

Study of surface properties of heavy atomic nuclei

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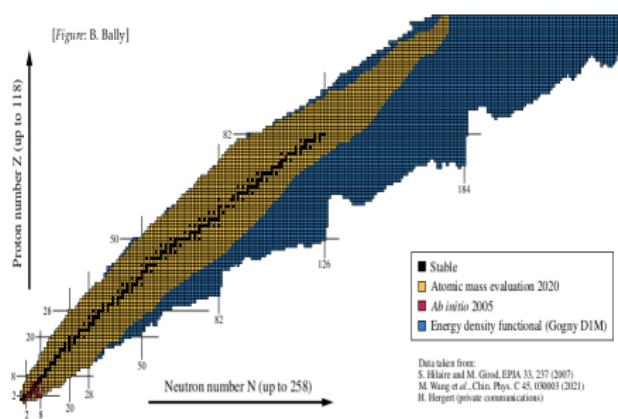
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1.1) Problematic

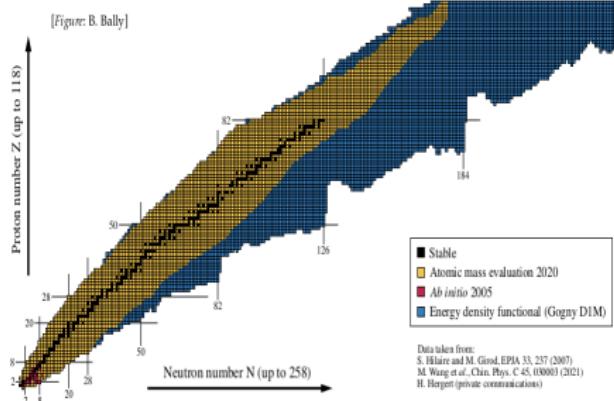
Nuclear structure is the study of system with N quantum body in interaction.
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1.1) Problematic

Nuclear structure is the study of system with N quantum body in interaction.
Thus its treatment is non trivial and we will face some difficulties such as :

- Effective potentiel unknown a priori ;
- Ambiguity for the choice of experimental data for constraining the interaction ;
- Numerical resolution cost non negligible.



1.2) Effective interaction

Non relativistic Energy density functionnal

- Contact interaction (Skyrme) $\rightarrow \delta(\vec{r}_1 - \vec{r}_2)$

$$\begin{aligned}
 V_{\text{Sky}} = & t_0 (1 + x_0 P^\sigma) \delta(\vec{r}) \\
 & + \frac{1}{2} t_1 (1 + x_1 P^\sigma) \left[\overleftarrow{k}^2 \delta(\vec{r}) + \delta(\vec{r}) \overrightarrow{k}^2 \right] \\
 & + t_2 (1 + x_2 P^\sigma) \overleftarrow{k} \cdot \delta(\vec{r}) \overrightarrow{k} \\
 & + \frac{1}{6} t_3 (1 + x_3 P^\sigma) \rho_0^\alpha \delta(\vec{r}) \\
 & + i W_0 \overrightarrow{\sigma_{12}} \cdot \overleftarrow{k} \times \delta(\vec{r}) \overrightarrow{k}
 \end{aligned}$$

1.2) Effective interaction

Penalty function

The parameters of a functional has to be adjusted by minimizing a penalty function built from a series of constraints :

$$\chi^2(\mathbf{p}) = \sum_{i=1}^{n_{\text{obs}}} \frac{(\mathcal{O}_i(\mathbf{p}) - \mathcal{O}_i^{\text{target}})^2}{\Delta \mathcal{O}_i^2}$$

