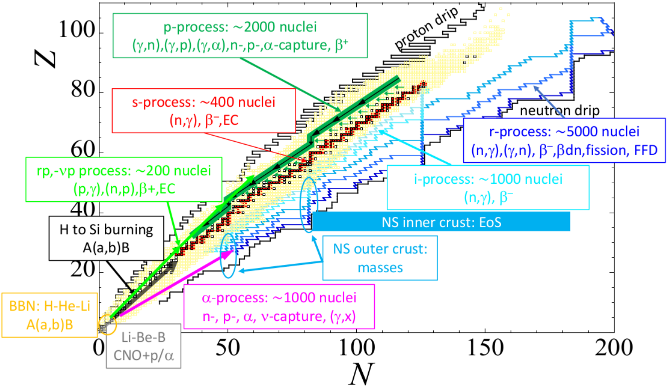
Symmetry breaking on the scale of the nuclear chart

W. Ryssens, G. Scamps, M. Bender, & S. Goriely

29th of September 2021

LA LIBERTÉ DE CHERCHER

Where did the elements originate?



M. Arnould & S. Goriely, Prog. Part. Nuc. Phys. **112**, 103766 (2020).

Energy density functionals (EDFs)

$$E \sim \int d^3 r \left[C^{\rho}\, \rho(\vec{r})\rho(\vec{r}) + C^{\tau}\, \rho(\vec{r})\, \tau(\vec{r}) + \ldots\ldots \right]$$

- Pheno. form and fit of C's
- Simple mean-field ansatz

Energy density functionals (EDFs)

$$E \sim \int d^3 r \left[C^{\rho} \, \rho(\vec{r})\rho(\vec{r}) + C^{\tau} \, \rho(\vec{r}) \, \tau(\vec{r}) + \ldots\ldots \right]$$

- Pheno. form and fit of C's
- Simple mean-field ansatz

+ microscopic method
+ feasible for 1000s of nuclei

Energy density functionals (EDFs)

$$E \sim \int d^3r \left[C^{\rho} \rho(\vec{r})\rho(\vec{r}) + C^{\tau} \rho(\vec{r}) \tau(\vec{r}) + \ldots\ldots \right]$$

- Pheno. form and fit of C's
- Simple mean-field ansatz

+ microscopic method
+ feasible for 1000s of nuclei

"Structure" fits

- Study observables **locally**
- Fitted on $\lesssim$ 10 nuclei
- Typically $\sim$ 15 parameters
- **Advanced** calculations

Energy density functionals (EDFs)

$$E \sim \int d^3r \left[C^{\rho}\, \rho(\vec{r})\rho(\vec{r}) + C^{\tau}\, \rho(\vec{r})\,\tau(\vec{r}) + \ldots\ldots \right]$$

- Pheno. form and fit of C's
- Simple mean-field ansatz

+ microscopic method
+ feasible for 1000s of nuclei

"Structure" fits

- Study observables **locally**
- Fitted on $\lesssim$ 10 nuclei
- Typically $\sim$ 15 parameters
- **Advanced** calculations

"Astro" fits

- Study **global** masses
- More parameters (22)
- **Simplified** calculations

Energy density functionals (EDFs)

$$E \sim \int d^3r \left[C^\rho \, \rho(\vec{r})\rho(\vec{r}) + C^\tau \, \rho(\vec{r})\, \tau(\vec{r}) + \ldots\ldots \right]$$

- Pheno. form and fit of C's
- Simple mean-field ansatz

+ microscopic method
+ feasible for 1000s of nuclei

"Structure" fits

- Study observables **locally**
- Fitted on $\lesssim$ 10 nuclei
- Typically $\sim$ 15 parameters
- **Advanced** calculations

"Astro" fits

- Study **global** masses
- ! Fitted on **2408** masses
- More parameters (22)
- **Simplified** calculations

