FROM RESEARCH TO INDUSTRY

THE SPY MODEL: HOW A MICROSCOPIC DESCRIPTION OF THE NUCLEUS CAN SHED SOME LIGHT ON FISSION

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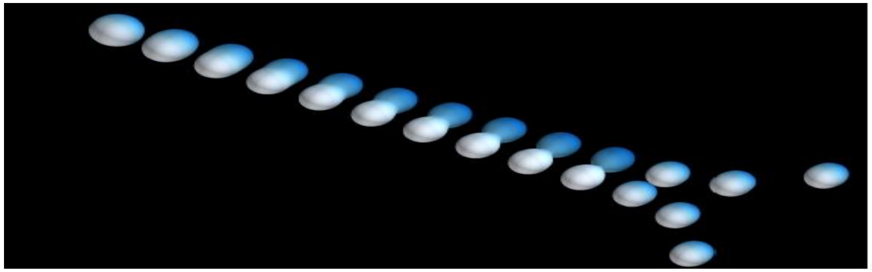
Bruyères-le-Châtel, France

INTRODUCTION

Why a scission-point model?



N-body problem

Nuclear structure

Deformations

High spin exotic nuclei

Intrinsic vs collective DoF

Event-odd effects

Non-adiabatic dynamics

Shell effects

Viscosity and friction

Fission is the ideal nuclear physics laboratory and is still a challenge for theory and experiments

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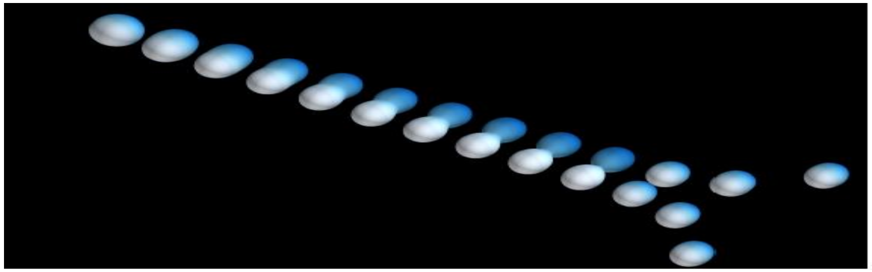

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Two main approaches are used to model the fission process:

Models based on phenomenology

- Based on experimental data
- Describe well know properties
- Low predictive power far from data
- Low computing cost

Models based on microscopy

- Only few parameters (N-N interaction)
- Less precise agreement with data
- High predictive power far from know regions
- High computing cost

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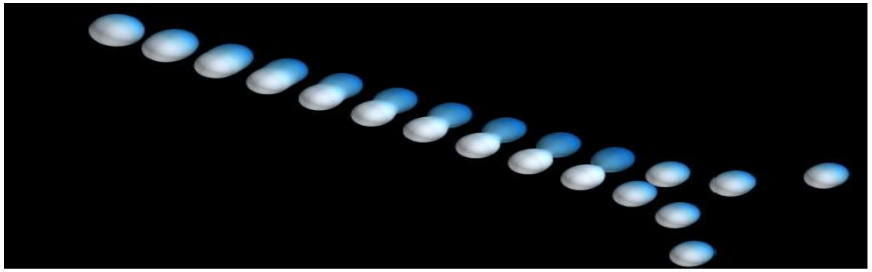

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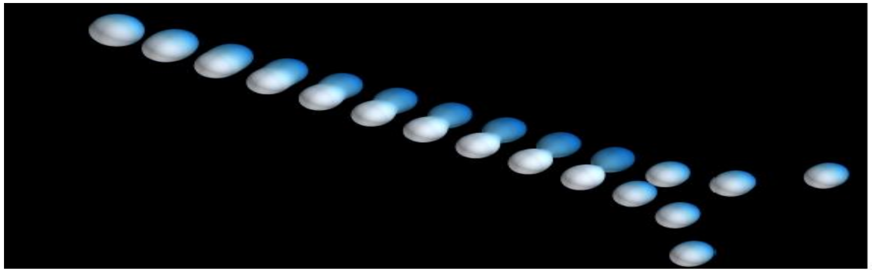
Scission-point model

B. D. Wilkins et al., Phys. Rev. C 14 (1976) 1832

- Strong hypothesis are needed:
  - Static
  - CN formation neglected
  - All fragment properties are freezed
- Energy balance at scission : LDM+shell corections (Strutinski)+pairing corrections
- Parameters needed (intrinsic and collective temperature)
- Very low computing cost

INTRODUCTION

Why a new scission-point model?



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Fission is the ideal nuclear physics laboratory and is still a challenge for theory and experiments

SPY : a new scission-point model based on microscopic ingredients

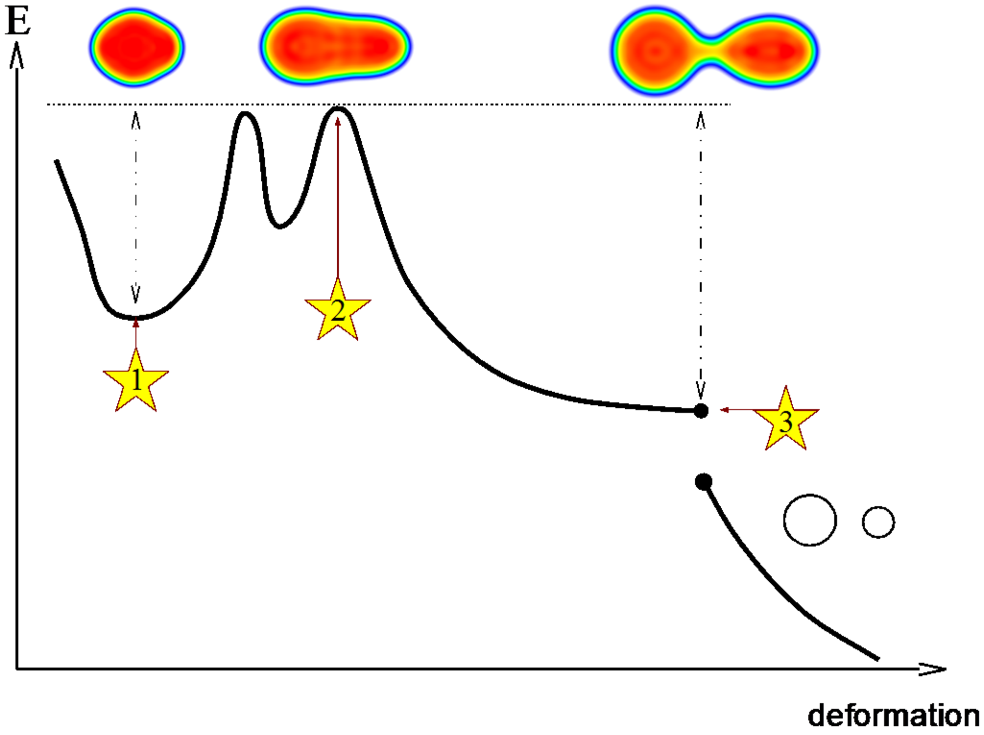
Scission-point model

- Strong hypothesis are needed:
  - Static
  - CN formation neglected
  - All fragment properties are freezed
- Very low computing cost