with

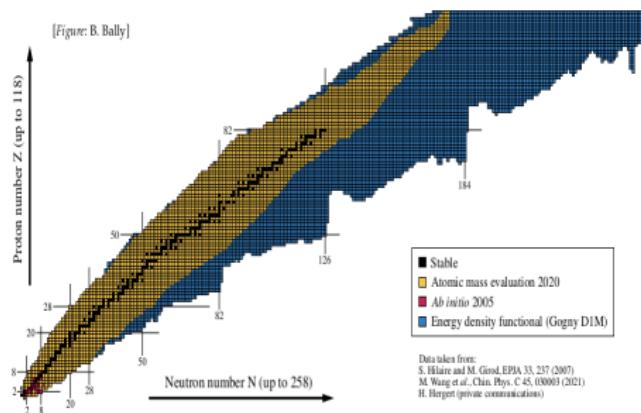
- \mathbf{p} : Parameters of the model ;
- $\mathcal{O}_i(\mathbf{p})$: Calculated observable (pseudo-oberstable) ;
- $\mathcal{O}_i^{\text{target}}$: Targeted value for the observable (pseudo-oberstable) ;
- $\Delta \mathcal{O}_i$: Adopted tolerance.

We can then build the penarly function as a sum of different componenents :

$$\chi^2 = \chi_{\text{inm}}^2 + \chi_{\text{pol}}^2 + \chi_{\text{BE}}^2 + \dots + \chi_{\text{rad}}^2,$$

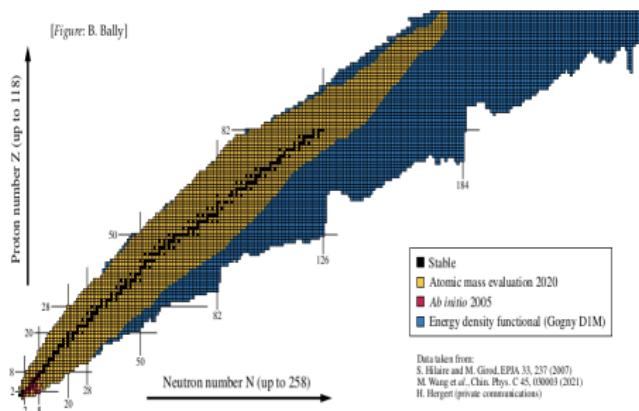
2.1) Why surface properties so important ?

[Figure: B. Bally]

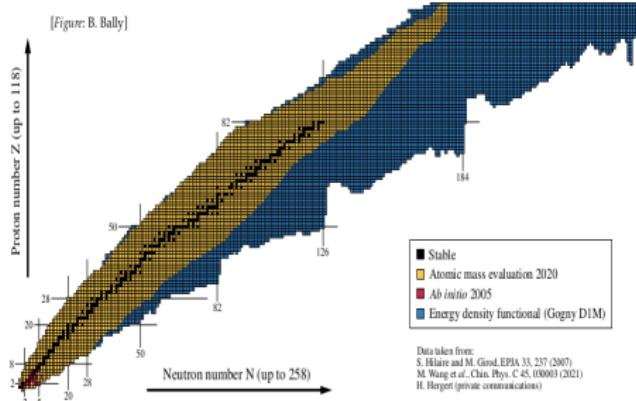


2.1) Why surface properties so important ?

- Most of the nuclei are deformed ;