Energy density functionals (EDFs)

$$E \sim \int d^3r \left[C^{\rho}\,\rho(\vec{r})\rho(\vec{r}) + C^{\tau}\,\rho(\vec{r})\,\tau(\vec{r}) + \ldots\ldots \right]$$

- Pheno. form and fit of C's
- Simple mean-field ansatz

+ microscopic method
+ feasible for 1000s of nuclei

"Structure" fits

- Study observables **locally**
- Fitted on $\lesssim$ 10 nuclei
- Typically $\sim$ 15 parameters
- **Advanced** calculations

$\rightarrow$ $\sigma_{\mathrm{rms}}(M) \sim$ **2-10** MeV

"Astro" fits

- Study **global** masses
- ! Fitted on **2408** masses
- More parameters (22)
- **Simplified** calculations

Energy density functionals (EDFs)

$$E \sim \int d^3r \left[C^\rho \rho(\vec{r})\rho(\vec{r}) + C^\tau \rho(\vec{r})\tau(\vec{r}) + \ldots\ldots \right]$$

- Pheno. form and fit of C's
- Simple mean-field ansatz

+ microscopic method
+ feasible for 1000s of nuclei

"Structure" fits

- Study observables **locally**
- Fitted on $\lesssim$ 10 nuclei
- Typically $\sim$ 15 parameters
- **Advanced** calculations

→ $\sigma_{\rm rms}(M) \sim$ **2-10** MeV

"Astro" fits

- Study **global** masses
- ! Fitted on **2408** masses
- More parameters (22)
- **Simplified** calculations

→ $\sigma_{\rm rms}(M) \sim$ **0.6** MeV

Energy density functionals (EDFs)

$$E \sim \int d^3r \left[C^{\rho}\, \rho(\vec{r})\rho(\vec{r}) + C^{\tau}\, \rho(\vec{r})\,\tau(\vec{r}) + \ldots\ldots \right]$$

- Pheno. form and fit of C's
- Simple mean-field ansatz

+ microscopic method
+ feasible for 1000s of nuclei

"Structure" fits

- Study observables **locally**
- Fitted on $\lesssim$ 10 nuclei
- Typically $\sim$ 15 parameters
- **Advanced** calculations

$\rightarrow$ $\sigma_{\rm rms}(M) \sim$ **2-10** MeV

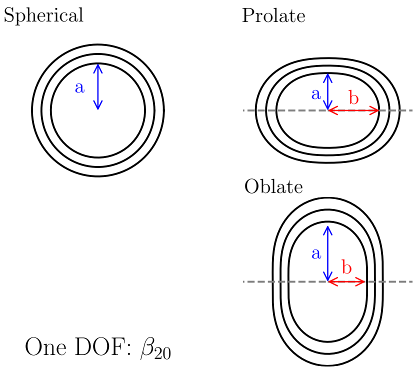
"Astro" fits

- Study **global** masses
- ! Fitted on **2408** masses
- More parameters (22)
- **Simplified** calculations

$\rightarrow$ $\sigma_{\rm rms}(M) \sim$ **0.6** MeV

We are bringing the "structure" to the "astro" scale!

Symmetry breaking and nuclear shapes

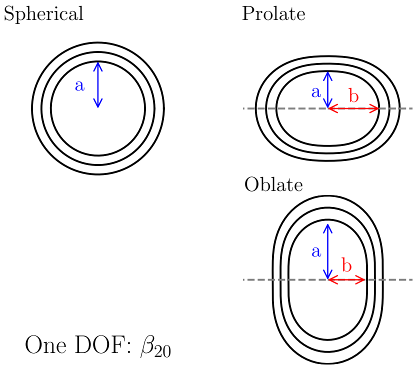


One DOF: β_{20}

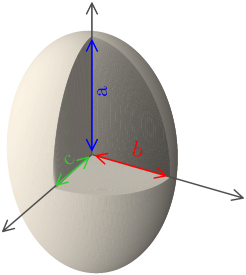
State-of-the-art "Astro" fits

- Axial symmetry

Symmetry breaking and nuclear shapes



One DOF: β_{20}



Two DOF: (β_{20}, β_{22}) or (β, γ)

