of time, volume and pair of reactants:

$$r_{ab} = \frac{n_a(v_a) n_b(v_b)}{(1+\delta_{ab})} \sigma(v) v, \quad \text{with} \quad v = |v_a - v_b|$$

Nuclei in stellar environments follow a Maxwell-Boltzmann thermal distribution:

$$P(v)dv = 4\pi v^2 \left(\frac{m}{2\pi kT}\right)^{3/2} \exp\left(-\frac{mv^2}{2kT}\right) dv$$

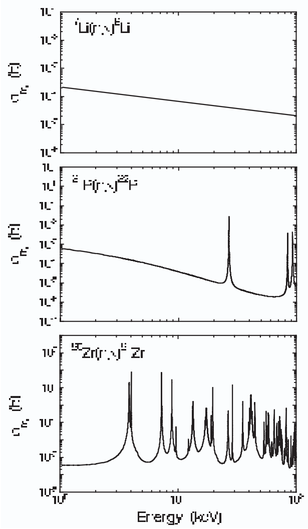
leading to the MB averaged cross section

$$\langle \sigma v \rangle = \int_0^\infty \sigma P(v) v dv = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma(E) E \exp\left(-\frac{E}{k_B T}\right) dE \quad \text{with } \mu = \frac{m_a m_b}{m_a + m_b}; \; E = \frac{\mu v^2}{2} .$$

The reaction rate $r_{ab} = n_a n_b \langle \sigma v \rangle$ depends critically on the cross section $\sigma(E)$.

Cross sections

C. Iliadis, *Nuclear Physics of Stars*



- Neutron-induced reactions cross sections can be computed within the Hauser-Feshbach statistical theory: statistical average over many resonances.
- For a $i(n,\gamma)m$ reaction proceeding from the target nucleus i in the state $\mu(J_i^\mu, \pi_i^\mu)$ to a final nucleus m in a state $\nu(J_m^\nu, \pi_m^\nu)$ through the compound state J^π with energy E:

$$\sigma_{n,\gamma}^{\mu\nu}(E_{i,n}) \propto \frac{T_n^\mu T_\gamma^\nu}{T_{\text{tot}}}$$

- Inverse $c(\gamma,b)a$ rates can be computed from detailed balance:

$$\lambda_\gamma = \left(\frac{m_u kT}{2\pi\hbar^2}\right)^{3/2} \frac{G_a G_b}{G_c} \left(\frac{A_a A_b}{A_c}\right)^{3/2} \exp(-Q/kT) \frac{\langle\sigma v\rangle_{ab}}{1+\delta_{ab}}$$

being $G(T) = \sum_i (2J_i+1) e^{-E_i/(kT)}$.

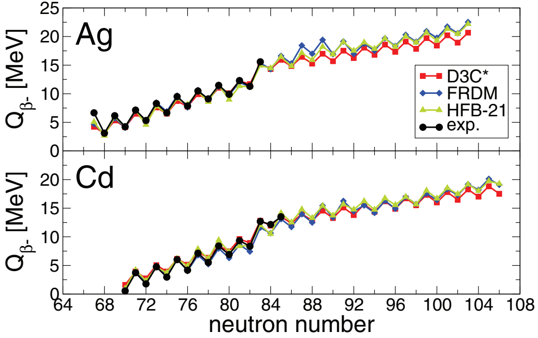
β decays

Beta-decay rates can be computed from Fermi's Golden rule:

$$\lambda_\beta = \frac{\ln(2)}{t_{1/2}} = \frac{g^2 m_e^5 c^4 |M_{fi}|^2}{f(Q_\beta) 2\pi^3 \hbar^7}$$

being $|M_{fi}|$ the (GT and F) nuclear matrix elements, and $f(Q_\beta)$ the Fermi integral.

T. Marketin *et al.*, Phys. Rev. C **93**,025805 (2016)



Two main ingredients:

- Q_β-values: large for neutron-rich nuclei.
- β-decay strength: determines the possible emission of delayed neutrons.

For heavy nuclei, forbidden transition ($l_{e\nu} > 0$) become relevant for the estimation of the rates.

