Impact of fission on r-process nucleosynthesis within the energy density functional theory

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Neutron star mergers: from gravitational waves to nucleosynthesis

Hirschegg, Austria

Outline

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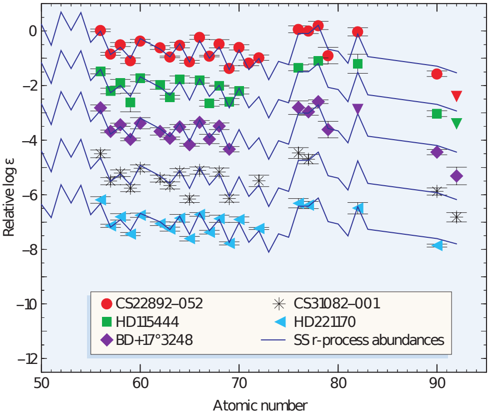
1. **Introduction**
   r-process in neutron star mergers (NSM)
2. **Fission rates from the BCPM EDF**
   Fission within the Energy Density Functional approach
   Fission properties of the BCPM EDF
   Stellar reaction rates
3. **r-process nucleosynthesis in NSM**
   r-process abundances: BCPM vs FRDM-TF
   Radioactivity
   Averaged fission rates
4. **Conclusions & Outlook**

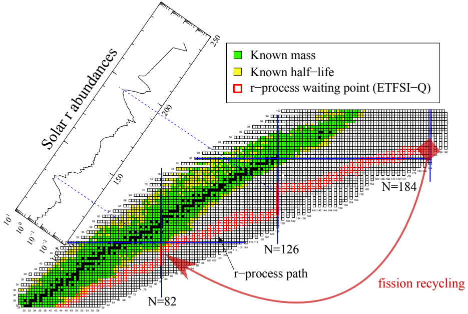
r-process abundances distributions

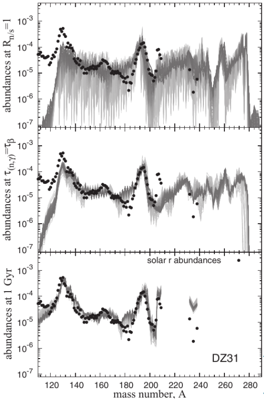
Cowan & Sneden, Nature 440, 1151 (2006).



- Site?

r-process in Neutron Star Mergers & fission





Mendoza-Temis et al., Phys. Rev. **C92**, 055805 (2015)

Condition for robust r-process abundances in NSM

Material in the fissioning region $(\mathrm{A} > 250)$ dominating at freeze-out $\rightarrow$ systematic calculations of fission rates using different models are required!

Outline

Fission within the Energy Density Functional approach

Potential Energy Surface

Energy evolution from the ground state to the scission point.

Relevant degrees of freedom?

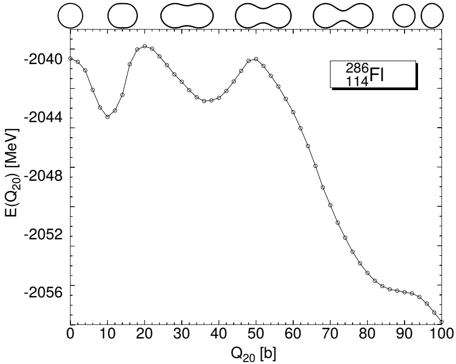
SAG+ PRC90(2014); Sadhukhan+ PRC90(2014)

Collective inertias

Resistance of the nucleus against the deformation forces.

Hard to compute.

Baran+ PRC84 (2011).



Static fission properties

- Parameters defining the potential energy surface:
  - inner and outer fission barrier heights,
  - isomer excitation energy.

- Probability of tunneling under the fission barrier (WKB):