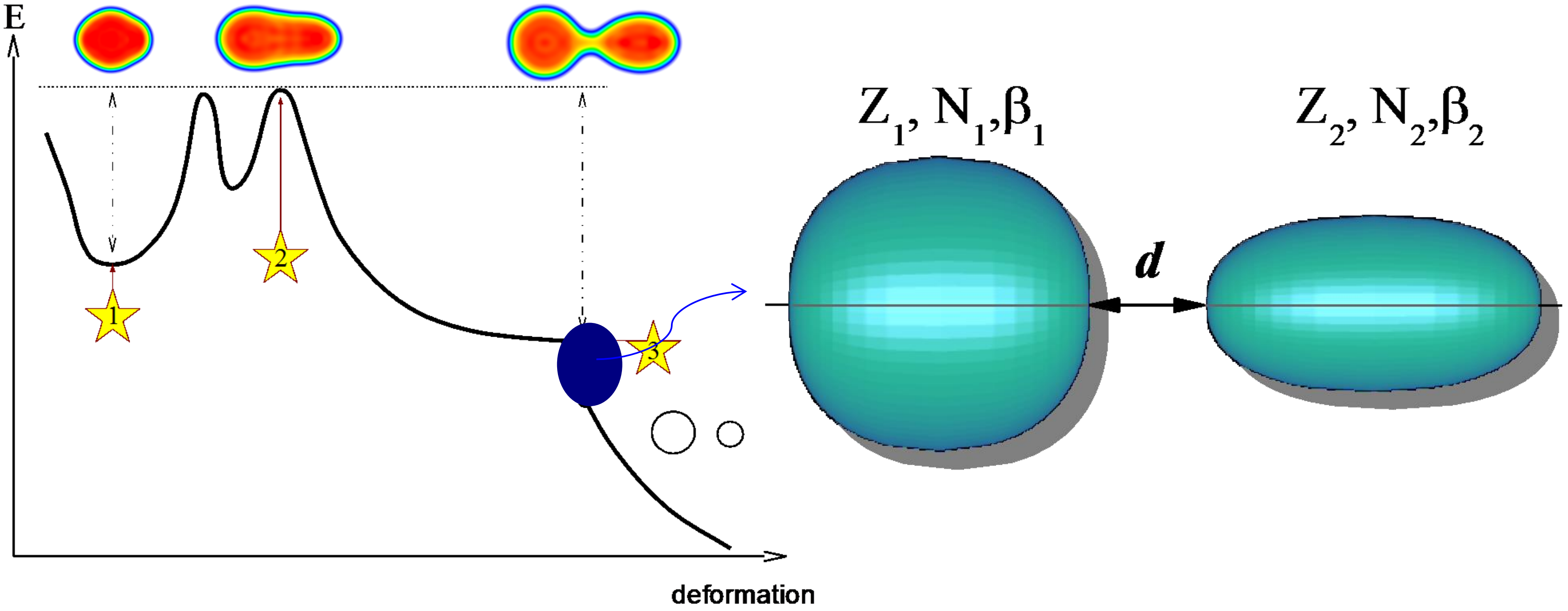
Microscopic data

- Precise treatement of nuclear structure
- No parameters needed
- Only way to explore unkown regions
- Microscopic data are tabulated (fast!)

THE SCISSION-POINT DEFINITION



THE SCISSION-POINT DEFINITION



- Thermodynamic equilibrium at scission is assumed

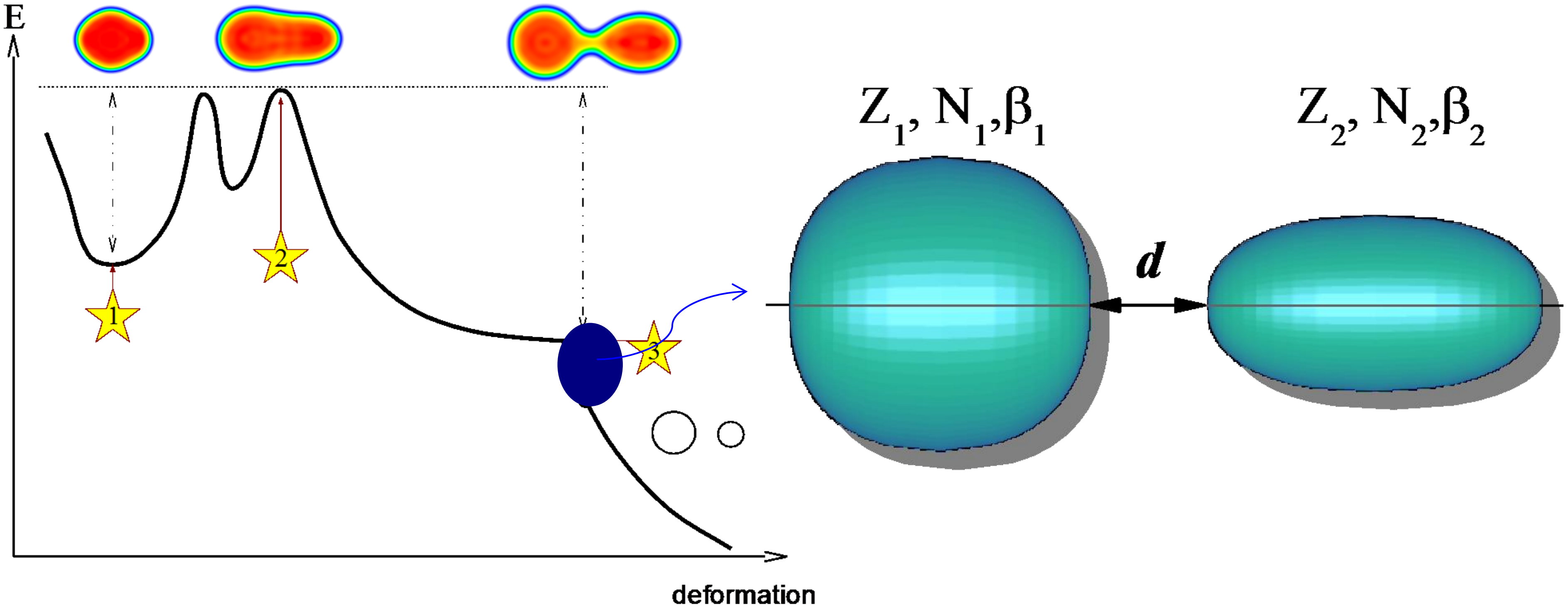
  → statistical equilibrium among system degrees of freedom

- Isolated fragments

  → microcanonical statistical description

⇒ all states at scission are equiprobable

THE SCISSION-POINT DEFINITION



The system configuration is defined by the two fragments DoF :

- proton and neutron numbers (Z_1, N_1, Z_2, N_2)
- quadrupolar deformations (β_1 , β_2)
- intrinsic excitation energy (E_1* , E_2*)

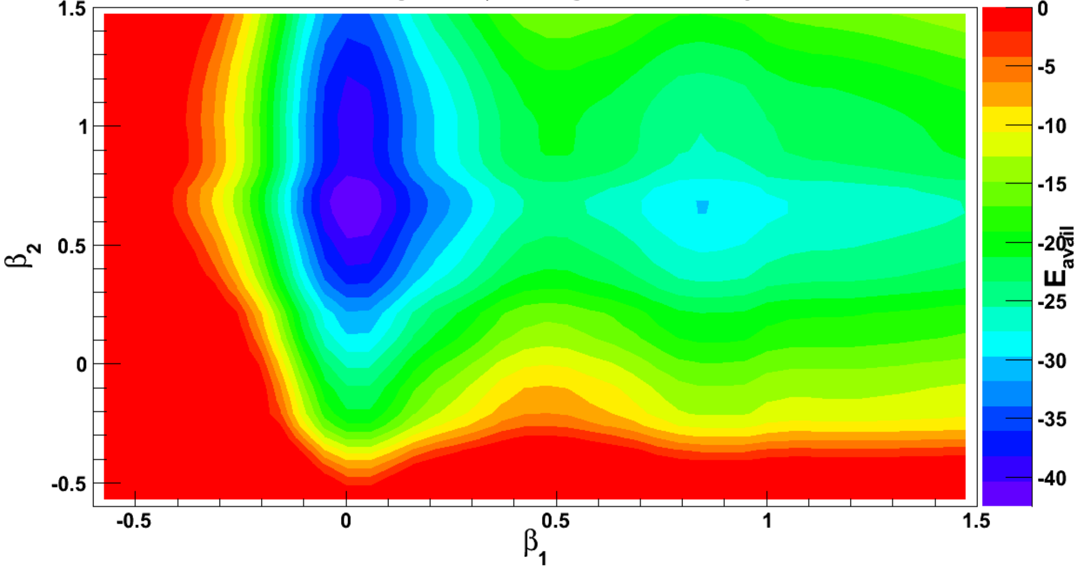
Two quantities are needed to calculate average observables :