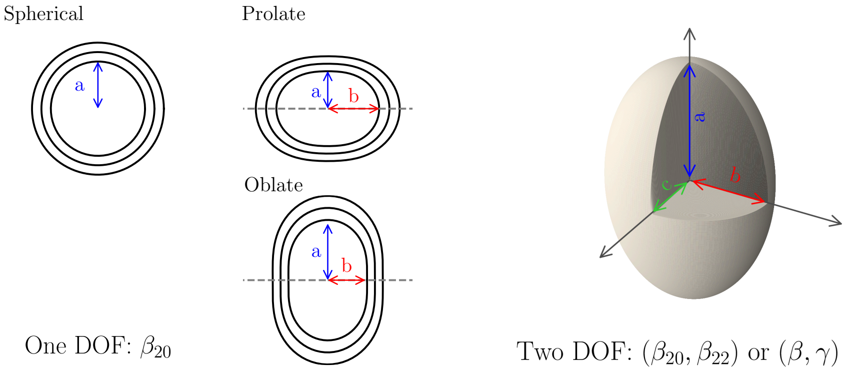
State-of-the-art "Astro" fits

- Axial symmetry

"Structure" calculations

- Triaxial deformation

Symmetry breaking and nuclear shapes



One DOF: β_{20}

Two DOF: (β_{20}, β_{22}) or (β, γ)

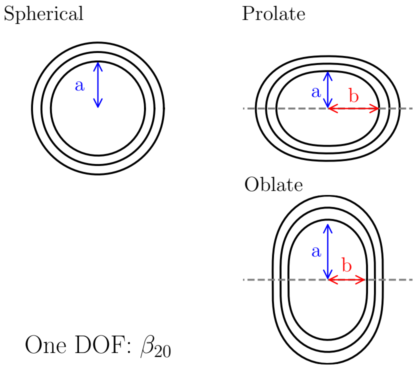
State-of-the-art "Astro" fits

- Axial symmetry

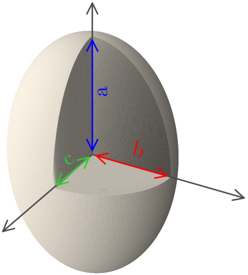
"Structure" calculations

- Triaxial deformation

Symmetry breaking and nuclear shapes



One DOF: β_{20}



Two DOF: (β_{20}, β_{22}) or (β, γ)

State-of-the-art "Astro" fits

- Axial symmetry
- Time-reversal symmetry
- Reflection symmetry

"Structure" calculations

- Triaxial deformation
- Time-reversal breaking
- Octupole deformation

BSkG = Brussels Skyrme on a Grid

Ingredients

- Standard Skyrme functional

$\rightarrow$ rotational correction

- 22 parameters

Techniques

BSkG = Brussels Skyrme on a Grid

Ingredients

- Standard Skyrme functional

→ rotational correction

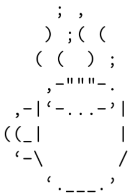
- 22 parameters

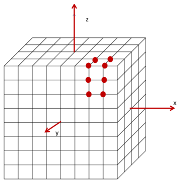
Techniques

- MOCCa

\+ 3D coordinate grid

\+ Fast and numerically accurate





Ingredients

- Standard Skyrme functional

→ rotational correction

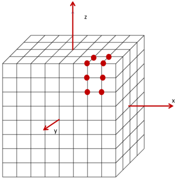
- 22 parameters

Techniques

- MOCCa

+ 3D coordinate grid
+ Fast and numerically accurate

```
      ;  ,
     )  ;( (
    (  (  )  ;
     ,_""""_.
  ,-|`-...-'|
 ((_|       |
  `-\       /
     `.___.'
```