Network equations

The time derivative of the abundances is modeled through a set of differential equations (reaction network equations):

$$\frac{dY_i}{dt} = \sum_j P^i_j \lambda_j Y_j + \sum_{jk} P^i_{jk} \frac{\rho}{m_u} \langle \sigma v \rangle_{jk} Y_j Y_k + \sum_{jkl} P^i_{jkl} \left(\frac{\rho}{m_u}\right)^2 \langle \sigma v \rangle_{jkl} Y_j Y_k Y_l$$

P^i describe how often the nucleus i is created or destroyed, and whether two or more identical nuclei are involved in the reactions.

- Stiff system: timescales change by several orders of magnitude.
- Decoupled from hydrodynamic.
- Tremendous simplifications at high T and ρ.

Nuclear statistical equilibrium (NSE)

- At high T and ρ, fusion reactions and photodissociation rates are large, leading to chemical equilibria

$$p + (Z,A) \rightleftarrows (Z+1,A) + \gamma \qquad \rightarrow \qquad \mu_p + \mu(Z,A) = \mu(Z+1,A+1)$$
$$n + (Z,A) \rightleftarrows (Z,A+1) + \gamma \qquad \rightarrow \qquad \mu_n + \mu(Z,A) = \mu(Z,A+1)$$

- Nuclear statistical equilibrium (NSE): chemical equilibria across the whole nuclear chart

$$Z\mu_p + N\mu_n = \mu(Z,A)$$

- At NSE, nuclear abundances depend on nuclear properties (binding energy B_i) and environment conditions (T, ρ, and $Y_e = \sum_i Z_i Y_i$), but not the individual rates!

$$Y_i(Z_i,N_i) = Y_n^{N_i} Y_p^{Z_i} \frac{G_i(T) A_i^{3/2}}{2_i^A} \underbrace{\left(\frac{\rho}{m_u}\right)^{(A_i-1)}}_{\substack{\text{high } \rho \\ \text{favor heavy nuclei}}} \overbrace{\left(\frac{2\pi\hbar^2}{m_u kT}\right)^{3(A_i-1)/2}}^{\substack{\text{high } T \\ \text{favor light nuclei}}} \underbrace{\exp\left(\frac{B_i}{kT}\right)}_{\substack{\text{intermediate:} \\ \text{tightly bound nuclei}}}$$

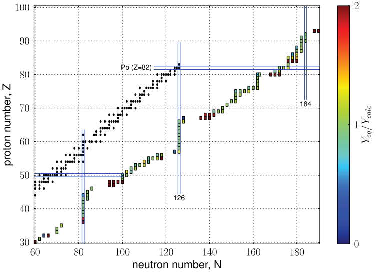
- Weak reactions?

Quasi statistical equilibrium (QSE)

For astrophysical conditions with large n_n and $T \sim 1\,\text{GK}$:

- Neutron-rich nuclei ($S_n \lesssim 2$ MeV) can be produced.
- Charge-particle reactions are frozen: isotopic chains are only connected through β decays.
- But chemical equilibrium between (n,γ) and (γ,n) reactions still holds.
- This produces a quasiequilibrium clusters along isotopic chains: $(\gamma,n) \rightleftarrows (n,\gamma)$ equilibrium. Abundance ratios in each isotopic chain independent of reaction rates:

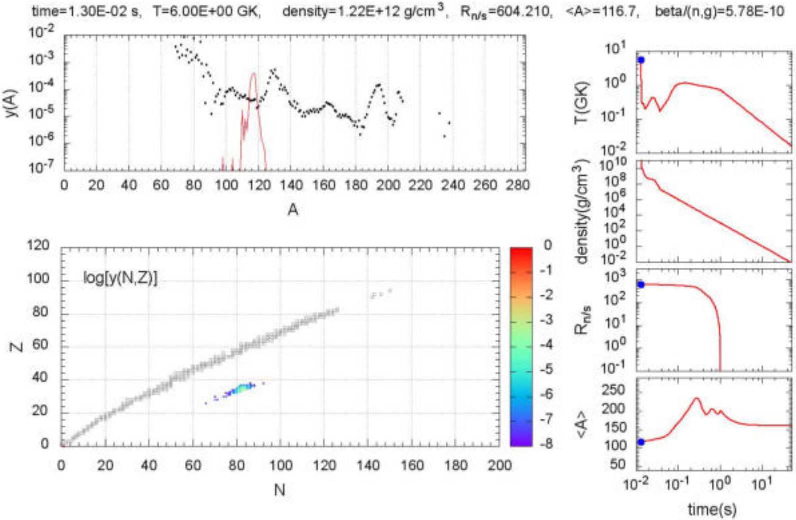
M. Eichler *et al.*, Astrophys. J. **808**, 30 (2015)