- available energy for each configuration : E_{avail}
- state density of the two fragments: ρ_1 , ρ_2

THE ENERGY BALANCE AT SCISSION

- Available energy calculation **for each fragmentation** (500-1000)

$^{236}U^* \rightarrow {}^{132}Sn + {}^{104}Mo$



→ fragments individual energy from HFB calculation with Gogny D1S interaction (***Amedee* data base**)

S. Hilaire et al., Eur. Phys. Jour. A 33 (2007) 237

→ interaction energy (nuclear + Couloub interactions)

J. Blocki et al., Annals of Physics 105 (1977) 427

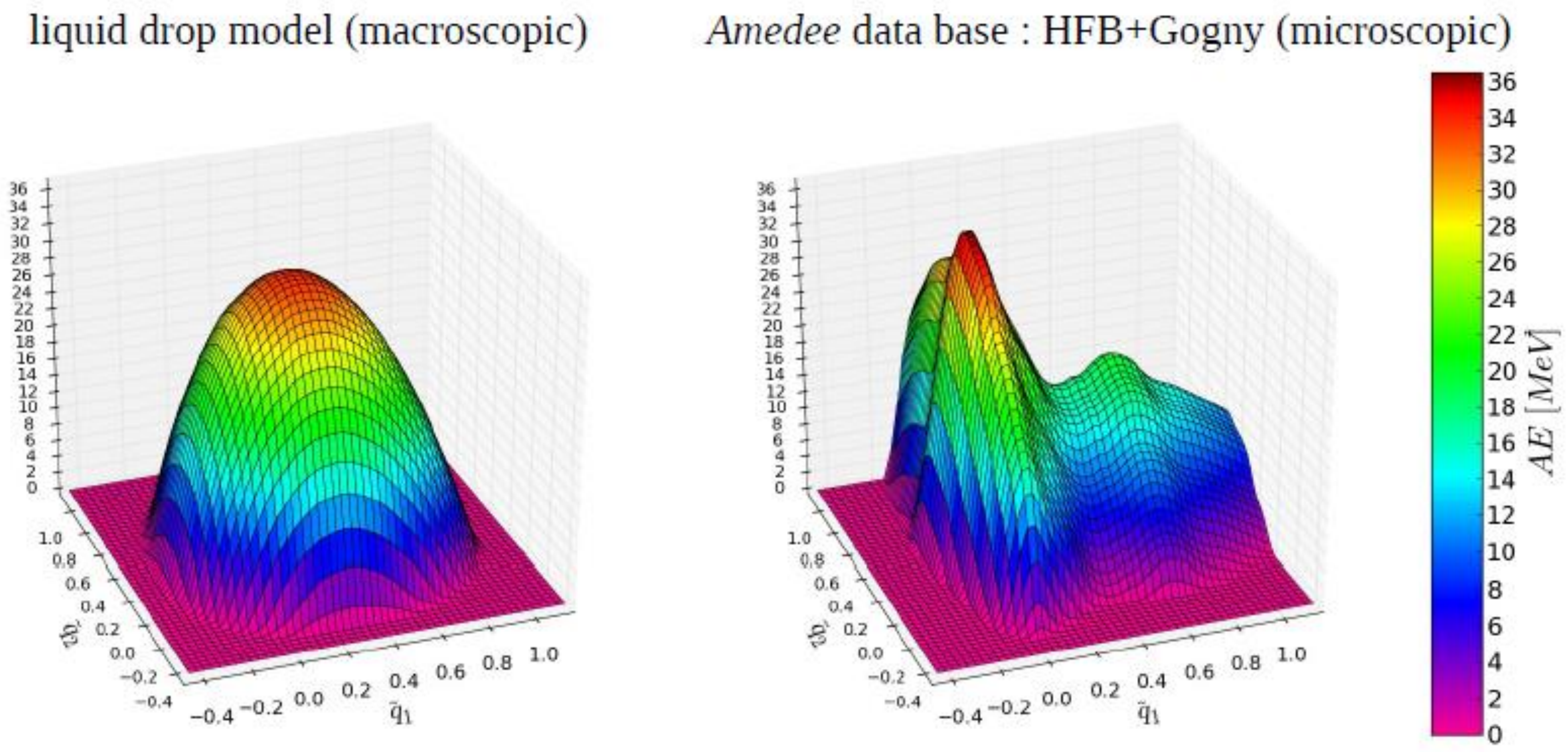
S. Cohen et al., Annals of Physics 19 (1962) 67

$$E_{avail} = E_{HFB1}(Z_1,N_1,\beta_1)+E_{HFB2}(Z_2,N_2,\beta_2)$$
$$+E_{coul}(d,Z_1,N_1,\beta_1,Z_2,N_2,\beta_2)+E_{nucl}(d,Z_1,N_1,\beta_1,Z_2,N_2,\beta_2)$$
$$-\ E_{CN}$$

if $E_{avail}<0$: fragmentation is allowed

WHAT THE MICROSCOPY BRINGS

- Available energy calculation **for each fragmentation** (500-1000)



liquid drop model (macroscopic)

Amedee data base : HFB+Gogny (microscopic)

$$E_{avail} = \left| E_{HFB1} + E_{HFB2} + E_{coul} + E_{nucl} - E_{CN} \right|$$

THE STATISTICS AT SCISSION

- The probability of a given fragmentation is related to the phase space available at scission
- The phase space is defined by the number of available states of each fragment, i.e. the intrinsic state density
- The energy partition at scission is supposed to be equiprobable between each state available to the system (microcanonical)
- Therefore the probability of a configuration is defined as:

$$\pi(Z_1, N_1, Z_2, N_2, \beta_1, \beta_2, x) = \rho_1(x|E_{avail}|)\rho_2((1-x)|E_{avail}|)\delta E^2$$

with x the fraction of energy available to excite fragment 1

- Hence, the probability of a fragmentation is easily calculated:

$$\Pi(Z_1, N_1, Z_2, N_2, \beta_1, \beta_2) = \int_0^1 \pi(Z_1, N_1, Z_2, N_2, \beta_1, \beta_2, x)\,dx$$

$$P(Z_1, N_1, Z_2, N_2) = \int_{-0.6}^{1.3}\int_{-0.6}^{1.3} \Pi(Z_1, N_1, Z_2, N_2, \beta_1, \beta_2)\,d\beta_1 d\beta_2$$

THE STATISTICS AT SCISSION

For the time being, a Fermi gas level density is used (CT model)