BSkG = Brussels Skyrme on a Grid

Ingredients

- Standard Skyrme functional

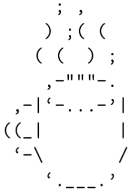
→ rotational correction

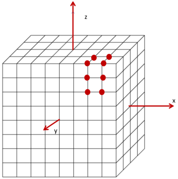
- 22 parameters
- Fitted to **2408** masses
- and **884** charge radii

Techniques

- MOCCa

+ 3D coordinate grid
+ Fast and numerically accurate





BSkG = Brussels Skyrme on a Grid

Ingredients

- Standard Skyrme functional

→ rotational correction

- 22 parameters
- Fitted to **2408** masses
- and **884** charge radii

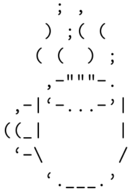
Techniques

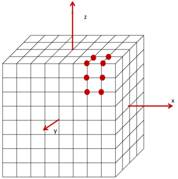
- MOCCa

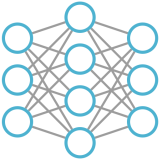
\+ 3D coordinate grid

\+ Fast and numerically accurate

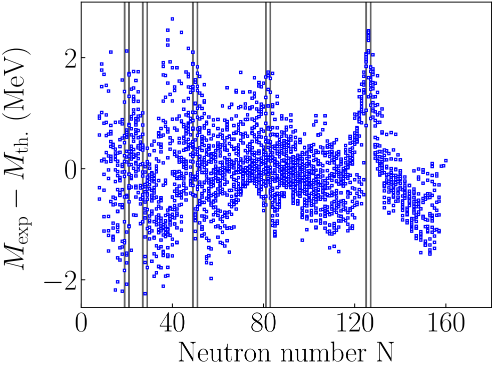
- Machine learning







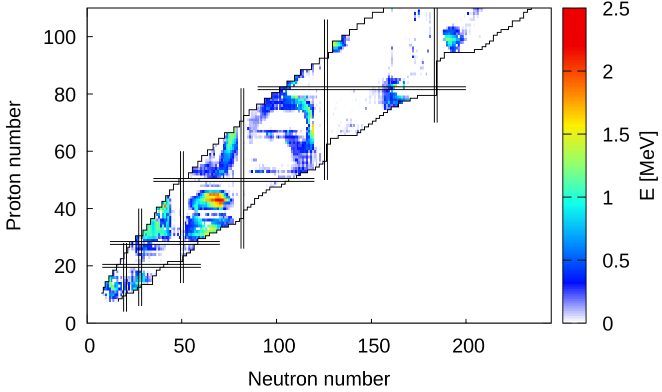
BSkG1



	BSkG1	HFB-21	FRDM (2012)
$\sigma(M)$ (MeV)	0.741	0.577	0.560
$\sigma(R_c)$ (fm)	0.024	0.027	0.038

HFB-21: S. Goriely *et al.*, PRC **82**, 035804 (2010).
FRDM: P. Möller *et al.*, At. Data Nucl. Data Tables, **109-110** (2016).

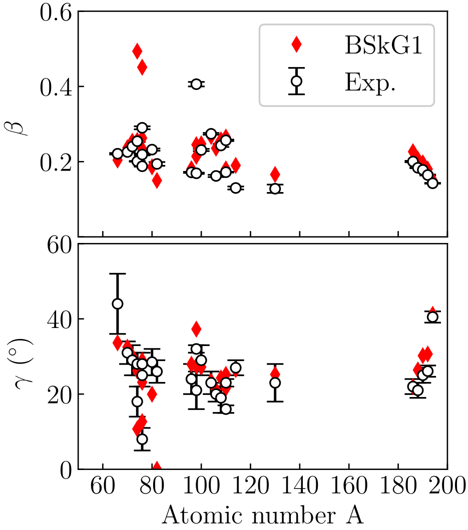
Triaxiality: where?