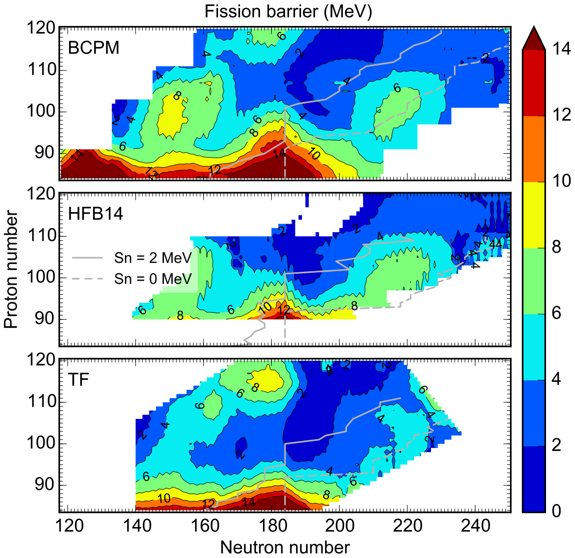
$$P = \frac{1}{1+\exp(2S)} ;$$

$$S = \int_a^b dQ_{20} \left[2 \underbrace{B(Q_{20})}_{\text{inertias}} \left(\underbrace{V(Q_{20})}_{\text{PES}} - E^* \right) \right]^{\frac{1}{2}} .$$

  - Spontaneous fission lifetimes: $t_{\mathsf{sf}} = \frac{\ln 2}{n \times P}$;
  - fission cross sections.

- Interaction:
  - Now: Barcelona-Catania-Paris-Madrid EDF Baldo et al., PRC87 (2013).
  - (next) Future: Gogny and BCPM* EDFs.

BCPM: systematic of fission barriers



- Mean-field models predict larger B_f than mic-mac for $Z \leq 110$;

BCPM: SG, Martínez-Pinedo and Robledo (in preparation); **HFB14**: S. Goriely et al., PRC75 (2007); **TF**: W. D. Myers and W. J. Swiatecki, PRC60 (1999); **FRDM**: P. Möller et al., At. Data Nucl. Data Tables 52 (1995).

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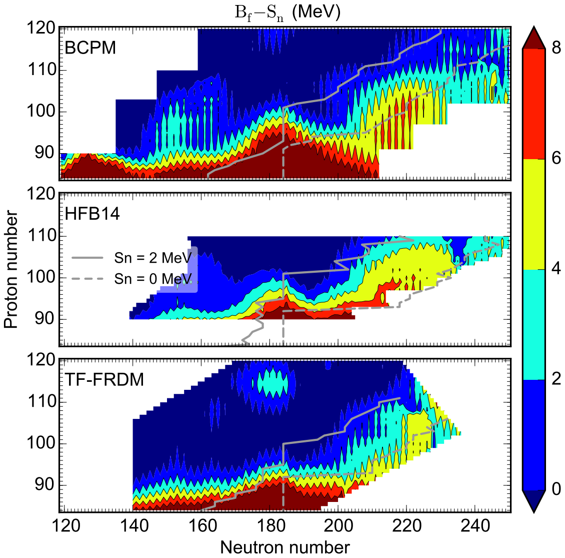

- Mean-field models predict larger B_f than mic-mac for $Z \leq 110$;
- n-induced fission important above $N = 184$.

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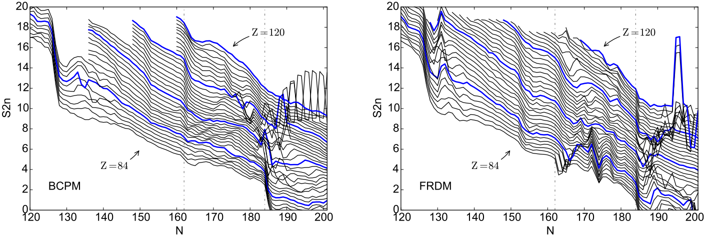
Nuclear inputs for reaction rates

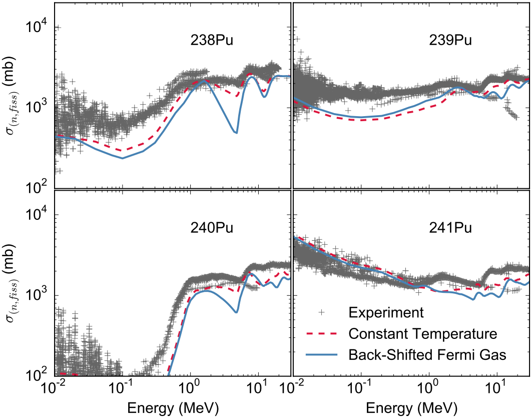
- Reaction rates require knowledge/modeling of nuclear level densities, γ-ray strengths, masses, fission barriers. . .
- The EDF theory useful framework for providing nuclear inputs:
  - neutron separation energies and barriers from the same interaction;



  - tunneling probability from full fission barrier and microscopic collective inertias.
- Several optical models, level densities and γ-ray strengths implemented in TALYS.