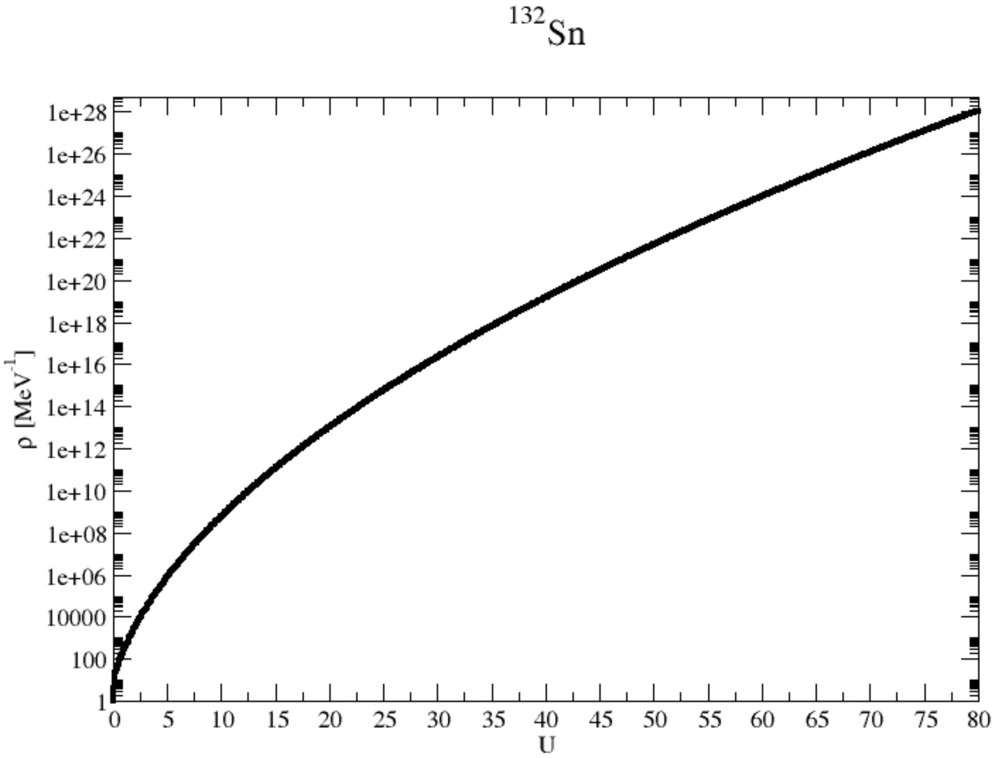
$$\rho_F(U) = \frac{1}{\sqrt{2\pi}\,\sigma}\frac{\sqrt{\pi}}{12}\frac{e^{2\sqrt{aU}}}{a^{1/4}U^{5/4}}$$

$$a = \alpha A + \beta A^{2/3}$$

$$\alpha = 0.0692559, \beta = 0.282769$$

$$\sigma = I_0 a\sqrt{U/a}$$

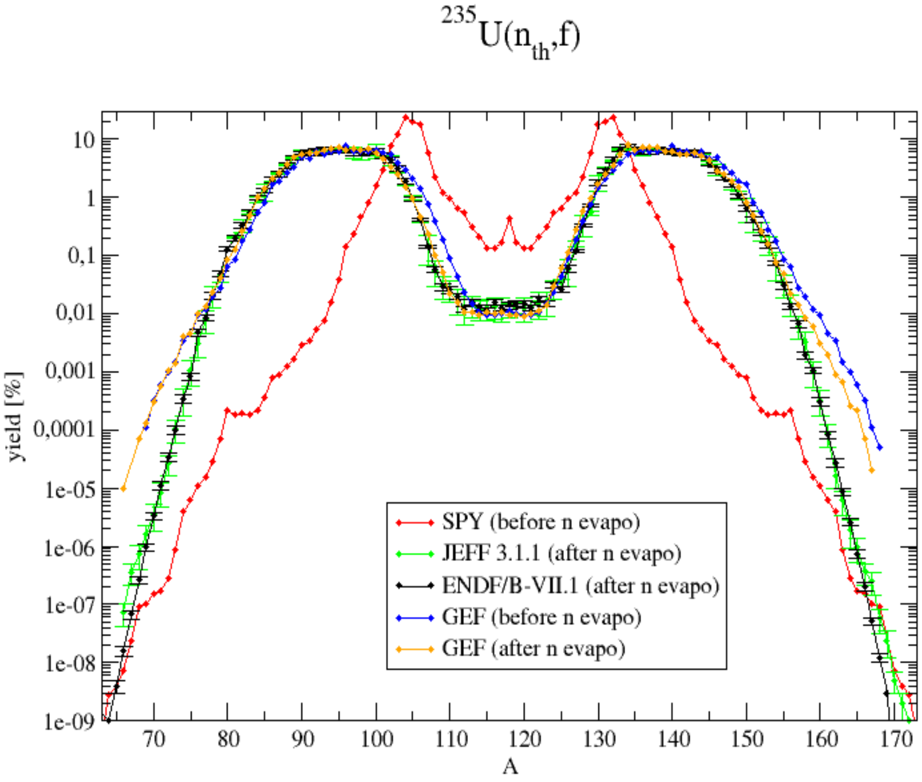
A. Koning et al., Nucl. Phys. A 810 (2008) 13