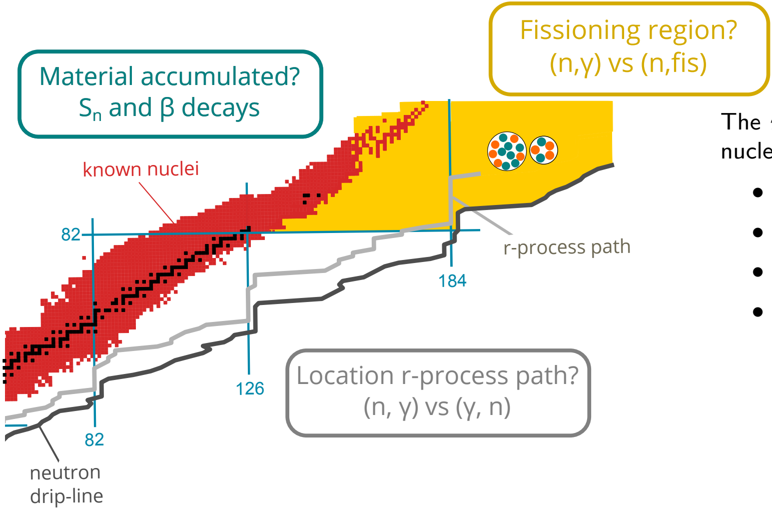
$$\frac{Y(Z,A+1)}{Y(Z,A)} = n_n \frac{G(Z,A+1)}{2G(Z,A)} \left(\frac{A+1}{A}\right)^{3/2} \left(\frac{2\pi\hbar^2}{m_u kT}\right)^{3/2} \exp\left(\frac{S_n(A+1)}{kT}\right)$$

- For a given n_n and T, abundance maximum in all isotopic chains have the same S_n ($\sim 2-3$ MeV).

r-process nucleosynthesis in NSM



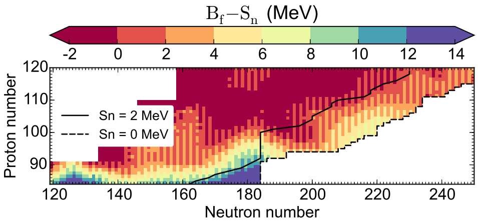
Nuclear inputs



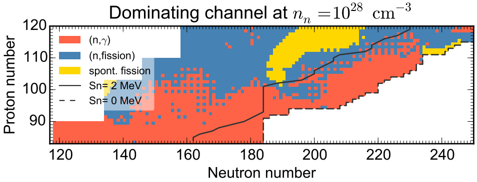
The r-process requires the knowledge of nuclear properties of neutron-rich nuclei:

- nuclear masses;
- β-decay rates;
- neutron capture rates;
- fission rates and yields.

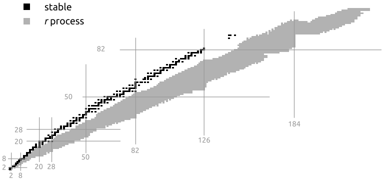
1) Compute nuclear properties using EDF.



2) Calculate stellar reaction rates from Hauser-Feshbach theory.



3) Obtain r-process abundances and light curve using nuclear network calculations.



The Hartree-Fock-Bogolyubov (HFB) formalism

The ground-state wavefunction is obtained by minimizing the total energy:

$$\delta E[|\Psi\rangle] = 0\,,$$

where $|\Psi\rangle$ is a quasiparticle (β) vacuum:

$$|\Psi\rangle = \prod_{\mu} \beta_\mu |0\rangle \quad \Rightarrow \quad \beta_\mu |\Psi\rangle = 0\,.$$

The energy density functionals (EDF) provide a phenomenological ansatz of the effective nucleon-nucleon interaction:

- Gogny, Skyrme, relativistic EDF, BCPM, ...