Cross sections: BCPM vs experiment

- n-induced fission, γ-induced fission, spontaneous fission and n-capture rates computed using the BCPM nuclear masses and fission barriers.



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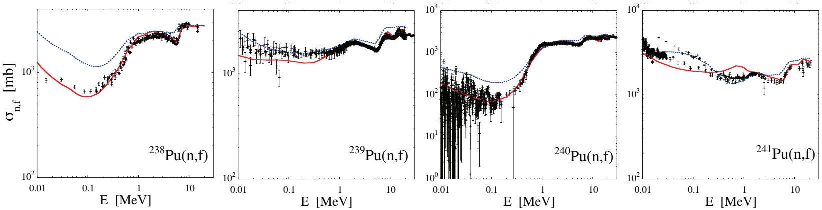

Goriely, Eur. Phys. J. A (2015) **51**:22.

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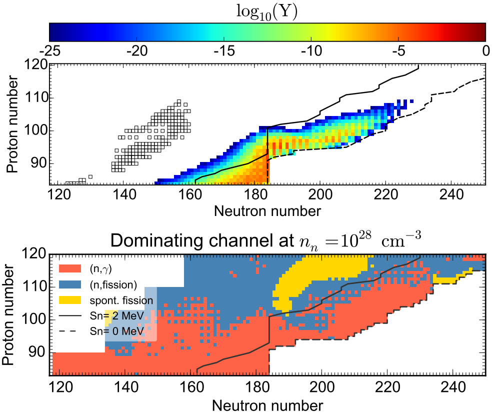
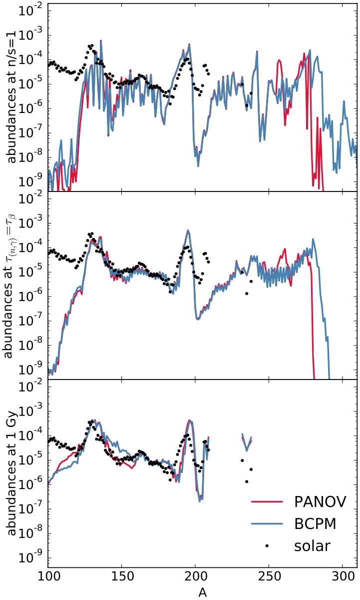
BCPM rates



- Narrow (n, γ) path through $\mathrm{A} \sim 300$; r-path up to $A \sim 320$.
- Fission dominates at $\mathrm{A} \gtrsim 350$: heavier nuclei cannot be produced.
- SF relevant when $\mathrm{B_f} < 2\,\mathrm{MeV}$.

r-process abundances: BCPM vs FRDM-TF Panov+, A&A 513 (2010)

- Trajectory: 3D relativistic simulations from $1.35\,\mathrm{M}_\odot$-$1.35\,\mathrm{M}_\odot$ NS mergers [Bauswein+(2013)].
- Same rates for $Z \leq 83$ and same τ_β.



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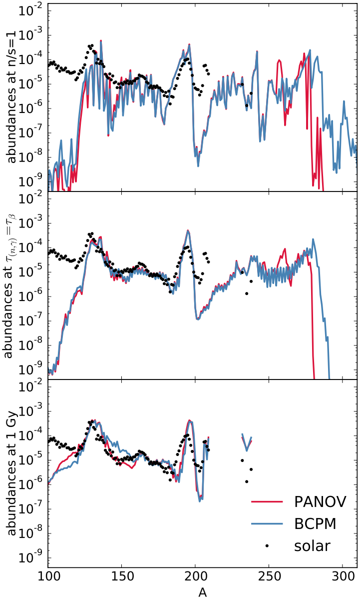
- $B_f^{\text{BCPM}} > B_f^{\text{TF}}$ and $\Delta_n^{\text{BCPM}} > \Delta_n^{\text{FRDM}}$ at $N = 184$: larger production of nuclei with $A > 280$.