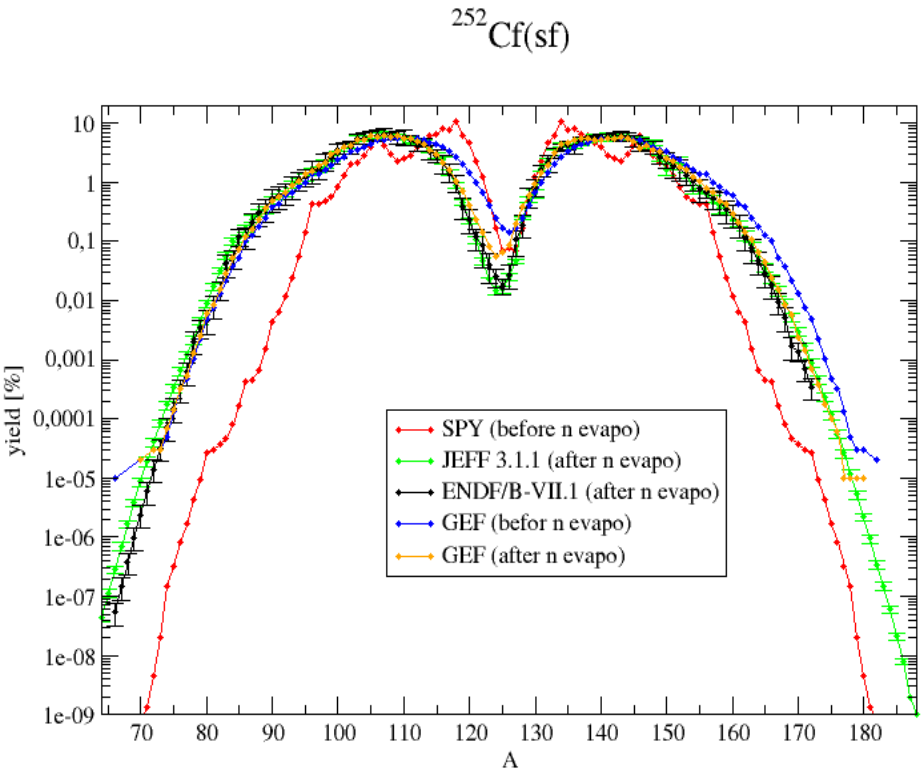
No dependence on deformation

SOME EXPECTED RESULTS

Fission yields of $^{235}U(n_{th},f)$ and $^{252}Cf(sf)$



$^{235}U(n_{th},f)$

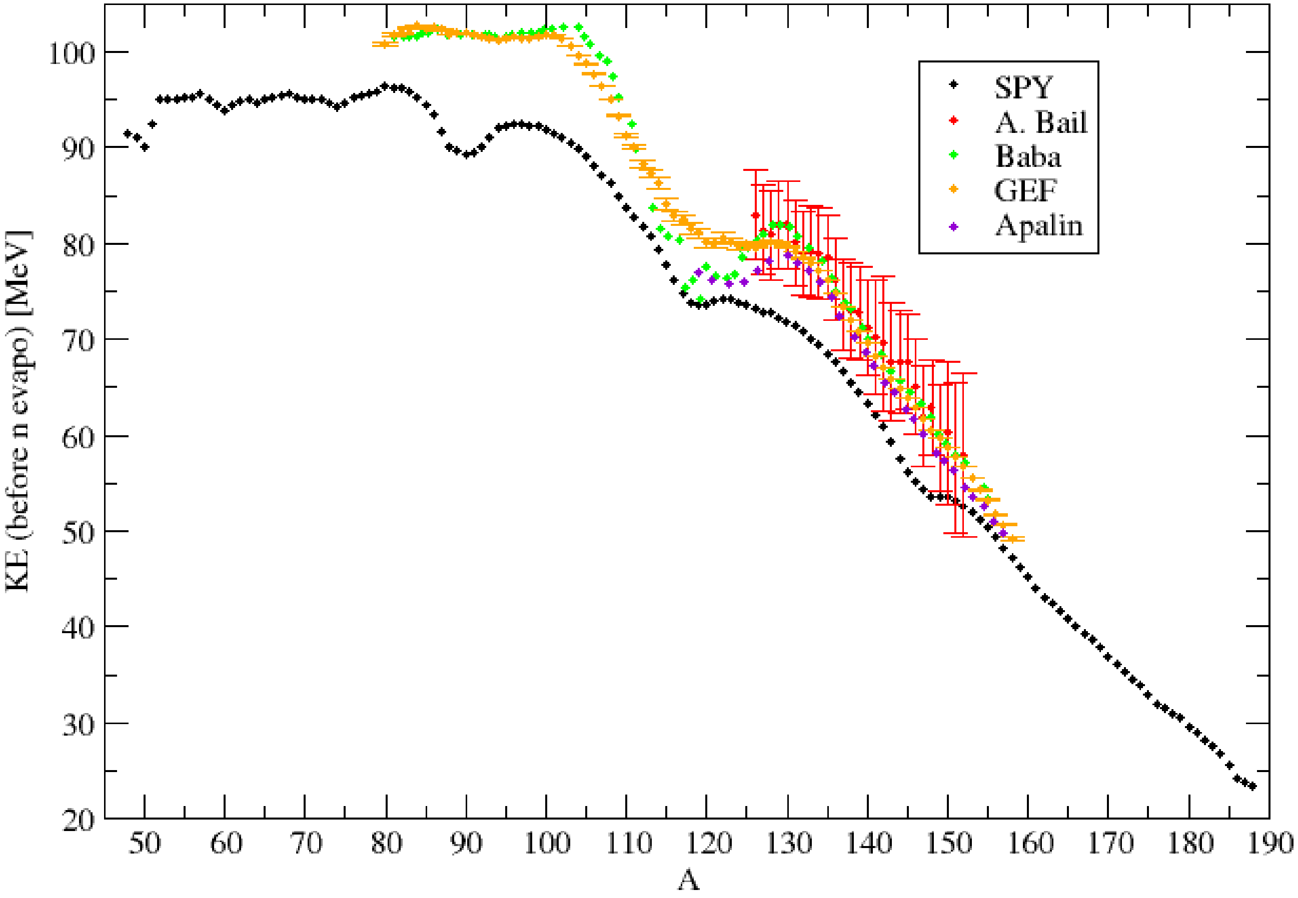


$^{252}Cf(sf)$

J. F. Lemaître et al., Proc. «Fission 2013», Caen (France), 28-31/05/2013.

SOME EXPECTED RESULTS

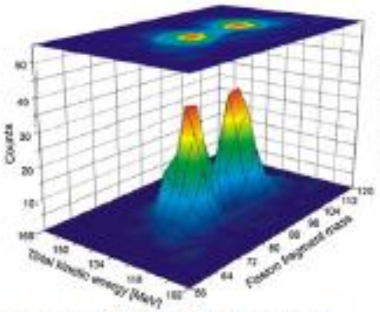
Kinectic Energy of fragments from $^{235}U(n_{th},f)$



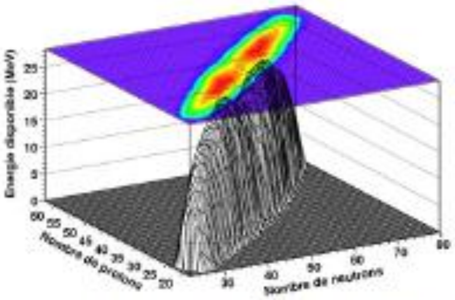
J. F. Lemaître et al., Proc. «Fission 2013», Caen (France), 28-31/05/2013.

SOME REMARKABLE RESULTS

Light exotic nucleus
Two-humped mass distribution



Andreyev et al., PRL 105 (2011) 252502



S. Panebianco et al., PRC 86 (2012) 064601

PHYSICAL REVIEW C **86**, 064601 (2012)

Role of deformed shell effects on the mass asymmetry in nuclear fission of mercury isotopes

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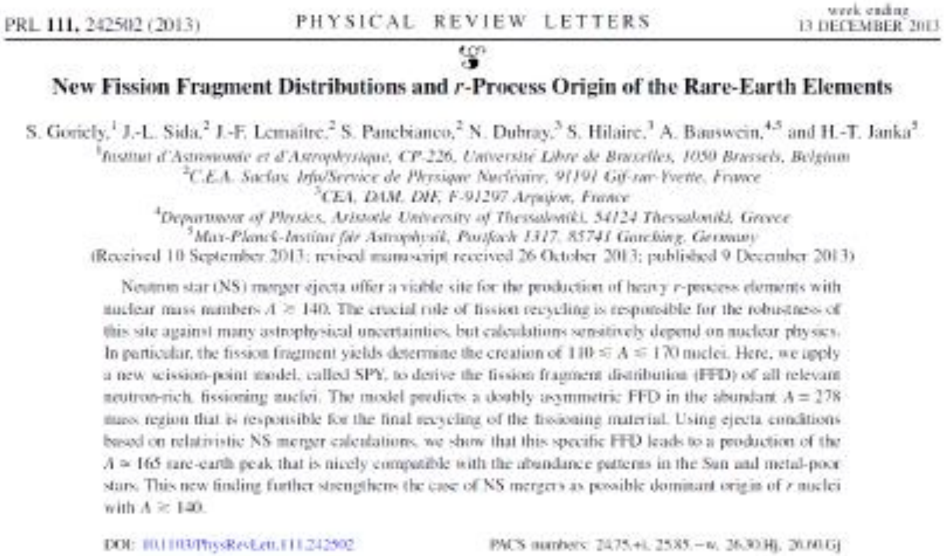
(Received 9 October 2012; published 3 December 2012)

Until now, the mass asymmetry in the nuclear fission process has been understood in terms of the strong influence of the nuclear structure of the nascent fragments. Recently, a surprising asymmetric fission has been discovered in the light mercury region and has been interpreted as the result of the influence of the nuclear structure of the parent nucleus, totally discarding the influence of the fragments' structure. To assess the role of the fragment shell effects in the mass asymmetry in this particular region, a scission-point model, based on a full energy balance between the two nascent fragments, has been developed using one of the best theoretical descriptions of microscopic nuclear structure. As for actinides, this approach shows that the asymmetric splitting of the ^{180}Hg nucleus and the symmetric one of ^{198}Hg can be understood on the basis of only the microscopic nuclear structure of the fragments at scission.

