The Abdus Salam
International Centre for Theoretical Physics

United Nations
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1930-18

Joint ICTP-IAEA Advanced Workshop on Model Codes for Spallation Reactions

4 - 8 February 2008

The de-excitation code ABLA07

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The de-excitation code ABLA07

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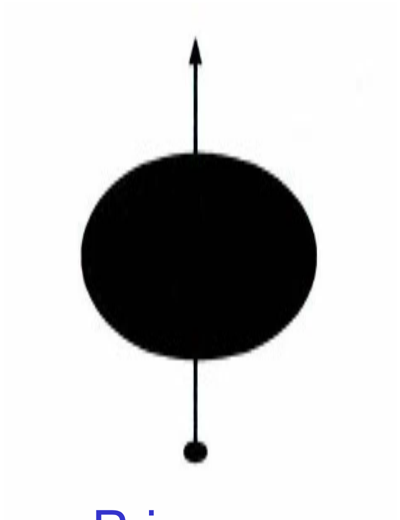
Layout

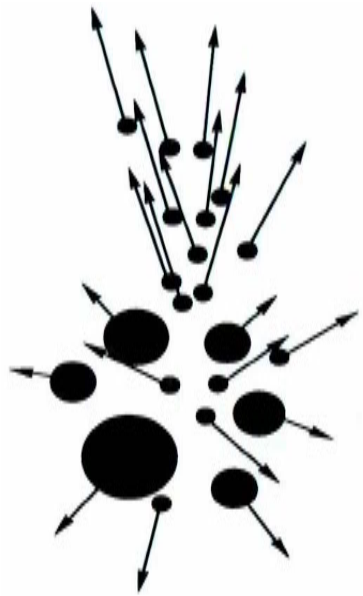
- Introduction
- Thermal breakup (related to A. Botvina's talk)
- Binary decay (related to R. Charity's talk)
  - Evaporation
  - Fission
- Influence of INC
- Conclusion

Introduction

Stages of a spallation reaction



Primary collisions



Final residues

- Primary collisions (≈10 fm/c = 3.3 10^{-23} s)
  - ▶ Distorted nuclear system
- Thermalisation of nucleonic motion (≈100 fm/c)
  - ▶ Compound nucleus