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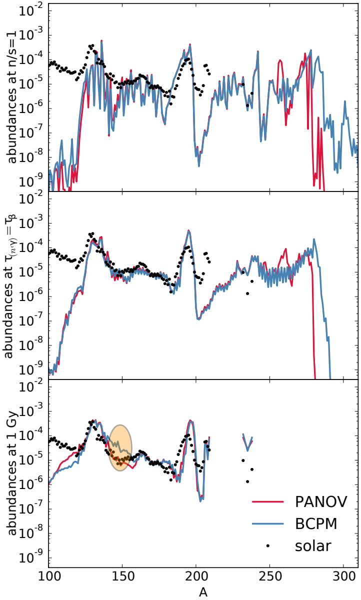
- Accumulation above the 2nd peak:



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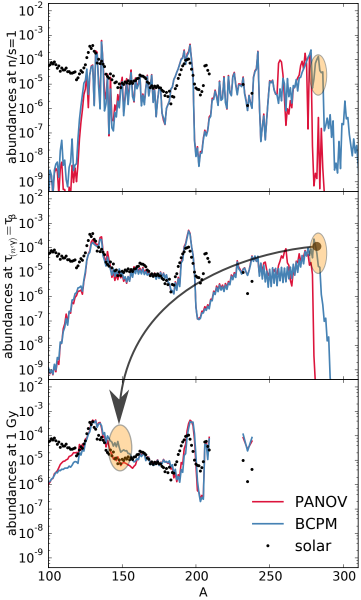

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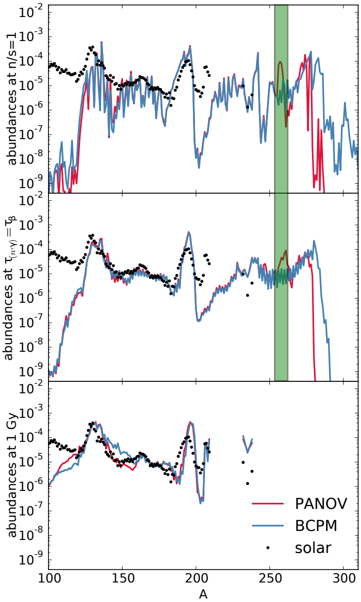
- FRDM-TF peak at $A \sim 257$:
  - jump in S_n at $N = 172$ (not present in BCPM).



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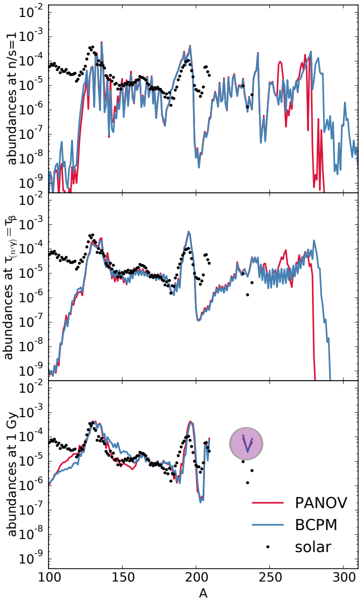
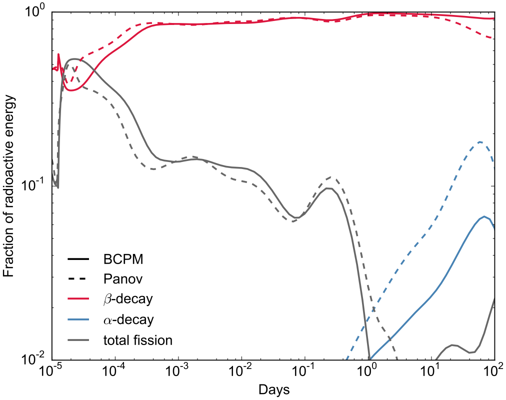
- FRDM-TF peak at $A \sim 257$:
  - jump in S_n at $N = 172$ (not present in BCPM).
- Similar 232Th/238U ratio: relevant physics below $Z = 84$ or close to stability.



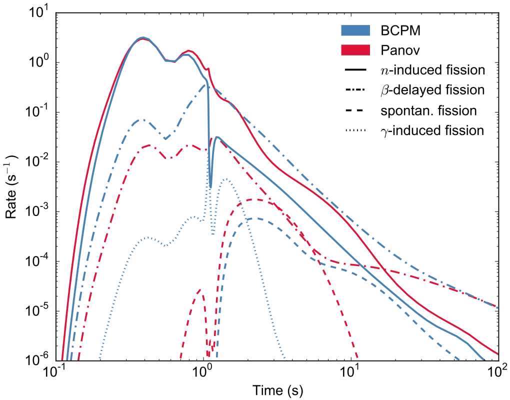
Emitted radioactive energy

Energy emitted by radioactive products in NSM crucial for predicting kilonova light curves [J. Barnes et al., ApJ **829** 110 (2016)].