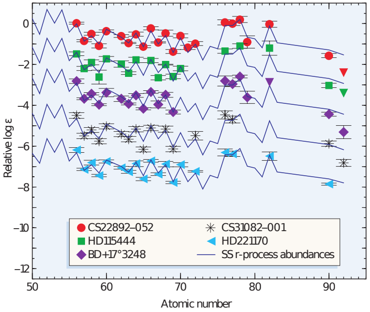
Sophisticated many-body methods can be built on top: QRPA (β-decays and excited stated), PGCM (excited states), TDDFT and TDGCM (fission)...

Fission and r process

Thielemann+(1983), Panov+(2005), Martinez-Pinedo+(2007), Beun+(2008), Petermann+(2012), Eichler+(2015), Goriely(2015), Mumpower+(2018), Giuliani+(2018,2020), Zhu+(2019), Wu+(2019), Vassh+(2019,2020), ...

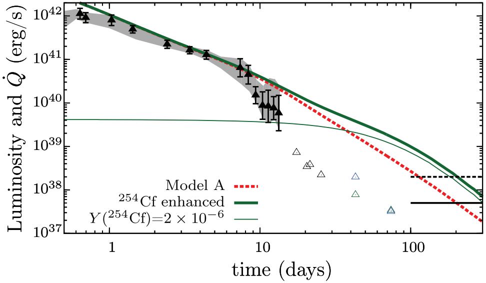
Abundances

J. J. Cowan and C. Sneden, Nature 440 1151 (2006)



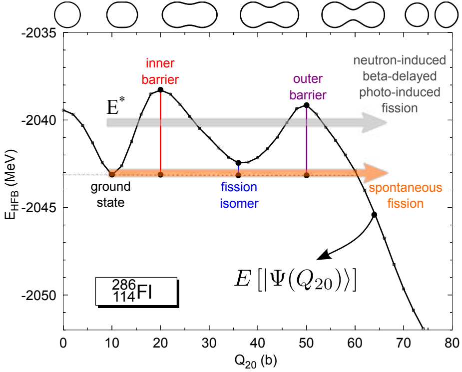
Kilonova

M.-R. Wu *et al.*, Phys. Rev. Lett. **122**, 062701 (2019)



Fission shapes abundances and kilonova light curve, providing a mechanism for a robust r-process nucleosynthesis.

The fission process



Potential Energy Surface $\mathcal{V}$

Energy evolution from the initial state to the scission point.

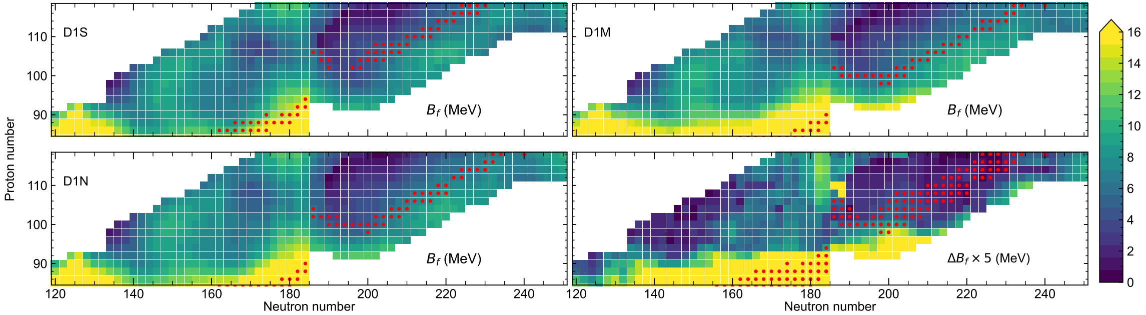
Collective inertias $\mathcal{M}$

Resistance of the nucleus against the deformation forces.

$$P \propto 1/\exp(2S[L]) \to S[L(Q_{20})] = \int_a^b dQ_{20} \sqrt{\mathcal{M}(Q_{20})[\mathcal{V}(Q_{20}) - E_0]}$$