DOI: 10.1103/PhysRevC.86.064601 PACS number(s): 24.75.+i, 25.85.−w, 27.80.+w



PRL **111**, 242502 (2013) PHYSICAL REVIEW LETTERS week ending 13 DECEMBER 2013

New Fission Fragment Distributions and *r*-Process Origin of the Rare-Earth Elements

S. Goriely,[1] J.-L. Sida,[2] J.-F. Lemaître,[2] S. Panebianco,[2] N. Dubray,[3] S. Hilaire,[3] A. Bauswein,[4,5] and H.-T. Janka[5]
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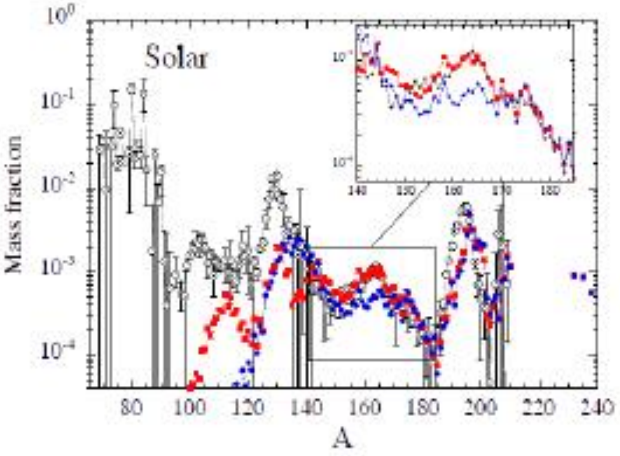
(Received 10 September 2013; revised manuscript received 26 October 2013; published 9 December 2013)

Neutron star (NS) merger ejecta offer a viable site for the production of heavy *r*-process elements with nuclear mass numbers $A \gtrsim 140$. The crucial role of fission recycling is responsible for the robustness of this site against many astrophysical uncertainties, but calculations sensitively depend on nuclear physics. In particular, the fission fragment yields determine the creation of $110 \lesssim A \lesssim 170$ nuclei. Here, we apply a new scission-point model, called SPY, to derive the fission fragment distribution (FFD) of all relevant neutron-rich, fissioning nuclei. The model predicts a doubly asymmetric FFD in the abundant $A = 278$ mass region that is responsible for the final recycling of the fissioning material. Using ejecta conditions based on relativistic NS merger calculations, we show that this specific FFD leads to a production of the $A \simeq 165$ rare-earth peak that is nicely compatible with the abundance patterns in the Sun and metal-poor stars. This new finding further strengthens the case of NS mergers as possible dominant origin of *r* nuclei with $A \gtrsim 140$.

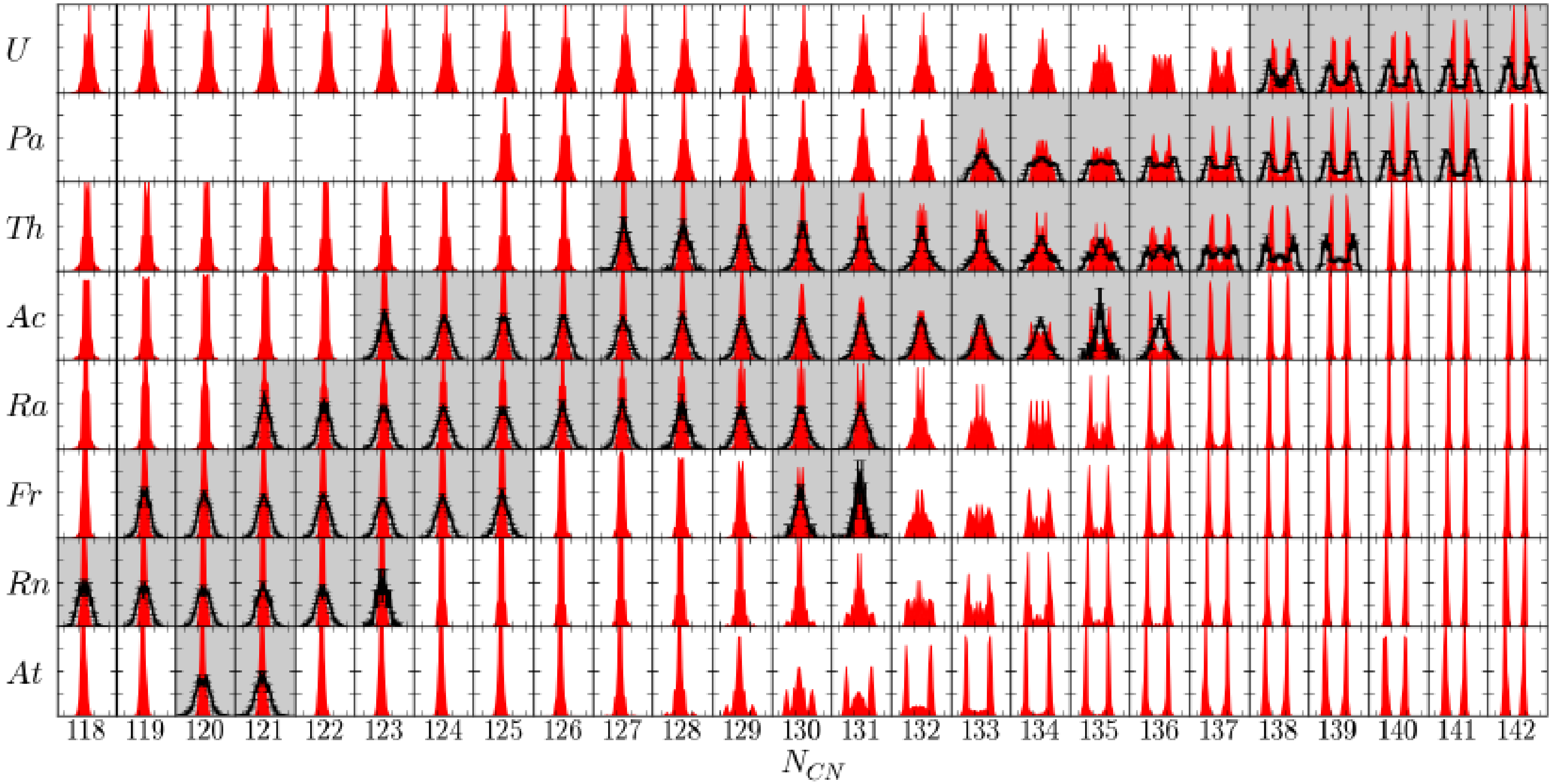
DOI: 10.1103/PhysRevLett.111.242502 PACS numbers: 24.75.+i, 25.85.−w, 26.30.Hj, 26.60.Gj