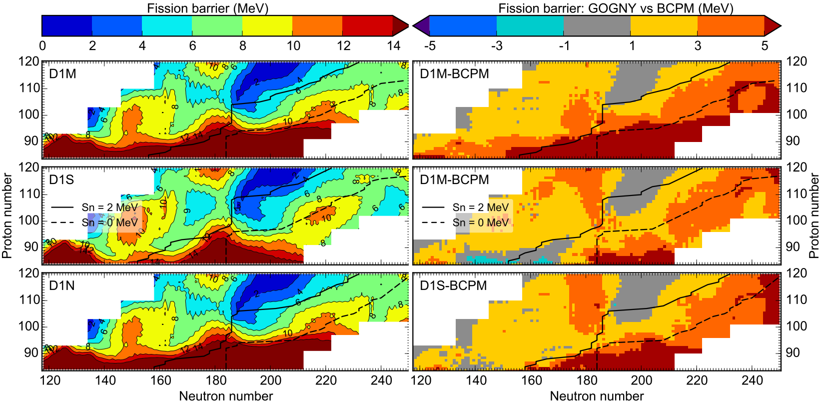
- Minor impact in the radioactive energy production $\Rightarrow$ physics $Z < 84$ and/or β-decay more relevant.

Averaged fission rates



- n-induced dominates until freeze-out and revived by β-delayed neutrons $\Rightarrow$ β-delayed fission rates from BCPM barriers required!
- photo-induced fission always subdominant;
- decay of material to stability triggers spontaneous fission.

What is next? Gogny interaction



- Three Gogny parametrizations in the market: D1S, D1M, D1N.
- BCPM and Gogny differ up to 5 MeV for r-process nuclei: impact in rates/abundances?

Outline

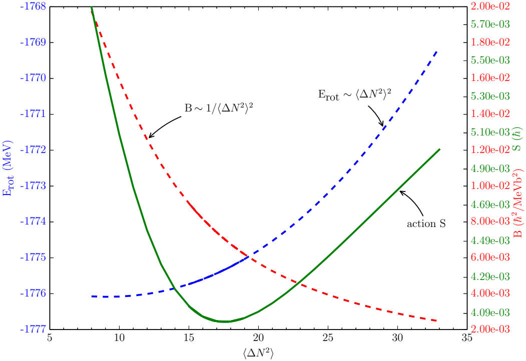
Conclusions

- Fission plays a crucial role in r-process nucleosynthesis.
- EDFs valuable tool for a microscopic description of the fission process.
- New set of stellar rates suited for r-process calculations using the BCPM EDF:
    - n-induced, γ-induced fission and spontaneous fission stellar rates.
- BCPM fission barriers higher than TF: r-process towards $\mathrm{A} \sim 320$.
- Small impact on radioactive energy generation and 232Th/238U ratio.
- Future work:
    - computation of fragments distributions;
    - β-delayed fission rates;
    - explore sensitivity to BCPM and different EDF's (Gogny, BCPM*).

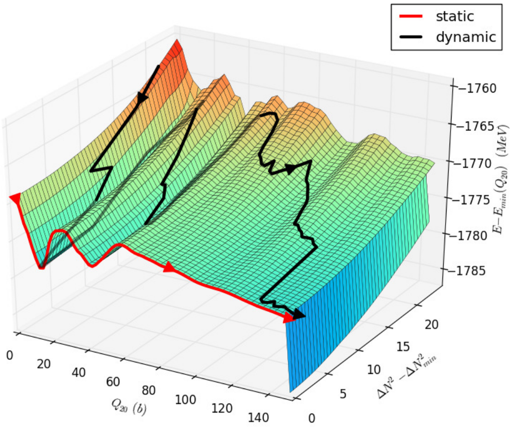
Thank you!

Minimizing the action: $B(\Delta N^2)$ vs $E(\Delta N^2)$ - ^{234}U

$$S = \int_a^b ds \sqrt{2 \times B(s) \left[E(s) - E_0 \right]}$$



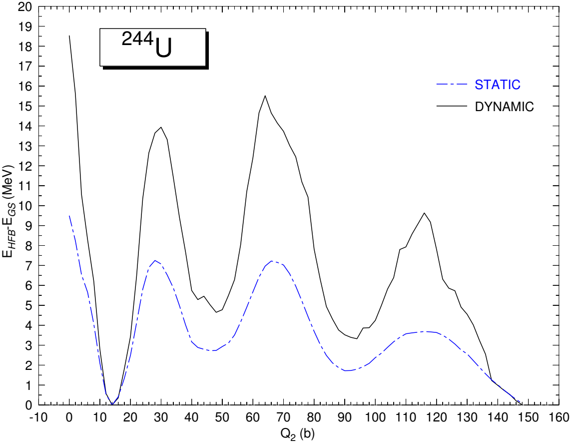
The least action path



- The least action path (black) strongly differ from the least energy one (red)!