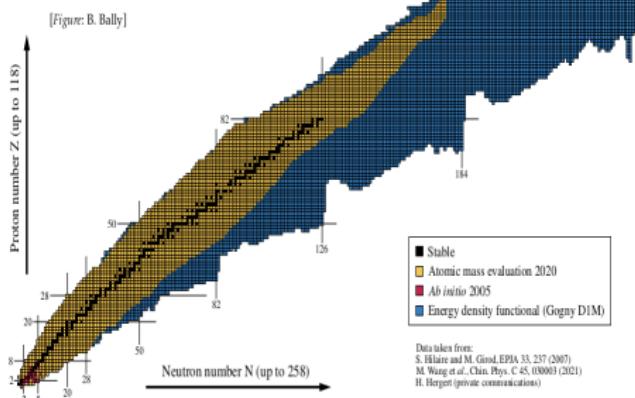


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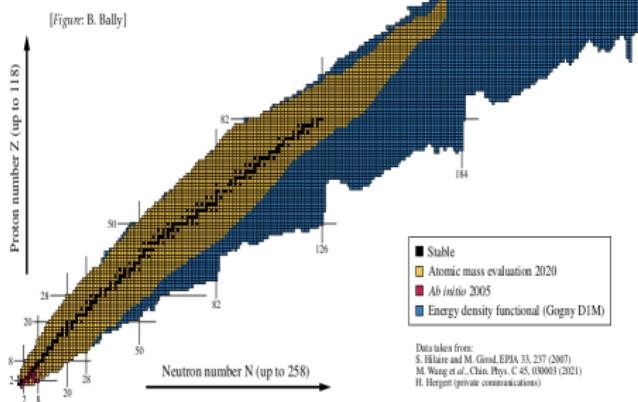
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- Isomeric states, shape coexistence ;
- Fission barriers ;
- Rotational bands.

2.1) Why surface properties so important ? Until now ?

Several attempts to reproduce nuclear surface properties : SkM*¹, D1S² and UNEDF2³.

SLy5s1⁴ { Able to reproduce a lot of heavy nuclei properties.
Not really good for mass residuals...

-
1. J. Bartel *et al.* Nuclear Physics A, 386(1), 79-100 (1982).
 2. J.F. Berger, M. Girod and D.Gogny, Comp. Phys. Comm., 63 (1991) 365.
 3. M. Kortelainen et al., Phys. Rev. C 89, 054314 (2014).
 4. R. Jodon, M. Bender, K. Bennaceur, and J. Meyer, Phys. Rev. C 94, 024335 (2016).

2.2) Goal of the study

Work in collaboration with M. Bender and J. Meyer.

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Work in collaboration with M. Bender and J. Meyer.

The aim of the study focuses on 3 points :

- Having a good description of ^{240}Pu isomer;
- Being able to describe ^{180}Hg fission barrier with an oblate ground state ;
- Improving binding energies predictions of nuclei compared to SLy5s1 interaction.

2.2) Goal of the study

How to treat this problem ?

3 changes on the fit protocol :

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- Different value for $a_{\text{surf}}^{\text{MTF}}$ [16.0 ; 20.0] MeV ;

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- Different value for $a_{\text{surf}}^{\text{MTF}}$ [16.0 ; 20.0] MeV ;
- Different recipies of center of mass correction 1F2F, 1T2F, 1T2T ;

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- Different value for $a_{\text{surf}}^{\text{MTF}}$ [16.0 ; 20.0] MeV ;
- Different recipies of center of mass correction 1F2F, 1T2F, 1T2T ;
- Different values for the effective mass $m_0^*/m = 0.70, 0.80, 0.85$.

2.2) Goal of the study

Effective interaction

We can separate the energy density into 4 component :

$$E_{\text{ph}} = E_{\text{kin}} + E_{\text{Sky}} + E_{\text{Coulomb}} + E_{\text{corr}}$$

E_{corr} is limited to the correction of the cm :