	BSkG1	HFB-21	FRDM (2012)
$\sigma(M)$ (MeV)	0.741	0.577	0.560
$\sigma(R_c)$ (fm)	0.024	0.027	0.038

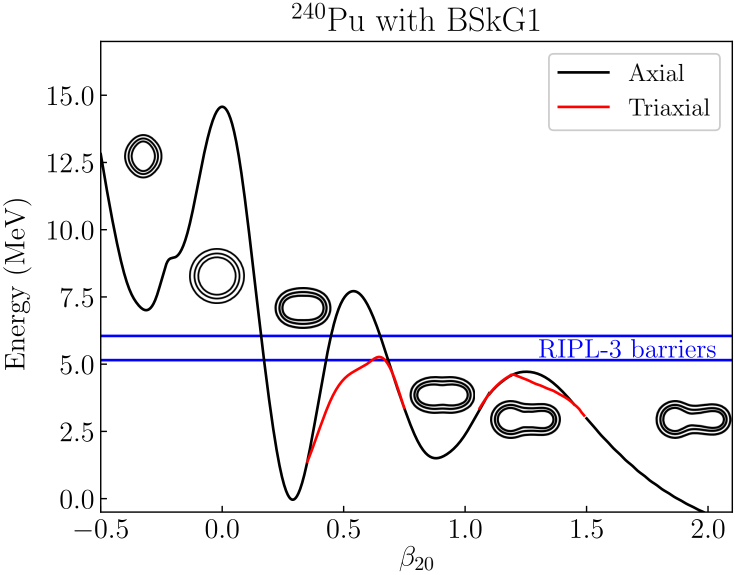
HFB-21: S. Goriely *et al.*, PRC **82**, 035804 (2010).
FRDM: P. Möller *et al.*, At. Data Nucl. Data Tables, **109-110** (2016).

Triaxiality: comparison to experiment

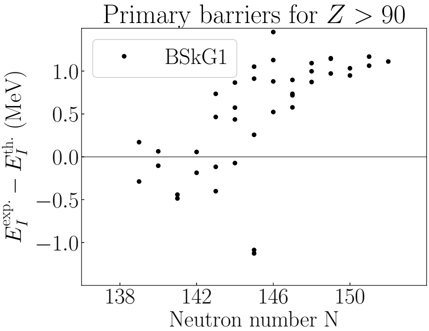


Exp. data from COULEX extracted by M. Zielińska

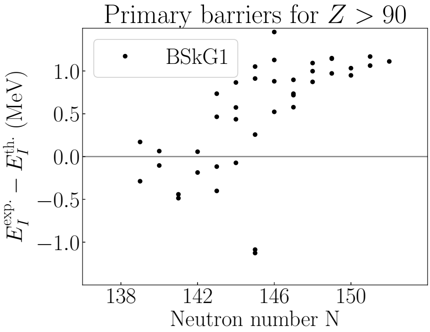
M. Rocchini et al., PRC **103**, 014311 (2021).
M. Sugawara et al., EPJA, **16**, 409 (2003).
A. D. Ayangeakaa et al., PLB **754**, 254 (2016).
Y. Toh et al. , EPJA **9**, 353 (2000).
A. D. Ayangeaka et al., PRL **123**, 102501 (2019).
E. Clément et al., PRC **75**, 054313 (2007).
A. E. Kavka et al., NPA **593**, 177 (1995).
E. Clément et al., PRC **94**, 054326 (2016).
M. Zielińska, Ph.D. thesis, Warsaw U., 2005.
M. Zielińska et al., NPA **712**, 3 (2002).
K. Wrzosek-Lipska et al., PRC **86**, 064305 (2012).
J. Srebrny et al., NPA **766**, 25 (2006).
K. Wrzosek-Lipska et al., APB **51**, 789 (2020).
C. Fahlander et al., NPA **485**, 327 (1988).
L. E. Svensson et al., NPA **584**, 547 (1995).
L. Morrison et al., PRC **102**, 054304 (2020).
C. Y. Wu et al., NPA **607**, 178 (1996).