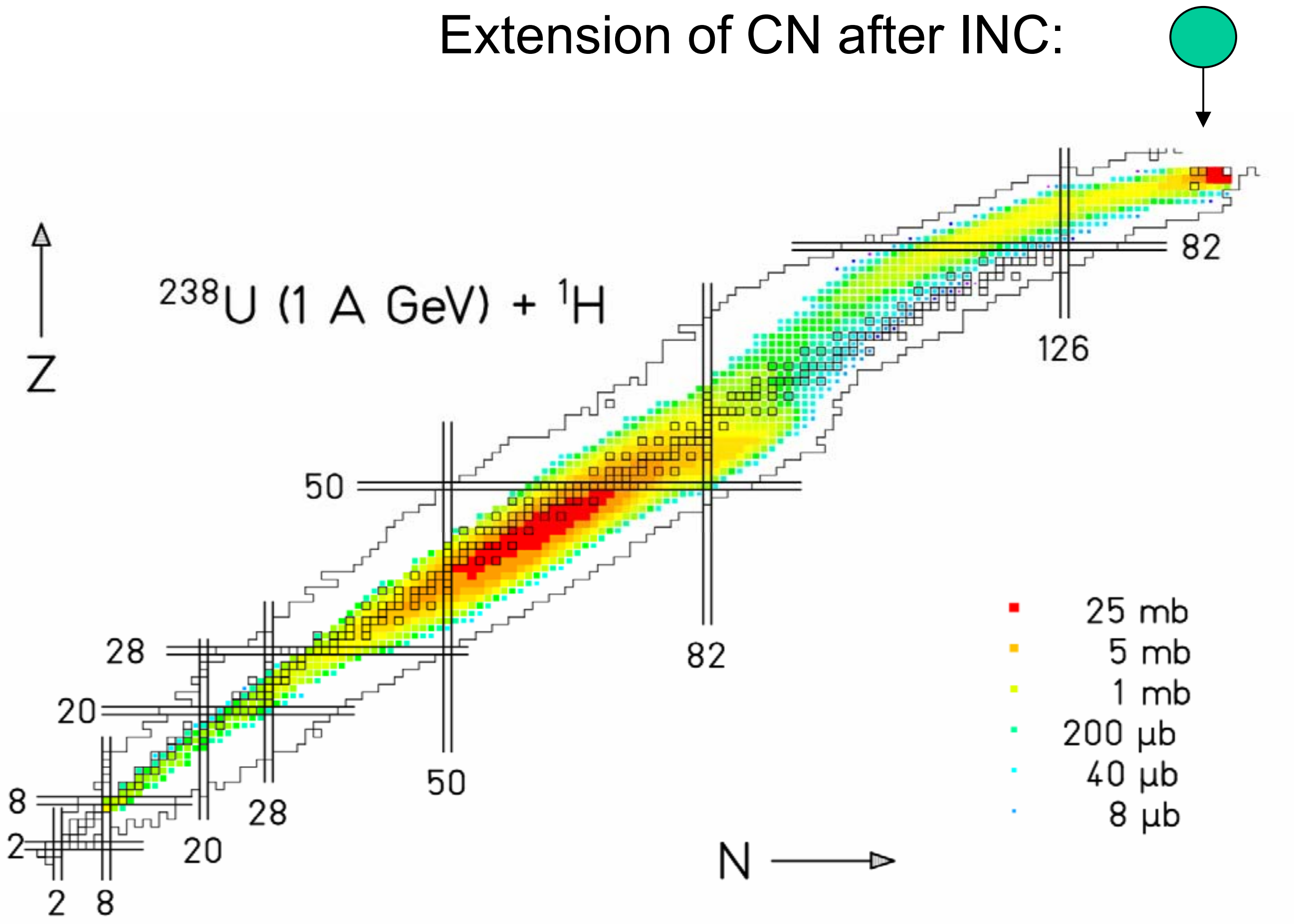
ABLA07 starts here

- Expansion (a few 100 fm/c)
  - ▶ Thermal instabilities
- Shape evolution (≈1000 fm/c)
  - ▶ Fission delay
- De-excitation (up to ≈10^7 fm/c)
  - ▶ Final residue

ABLA07 is 2nd part of ABRABLA07 (Abrasion-ablation code).

Fingerprints of the de-excitation process

Extension of CN after INC:



The de-excitation process wipes out most of the properties of the heated thermalised system. Most of the characteristica of the final residues are fingerprints of the de-excitation process.

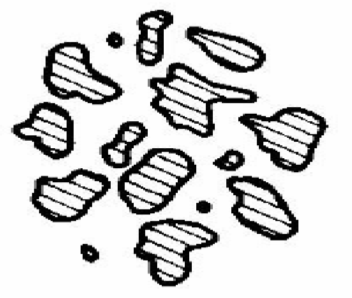
The situation after the primary collision process can be expressed by the parameters of the compound nucleus. They define the starting point of the de-excitation process.

P. Armbruster et al., PRL 93 (2004) 212701

Parameters of the compound nucleus

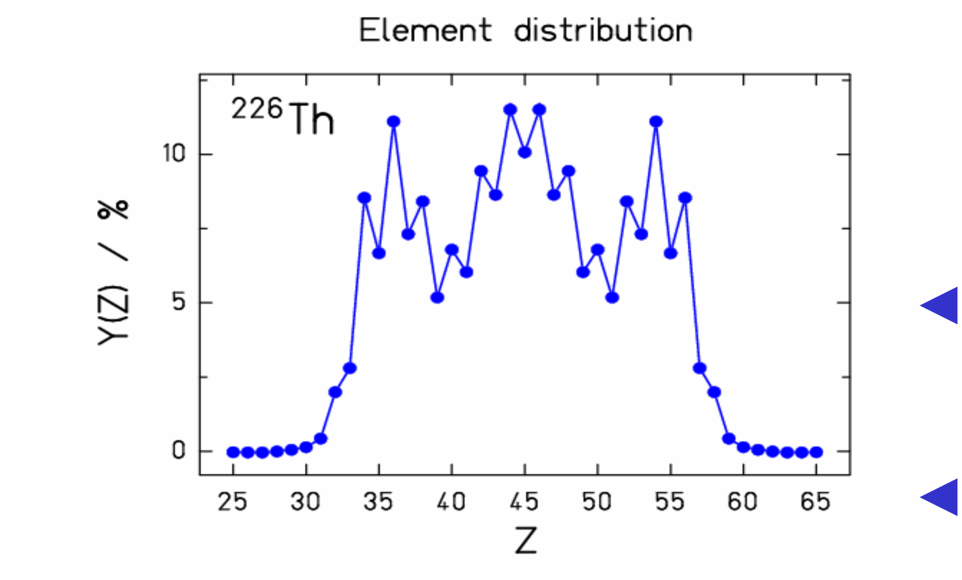
- Composition in A and Z
  - Starting point on the chart of the nuclides
- Thermal excitation energy (Bohr) (nucleonic motion)
  - Influence on emission rates
  - Reduced in de-excitation
- Angular momentum (Bohr)
  - Influence on barriers (mostly fission)
  - Modified in de-excitation
- Linear momentum
  - No influence on de-excitation
  - Signature of reaction channel
- Volume (extended)
  - Response to heating - breakup