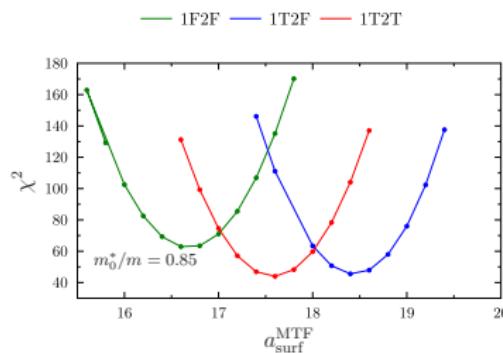
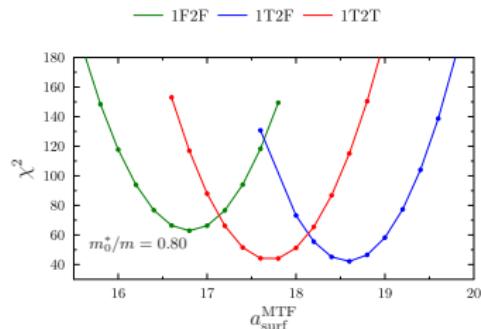
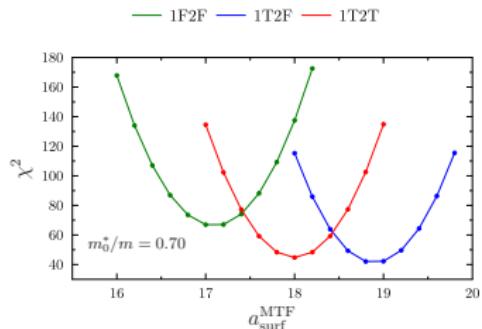
$$E_{\text{cm}} = -\frac{\langle \mathbf{P}^2 \rangle}{2Am} = -\left(\sum_i \frac{\langle \mathbf{p}_i^2 \rangle}{2Am} + \sum_{i < j} \frac{\langle \mathbf{p}_i \cdot \mathbf{p}_j \rangle}{Am} \right)$$

With \mathbf{P} the sum of the impulsions of the A nucleons in the nucleus.

$$E_{\text{cm}}^{(1)} = \sum_i \frac{\langle \mathbf{p}_i^2 \rangle}{2Am} \quad E_{\text{cm}}^{(2)} = \sum_{i < j} \frac{\langle \mathbf{p}_i \cdot \mathbf{p}_j \rangle}{Am}$$

Interaction	$E_{\text{cm}}^{(1)}$	$E_{\text{cm}}^{(2)}$
1F2F	✗	✗
1T2F	✓	✗
1T2T	✓	✓

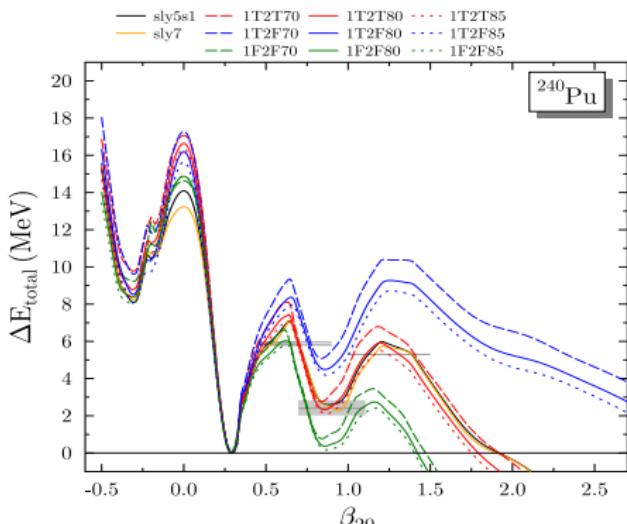
3.1) Penalty function



χ^2 as a function of $a_{\text{surf}}^{\text{MTF}}$

3.2) Fission barriers

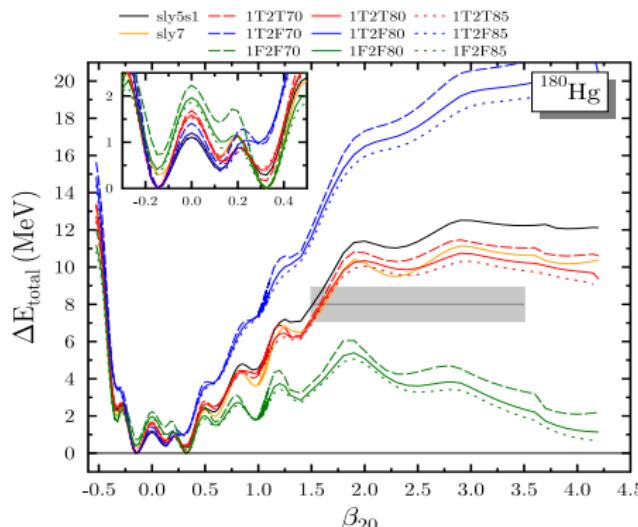
Calculation are compared with SLy5s1 and SLy7⁵ interaction.