^{240}Pu with BSkG1
Axial
Triaxial
RIPL-3 barriers
Energy (MeV)
15.0
12.5
10.0
7.5
5.0
2.5
0.0
−0.5
0.0
0.5
1.0
1.5
2.0
β_{20}

BSkG2


Primary barriers for $Z > 90$
BSkG1
$E_I^{\text{exp.}} - E_I^{\text{th.}}$ (MeV)
1.0
0.5
0.0
−0.5
−1.0
138
142
146
150
Neutron number N

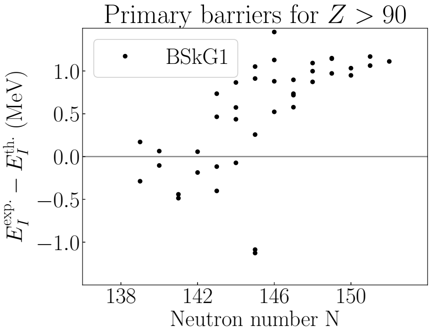
BSkG2



BSkG2

- Fit with complete $\check{T}$-breaking
- 22 + **3** parameters
- Vibrational correction

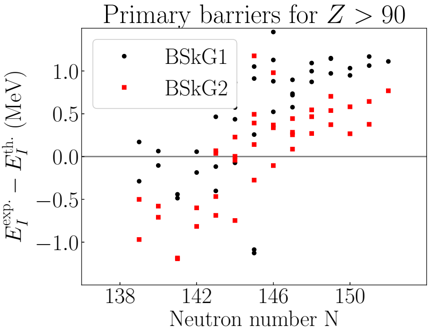
BSkG2



BSkG2

- Fit with complete $\check{T}$-breaking
- 22 + **3** parameters
- Vibrational correction
- fit to RIPL-3 data
  for **12** even-even nuclei
- Full eval.: 40 barriers $Z \geq 90$

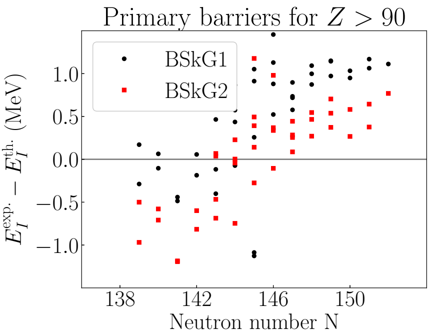
BSkG2



BSkG2

- Fit with complete $\check{T}$-breaking
- 22 + **3** parameters
- Vibrational correction
- fit to RIPL-3 data
  for **12** even-even nuclei
- Full eval.: 40 barriers $Z \geq 90$

BSkG2



BSkG2

- Fit with complete $\check{T}$-breaking
- 22 + **3** parameters
- Vibrational correction
- fit to RIPL-3 data
  for **12** even-even nuclei
- Full eval.: 40 barriers $Z \geq 90$

	BSkG1	BSkG2	HFB-14	FR(L)DM
$\sigma(M)$ (MeV)	0.741	0.668	0.729	0.560
$\sigma(E_I)$ (MeV)	0.853	**0.447**	0.621	0.767

HFB-14 from S. Goriely *et al.*, PRC **75**, 064312 (2007).
FRDM from P. Möller *et al.*, At. Data Nucl. Data Tables, **109-110** (2016).