Systematic of fission barriers B_f

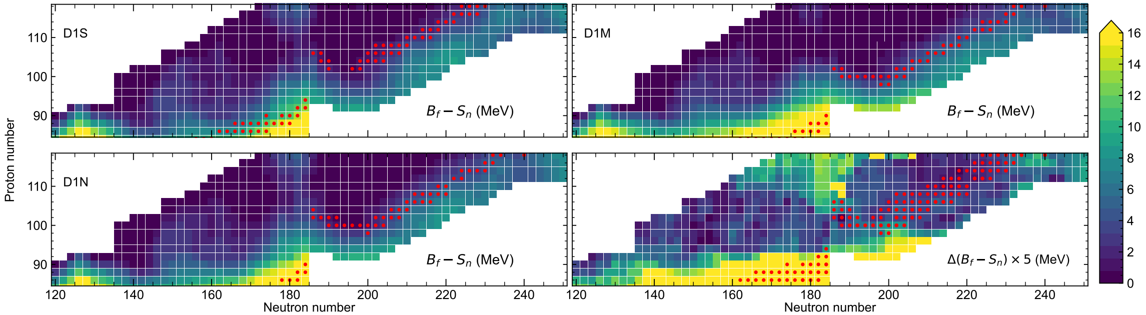
- $B_f \rightarrow$ stability against fission.



- B_f trends qualitatively similar across different Gogny interactions:
  - $Z > 94$: systematic deviations $\sim$ 1–2 MeV.
  - $Z \leq 94$: deviations up to 10 MeV (but very high B_f).
- Location of the r process differ above $N = 184$.

Systematic of $B_f - S_n$

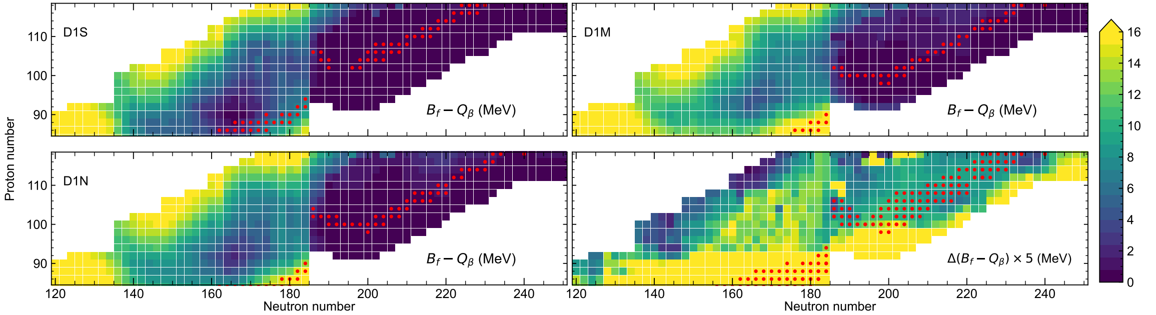
- For $B_f - S_n \lesssim 2\,\text{MeV}$ (n, fis) dominates over (n, γ).



- Production of (super)heavy nuclei requires the overcoming of neutron shell closure at $N = 184$.
- r-process path pushed into a region of low $B_f - S_n$.

Systematic of $B_f - Q_\beta$

- $B_f - Q_\beta \rightarrow$ competition between fission and β-decay.

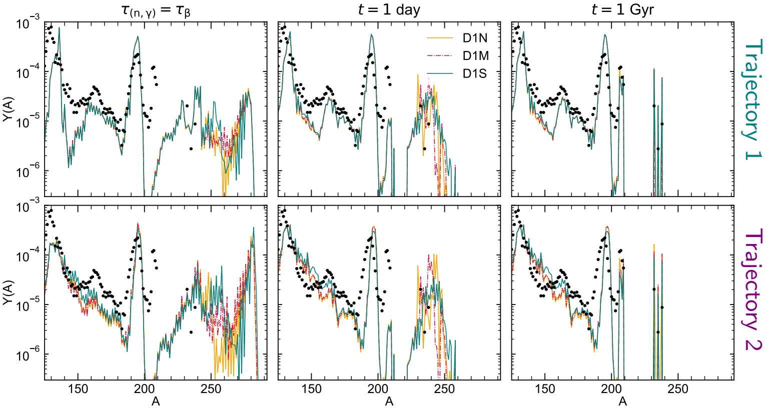


- Path towards stability interrupted by region of low fission barriers.