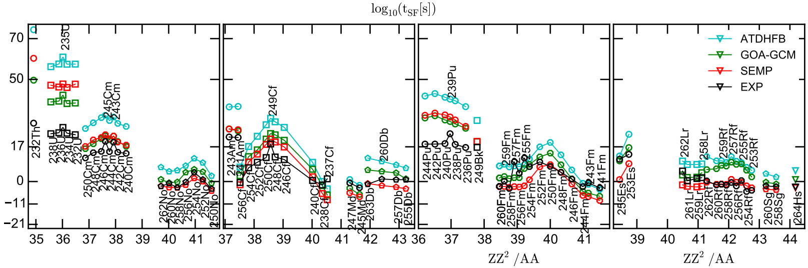
Fission barriers and E_0 - ^{244}U

$$S = \int_a^b ds \sqrt{2 \times B(s) \left[E(s) - E_0 \right]}$$



Spontaneous fission lifetimes (BCPM results)

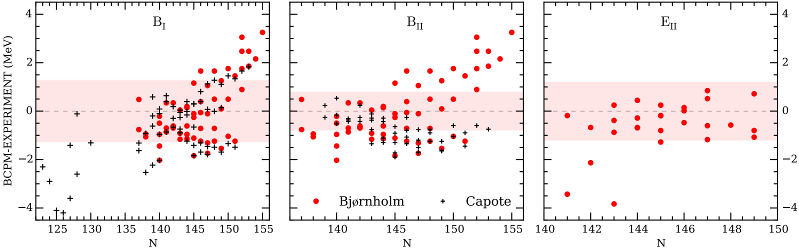
- Exp: Xiaojun Bao et al., Nucl. Phys. **A906**, 1–13 (2013).



BCPM barrier heights and isomer energy

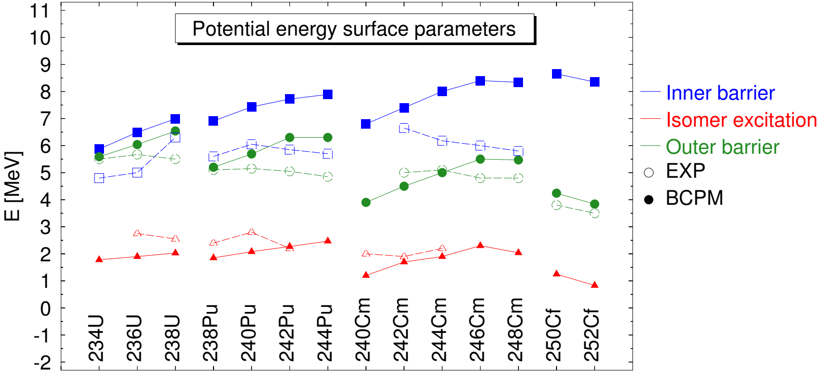
- Exp:R. Capote et al., Nucl. Data Sheets **110**, 3107 (2009);

S. Bjørnholm and J. E. Lynn, Rev. Mod. Phys. **52**, 725 (1980).



BCPM barrier heights and isomer energy BCPM: Baldo et al., PRC87 (2013)

Exp: Sing et al., Nucl. Data Sheets **97**, 241 (2002); R. Capote et al., Nucl. Data Sheets **110**, 3107 (2009).