Conclusions & Outlook

BSkG1

- Large-scale mass model
- fitted to **2408** masses
- on a 3D mesh, ML fit
- ground state triaxiality

Conclusions & Outlook

BSkG1

- Large-scale mass model
- fitted to **2408** masses
- on a 3D mesh, ML fit
- ground state triaxiality

G. Scamps *et al.*,
arXiv:2011.07904 (nucl-th)

Conclusions & Outlook

BSkG1

- Large-scale mass model
- fitted to **2408** masses
- on a 3D mesh, ML fit
- ground state triaxiality

BSkG2

- The next generation
- Full $\check{T}$-breaking
- Added vibrational corr.
- Improved fission barriers

G. Scamps *et al.*,
arXiv:2011.07904 (nucl-th)

Conclusions & Outlook

BSkG1

- Large-scale mass model
- fitted to **2408** masses
- on a 3D mesh, ML fit
- ground state triaxiality

G. Scamps *et al.*,
arXiv:2011.07904 (nucl-th)

BSkG2

- The next generation
- Full $\check{T}$-breaking
- Added vibrational corr.
- Improved fission barriers

W.R. *et al.*,
in preparation.

Conclusions & Outlook

BSkG1

- Large-scale mass model
- fitted to **2408** masses
- on a 3D mesh, ML fit
- ground state triaxiality

G. Scamps *et al.*,
arXiv:2011.07904 (nucl-th)

BSkG2

- The next generation
- Full $\check{T}$-breaking
- Added vibrational corr.
- Improved fission barriers

W.R. *et al.*,
in preparation.

Outlook

- (Local) comparisons with experiment underway
- Complete fission model (2000 nuclei, half-lives, . . .)
- Fission barriers for odd nuclei
- . . .

Conclusions & Outlook

BSkG1

- Large-scale mass model
- fitted to **2408** masses
- on a 3D mesh, ML fit
- ground state triaxiality

G. Scamps *et al.*,
arXiv:2011.07904 (nucl-th)

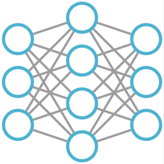
BSkG2

- The next generation
- Full $\check{T}$-breaking
- Added vibrational corr.
- Improved fission barriers

W.R. *et al.*,
in preparation.

Outlook

- (Local) comparisons with experiment underway
- Complete fission model (2000 nuclei, half-lives, . . .)
- Fission barriers for odd nuclei
- . . .



Thanks!

Thanks for. . .

. . . the **help**:

BSkG1/2		MOCCa	
S. Goriely	ULB	P.-H. Heenen	ULB
G. Scamps	ULB	M. Bender	IP2I
E. Olsen	ULB	B. Bally	UAM
J.-F. Lemaître	CEA		

Thanks!

Thanks for. . .

. . . the **help**:

BSkG1/2

- S. Goriely — ULB
- G. Scamps — ULB
- E. Olsen — ULB
- J.-F. Lemaître — CEA

MOCCa

- P.-H. Heenen — ULB
- M. Bender — IP2I
- B. Bally — UAM

. . . the **CPU time**:

- CÉCI network, Belgium
- The Zenobe cluster

Thanks!

Thanks for. . .

. . . the **help**:

BSkG1/2

- S. Goriely — ULB
- G. Scamps — ULB
- E. Olsen — ULB
- J.-F. Lemaître — CEA

MOCCa

- P.-H. Heenen — ULB
- M. Bender — IP2I
- B. Bally — UAM

. . . the **CPU time**:

- CÉCI network, Belgium
- The Zenobe cluster

. . . the **support**:

ULB

fnrs LA LIBERTÉ DE CHERCHER

Thanks!

Thanks for. . .

. . . the **help**:

BSkG1/2

- S. Goriely ULB
- G. Scamps ULB
- E. Olsen ULB
- J.-F. Lemaître CEA

MOCCa

- P.-H. Heenen ULB
- M. Bender IP2I
- B. Bally UAM

. . . the **CPU time**:

- CÉCI network, Belgium
- The Zenobe cluster

. . . the **support**:

LA LIBERTÉ DE CHERCHER

. . . your **attention**!