Impact of fission on the r-process: abundances Y

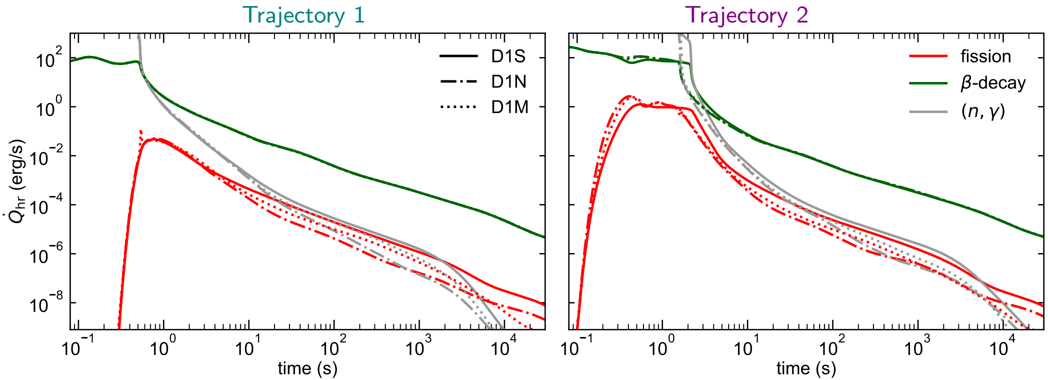
Dynamical ejecta from neutron star merger (C. E. Collins *et al.*, MNRAS 101093 (2023)):

- Trajectory 1: $Y_e = 0.151$; $n/s = 105$;
- Trajectory 2: $Y_e = 0.027$; $n/s = 1100$.



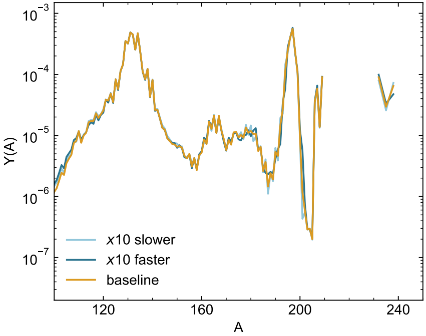
Impact of fission on the r-process: heating rates

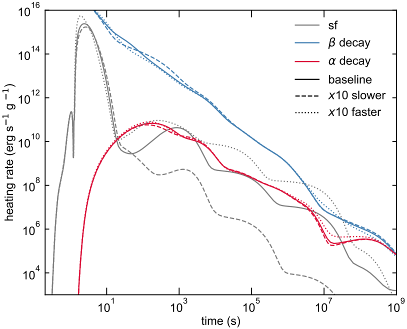
- Trajectory 1: $Y_e \lesssim 0.05$; $n/s \approx 600$
- Trajectory 2: $Y_e \lesssim 0.15$; $n/s \approx 120$



Impact of β-decay rates on fission

- Impact of β-decay half-lives varies with the observable.
- We modified $t^{\beta}_{1/2}$ (FRDM) $\geq 3\ s$ and study the impact on abundances and heating rates.

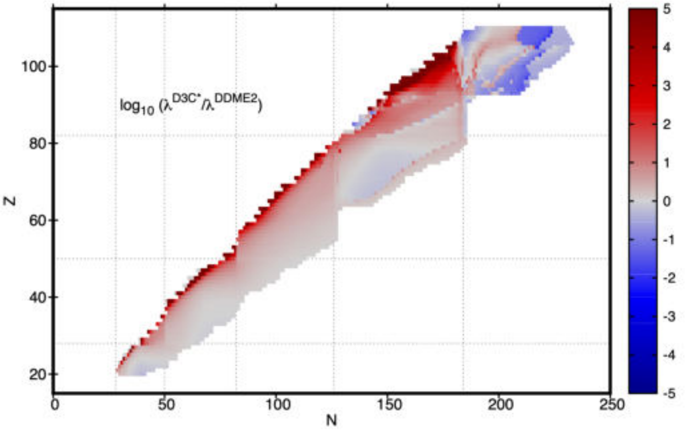




Fission heating rate sensitive to "slow" β-decay rates
($\tau_\beta \gtrsim$ few seconds)

Systematic of β-decay rates

credit: Caroline Robin (U. Bielefeld)

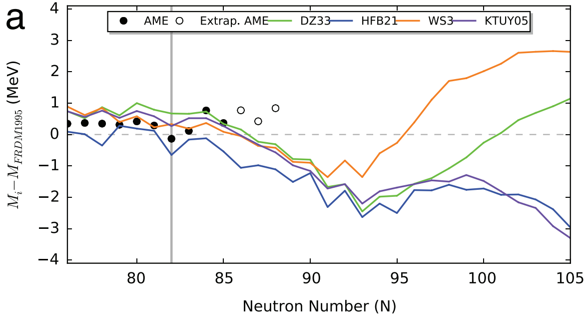


- β-decay rates closer to stability show larger uncertainties $\rightarrow$ more systematic studies are required (see also E. M. Ney *et al.*, Phys. Rev. C **102**, 034326 (2020)).