Phenomena in the de-excitation process



Some processes let particularly strong fingerprints in the decay products:

- E* > 3 A MeV: Thermal (spinodal) instabilities
  - ► Multifragmentation
- E* < 3 A MeV Binary decay
  - ► Fission – evaporation
- E* < 20 MeV: Shell effects
  - ► Fission channels
- E* < 10 MeV: Pairing correlations
  - ► Even-odd structure

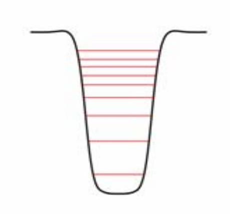


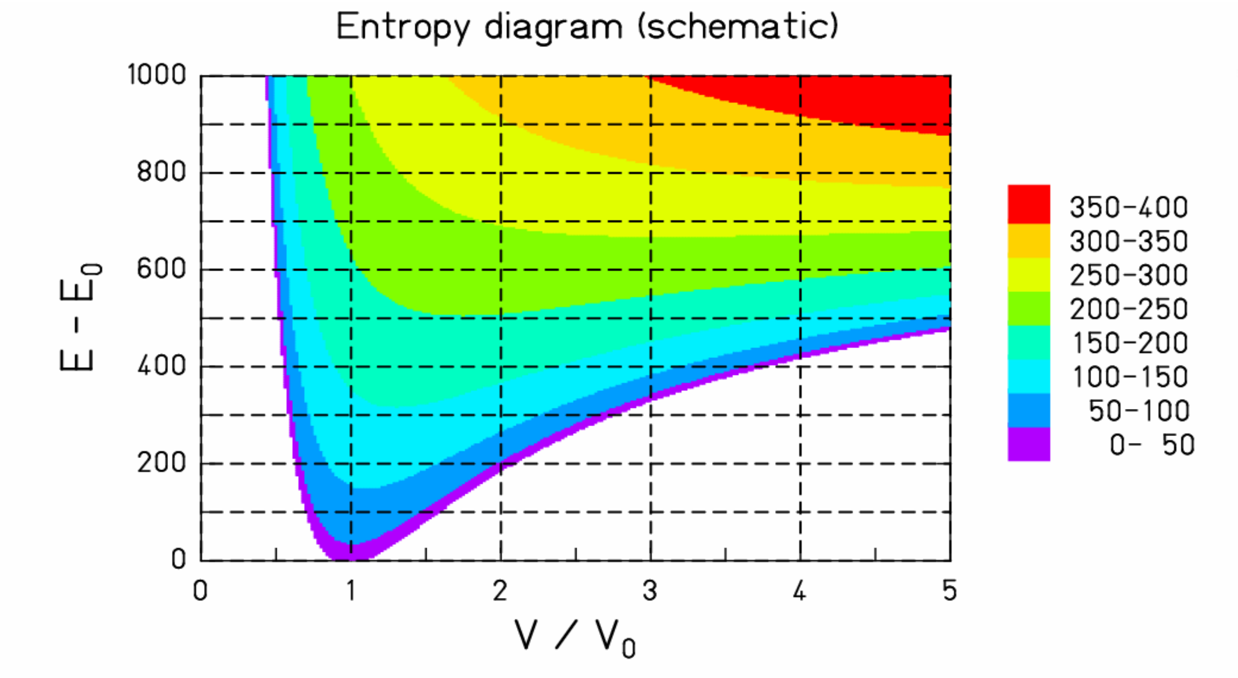
Spirit of ABLA07

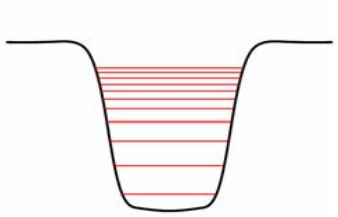
- Coverage of all phenomena relevant for residue production (in contrast to old ABLA).
- As much theory as possible for good predictive power.
- As much empirical information as needed for good reproduction of data.
- Code should be "fast" (analytical whenever possible).