Fission barrier of ^{240}Pu

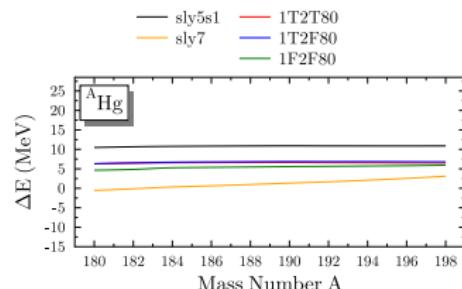
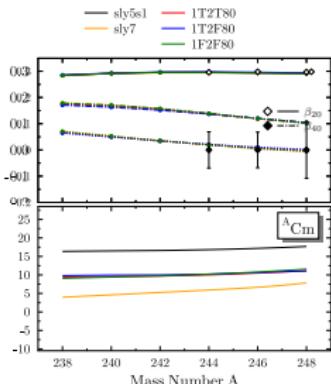
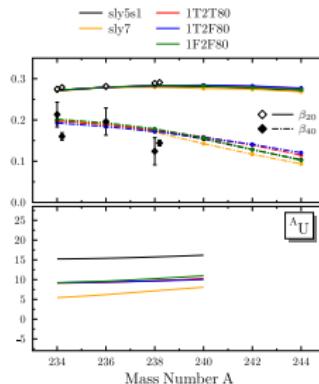
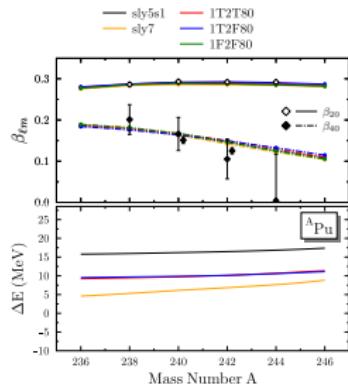
- Grey areas indicate experimental excitation energies and barriers height.

3.2) Fission barriers



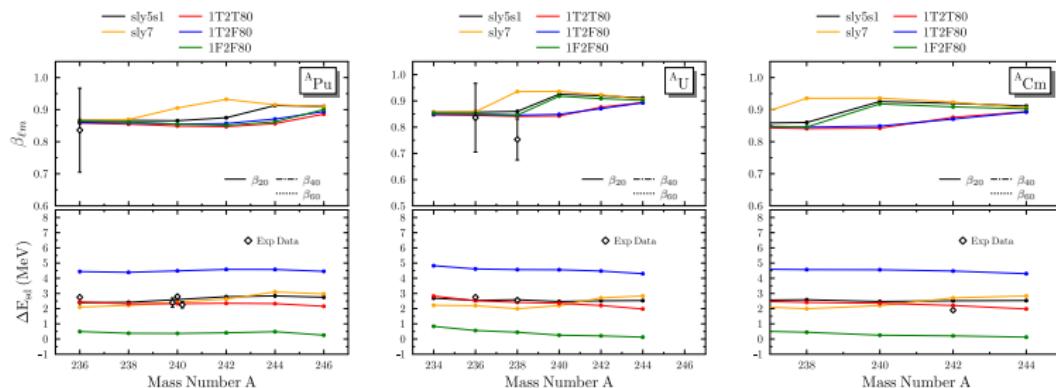
- Grey areas indicate experimental excitation energies and barriers height ;
- Experimentally, the ground state of is ^{180}Hg oblate.