Nuclear masses - Global and local changes

Nuclear masses determine thresholds energy for n captures, β decays and fission, and the location of r-process path in $(n,\gamma) \rightleftarrows (\gamma,n)$ equilibrium.

M. R. Mumpower et al., PPNP 86 (2016)



Very different predictions far from stability: are these differences relevant for the r-process abundances?

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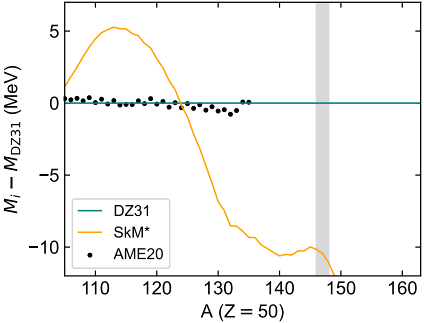

Very different predictions far from stability: are these differences relevant for the r-process abundances?

Masses = homogeneous part (global, LDM) + quantum shell-correction (local)

Nuclear masses - Global and local changes

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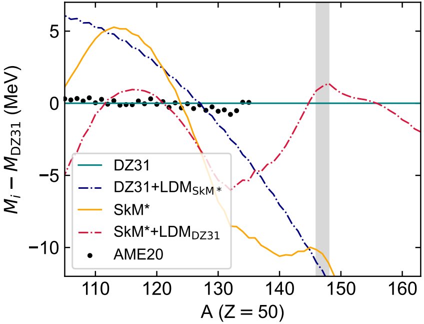

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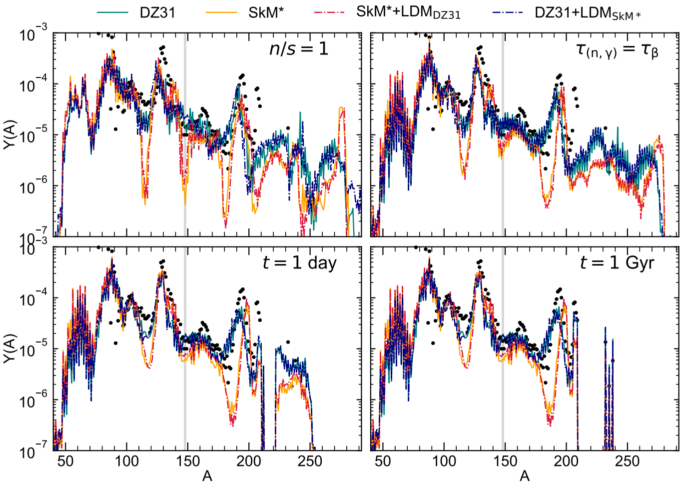
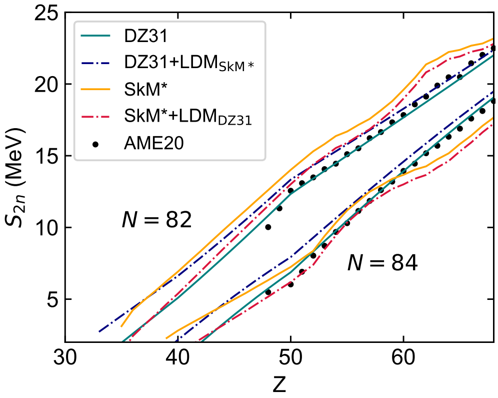
Symmetry energy and r process

NSM trajectories from Collins *et al.*, MNRAS 101093 (2023)



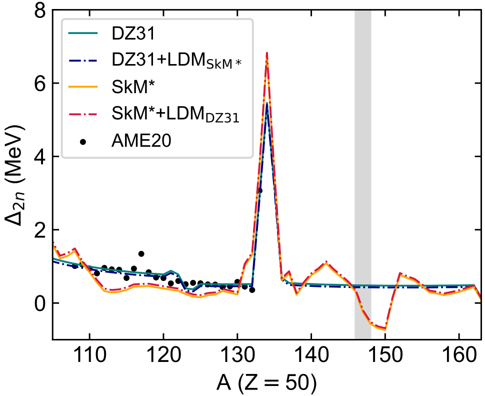
Abundances insensitive to global changes in masses (e.g., symmetry energy).