Heavy exotic nuclei – Huge # of nuclei
Four-humped mass distributions

A REMARKABLE POWER OF DESCRIPTION

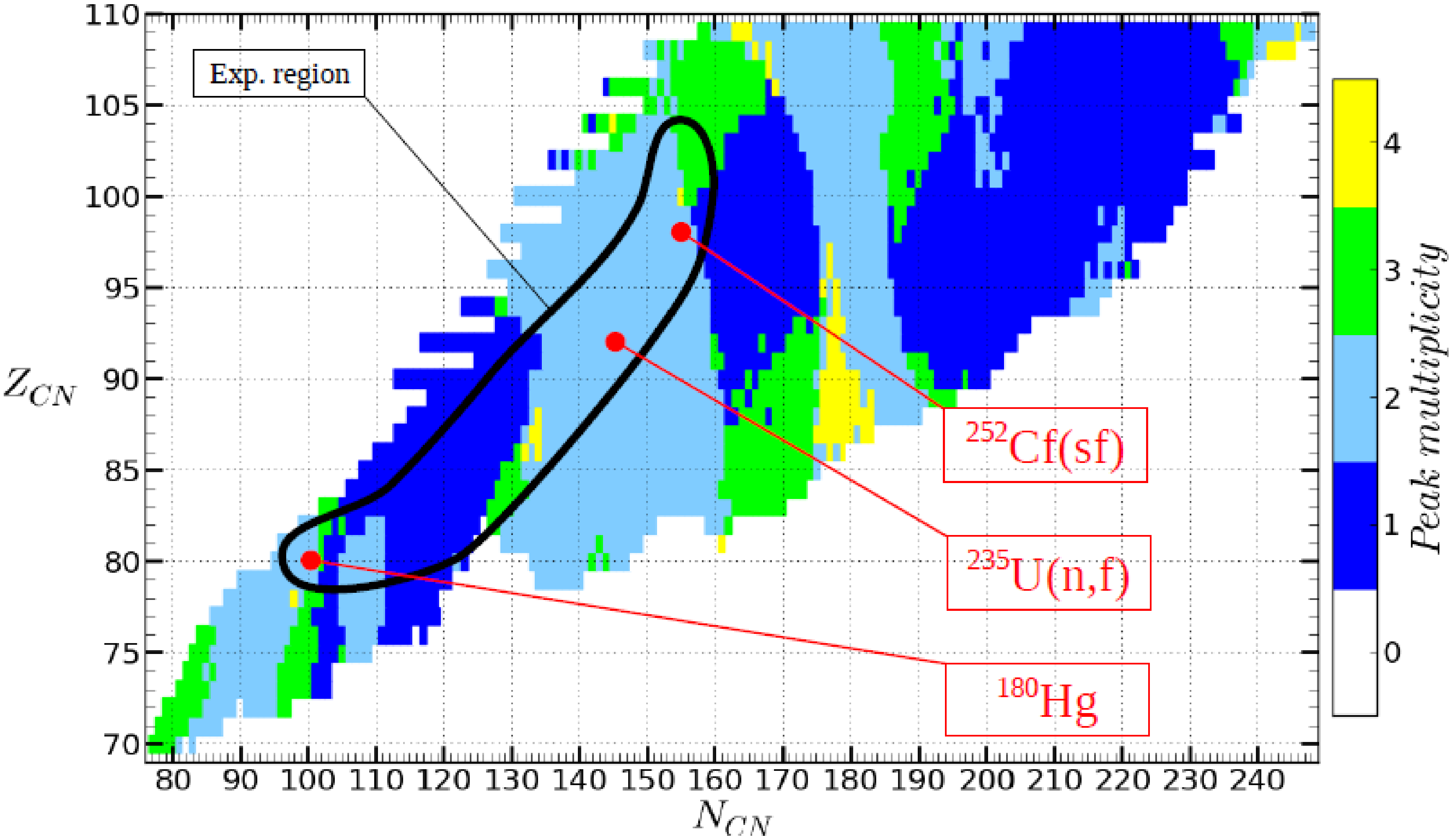
Charge yields from Ac to U isotopic chains



SPY vs GSI data (Nucl. Phys. A 665, 221)

J. F. Lemaître et al., Proc. «Zakopane 2014», 31/08-07/09/2014

Peak multiplicity over the whole nuclear chart



J. F. Lemaître et al., Proc. «Zakopane 2014», 31/08-07/09/2014

WHAT THE MICROSCOPY BROUGHT

The integration of microscopic description of the nuclei in a statistical scission point model shows that shell effects drive the mass asymetry

However, these effects are energy (temparature) and deformation dependent and still too pronounced (i.e., ^{132}Sn plays as a strong attractor)

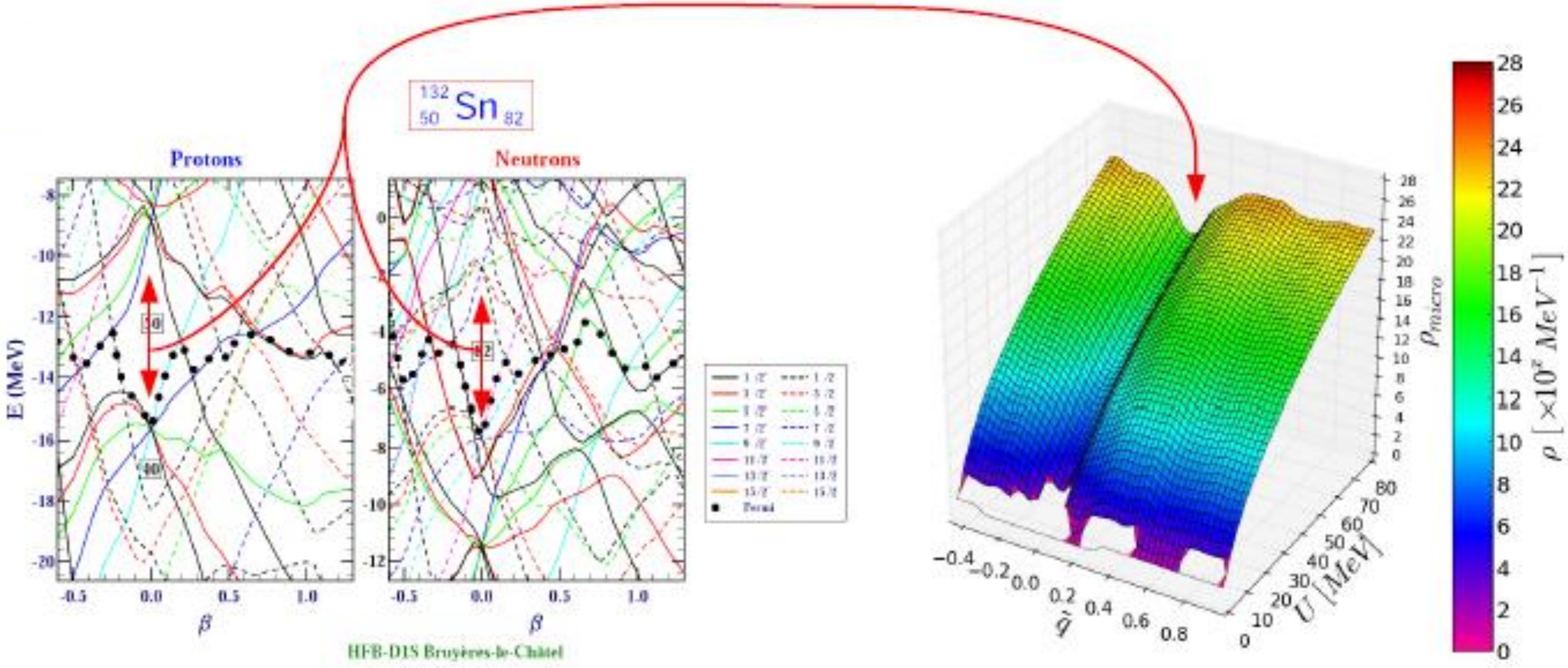
J. F. Lemaître et al., paper in preparation for PRC

WHAT THE MICROSCOPY CAN STILL BRING

But : **nuclear structure affects also state density**:

- Include microscopic state density from combinatorial on HFB nucleonic level diagram