3.3) Normal deformation



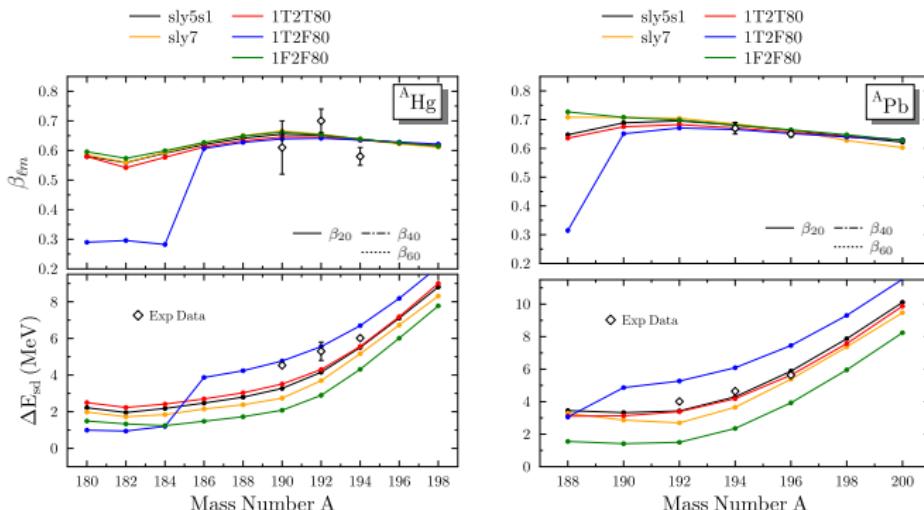
Lower panels : mass residuals of the calculated ground states

3.4) Super deformation for actinide



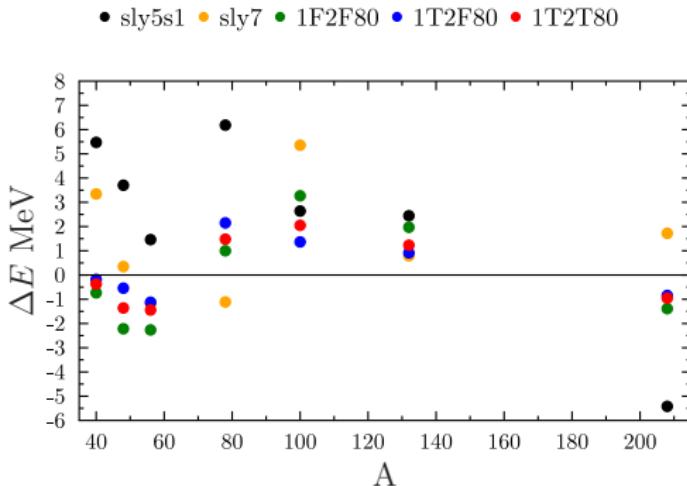
- Lower panel : excitation energy of the 0^+ fission isomers of even-even Pu, U and Cm isotopes.
- Upper panel : calculated β_{20} values, and experimental data for charge quadrupole deformation β_{20} for comparison.

3.4) Super deformation Hg and Pb



- Lower panel : excitation energy of the 0^+ band head of the superdeformed rotational bands of Hg and Pb isotopes.
- Upper panel : Deformation parameter $\beta_{Im} = \beta_{20}, \beta_{40}, \text{and } \beta_{60}$.

3.5) Mass of doubly magic nuclei



Mass residuals of doubly magic nuclei : $\Delta E = E_{calc} - E_{exp}$

Used nuclei :

- ^{40}Ca , ^{56}Ni , ^{78}Ni , ^{100}Sn , ^{132}Sn , ^{208}Pb .

Conclusion

- Better description of nuclei masses ;
- Able to reproduce the oblate ground state of the ^{180}Hg ;
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Perspective :

- Study of more nuclei ;
- Adding tensor contribution ;
- Spin orbit N2LO ;
- Covariant analysis.

Thanks for your attention.