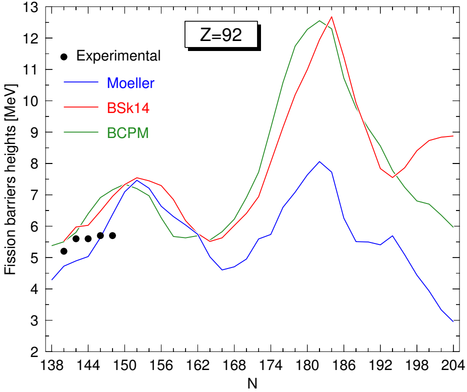


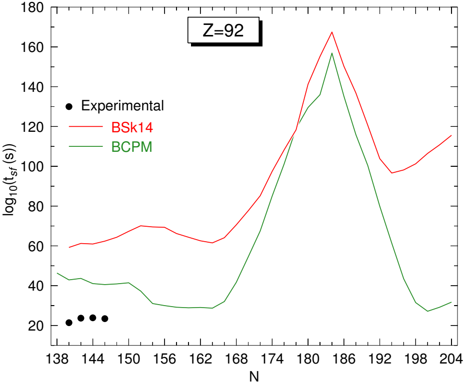
SAG and Robledo, Phys. Rev. C88, 054325 (2013)

- Outer barriers and isomer energies quite well reproduced for all nuclei.
- Inner barriers are reduced when triaxiality is allowed (Erler+(2012), Guzmán+(2014)).

Uranium fission barrier heights: theoretical predictions

BSk14: S. Goriely et al., Phys. Rev. **C75**, 064312 (2007). Möller: P. Möller et al., Phys. Rev. **C91**, 024310 (2015).





Collective inertias

BSk14: $B = 0.054 A^{5/3}\,\mathrm{MeV}^{-1}$

BCPM: $B = \dfrac{1}{2}\dfrac{(M_{-2})^2}{(M_{-1})^3}$ with $M_{(-n)} = \displaystyle\sum_{\alpha>\beta} \frac{|\langle \alpha\beta | Q_{20} | 0\rangle|^2}{(E_\alpha + E_\beta)^n}$

The BCPM functional

The energy of a finite nucleus is given by

$$E = T_0 + E_{int}^{\infty} + E_{int}^{FR} + E^{s.o.} + E_C + E_{pair}$$

$$E_{int}^{\infty}[\rho_p, \rho_n] = \int d\vec{r}\Big[P_s(\rho)(1-\beta^2) + P_n(\rho)\beta^2\Big]\rho$$

with $\rho(\vec{r}) = \rho_n(\vec{r}) + \rho_p(\vec{r})$ and $\beta(\vec{r}) = (\rho_n(\vec{r}) - \rho_p(\vec{r}))/\rho(\vec{r})$.

P_s and P_n are polynomial fits to reproduce microscopic EoS in nuclear matter.

- Phenomenological surface contribution

$$E_{int}^{FR}[\rho_n, \rho_p] = \frac{1}{2}\sum_{t,t'}\iint d\vec{r}d\vec{r'}\rho_t(\vec{r})v_{t,t'}(\vec{r}-\vec{r'})\rho_{t'}(\vec{r'})$$

with $v_{t,t'}(r) = V_{t,t'}\, e^{-r^2/r_{0\;tt}{}^2}$; $V_{n,n} = V_{p,p} = V_L = 2\tilde{b}_1/(\pi^{3/2} r_{0L}^3 \rho_0)$;
$V_{n,p} = V_{p,n} = V_U = (4a_1 - 2\tilde{b}_1)/(\pi^{3/2} r_{0U}^3 \rho_0)$.

M.Baldo et al. Phys. Lett. B663 (2008) 390; Phys. Rev. C87 064305 (2013)

Remaining contributions to the EDF

- Coulomb Direct $E_C^H = (1/2)\iint d\vec{r}d\vec{r'}\rho_p(\vec{r})|\vec{r}-\vec{r'}|^{-1}\rho_p(\vec{r'})$ Exchange: $E_C^{ex} = -(3/4)(3/\pi)^{1/3}\int d\vec{r}\rho_p(\vec{r})^{4/3}$
- Spin-Orbit

$$\hat{v}_{ij}^{so} = iW_{LS}(\vec{\sigma}_i + \vec{\sigma}_j)\cdot[\vec{k}'\times\delta(\vec{r}_i-\vec{r}_j)\vec{k}]$$

Free parameters

W_{LS} and r_{0L}, r_{0U}

- Pairing Correlations (E. Garrido et al. Phys. Rev. C **60**, 064312 (1999)) Zero-range interaction,

$$v^{pp}(\rho(\vec{r})) = \eta\times\frac{v_0}{2}\left[1-\gamma\left(\frac{\rho(\vec{r})}{\rho_0}\right)^{\alpha}\right], \qquad \rho_0 = \frac{2}{3\pi^2}k_F^3\,.$$

$\eta \equiv$ multiplicative parameter setting the pairing strength...