energy gap in nucleonic level diagram ⇒ drop of state density

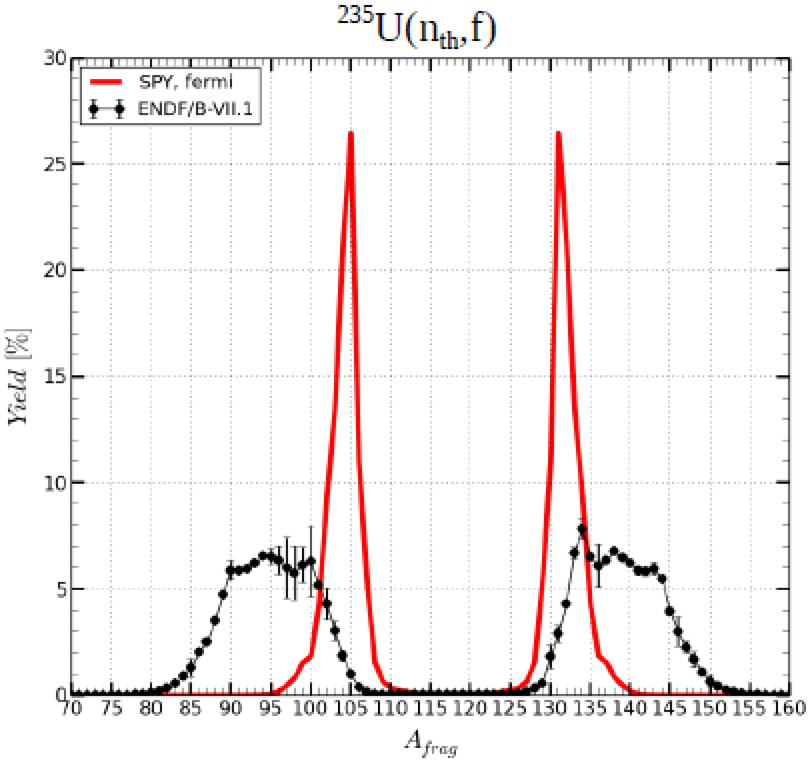


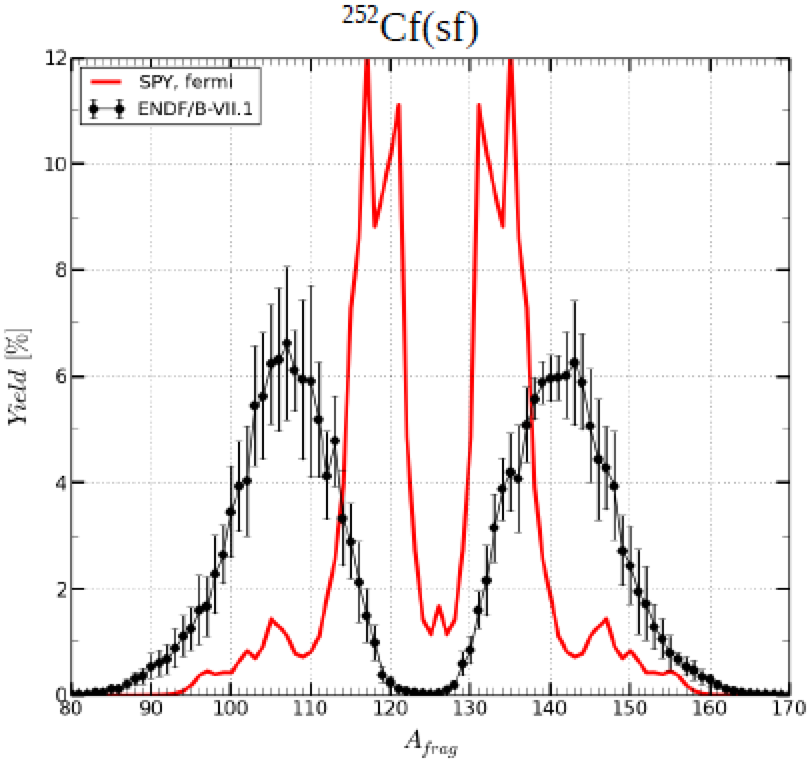
SOME PRELIMINARY RESULTS

Fission yields of $^{235}U(n_{th},f)$ and $^{252}Cf(sf)$

Fragment nuclear structure is present on:

- ✓ Individual energy (HFB – Gogny D1S)
- State density (Fermi gas)





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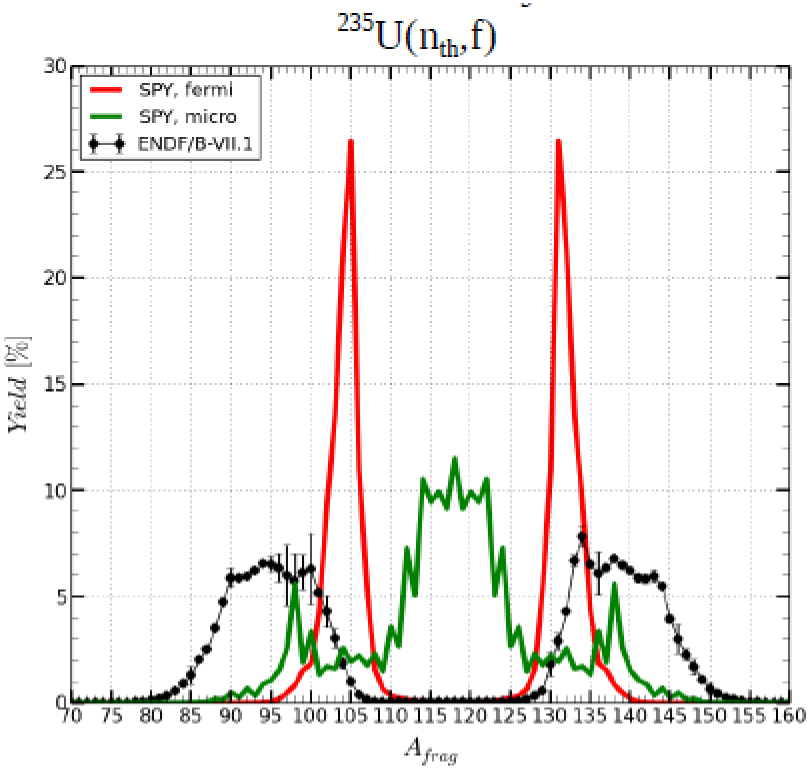

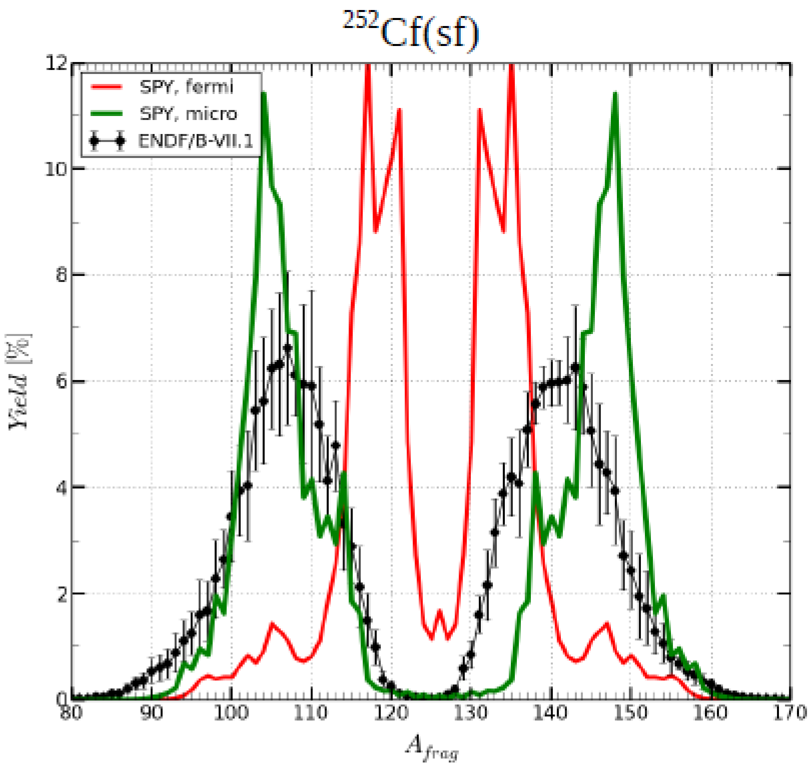

PERSPECTIVES

The integration of microscopic description of the nuclei in a statistical scission point model showed that shell effects drive the mass asymetry

However, these effects are energy (temparature) and deformation dependent and still too pronounced (i.e., ^{132}Sn plays as a strong attractor)

The ongoing developments consist of:

- Explore the richness of microscopic state density from HFB
- Include collectivity on both HFB energy and states density
- Include HFB data at finite temperature (Gogny D1M)

THE LESSON WE’VE LEARNT

Fission = competition between available energy & available states

THE LESSON WE'VE LEARNT

Fission = competition between available energy & available states

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