Nuclear masses - Global and local changes



Abundance mostly related to local changes on S_{2n} (rather than bulk properties of masses).

Nuclear masses - Global and local changes



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Collaborators

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Funding

Postdoc position

Postdoc position in Nuclear Physics Group at Universidad Autónoma de Madrid.

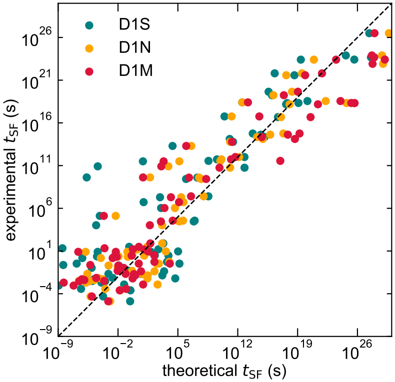
Starting date: mid-end 2024

Contact: samuel.giuliani@uam.es

Backup

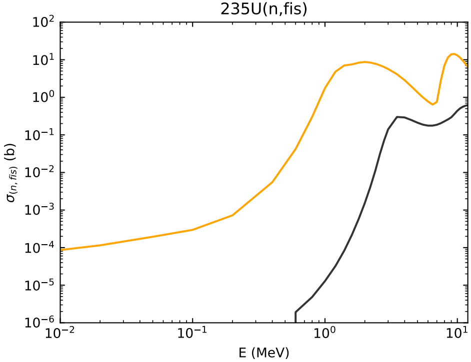
$t_{1/2}^{\mathrm{sf}}$: theory vs experiment

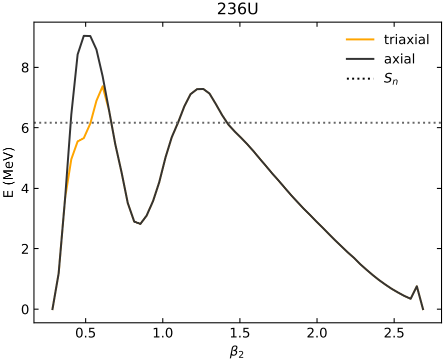
- D1S, D1N and D1M $t_{1/2}^{\mathrm{sf}}$ are systematically overpredicted:
  - inclusion of pairing as dof (minimum action path vs minimum energy path), collective inertias, triaxiality. . .
- Collective inertias are renormalized in order to reproduce experimental $t_{1/2}^{\mathrm{sf}}$.



Global calculation of fission nuclear properties

- Model assumptions → systematic uncertainties → impact on nucleosynthesis?
- Relevant physics close to stability ≠ relevant physics in exotic nuclei.





- Systematic deviations close to stability could be compensated in exotic nuclei (and vice versa) → global calculations from different models are required.

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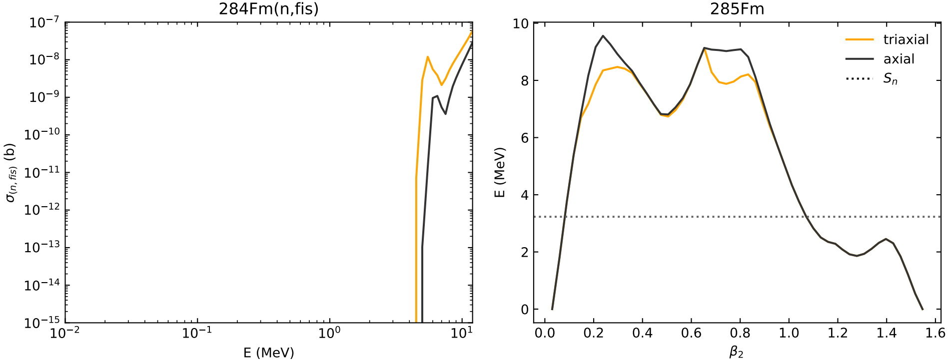

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