Simultaneous break-up

Importance of the density degree of freedom





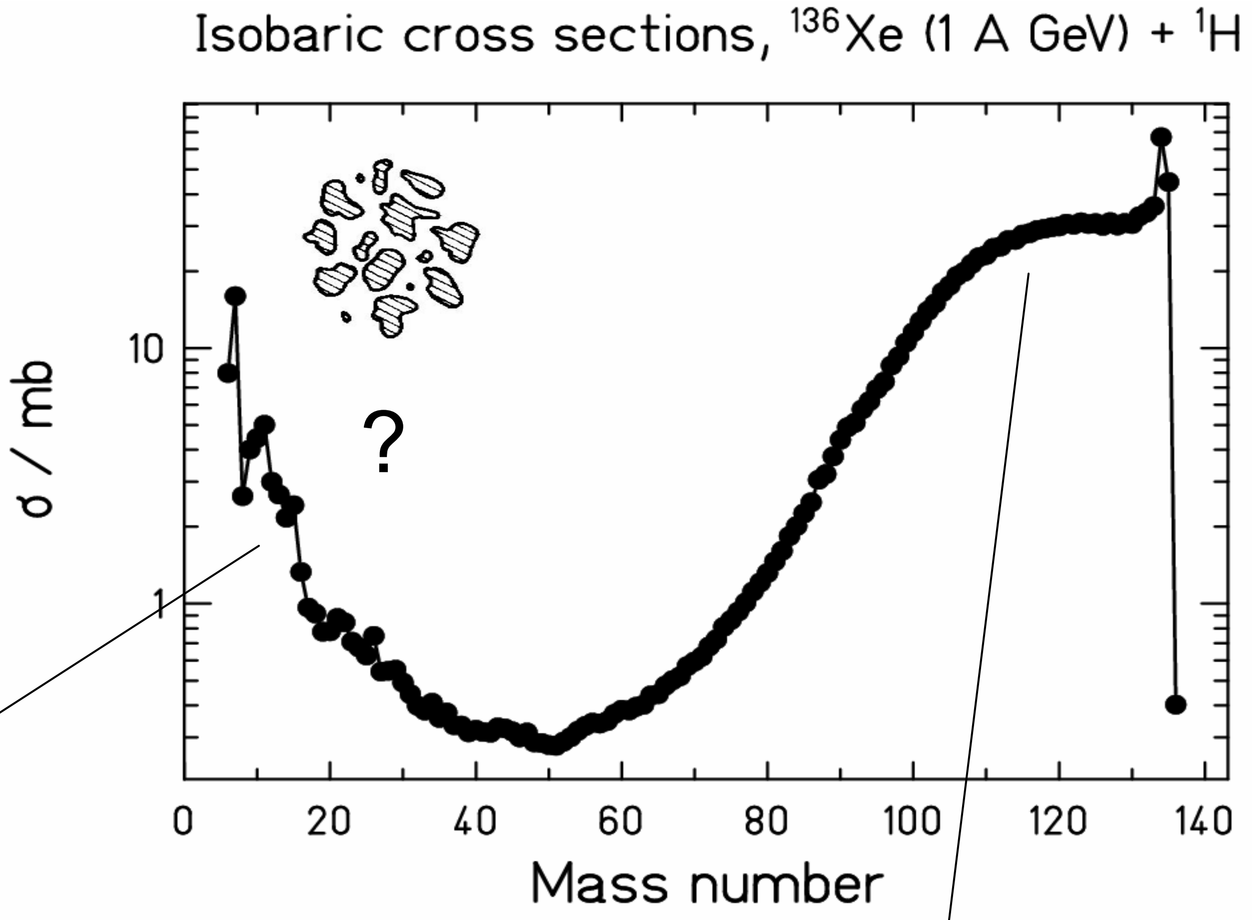


Level density: $\omega \propto \exp\left(2\sqrt{a(E - E_c)}\right)$

Compressional energy: $E_c = K \cdot (\rho - \rho_0)^2$

Level-density parameter: $a \propto \rho^{-1} \propto V$

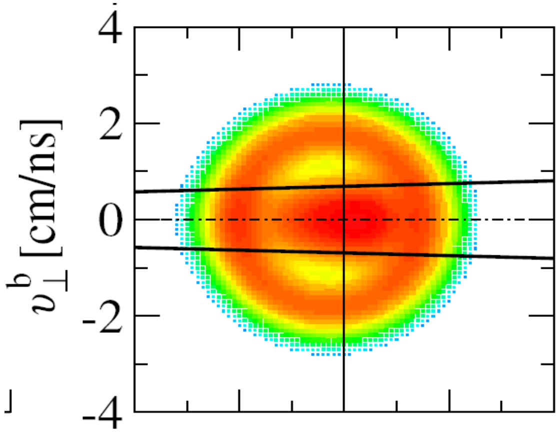
Two components in mass distribution



Data:
P. Napolitani,
PhD thesis

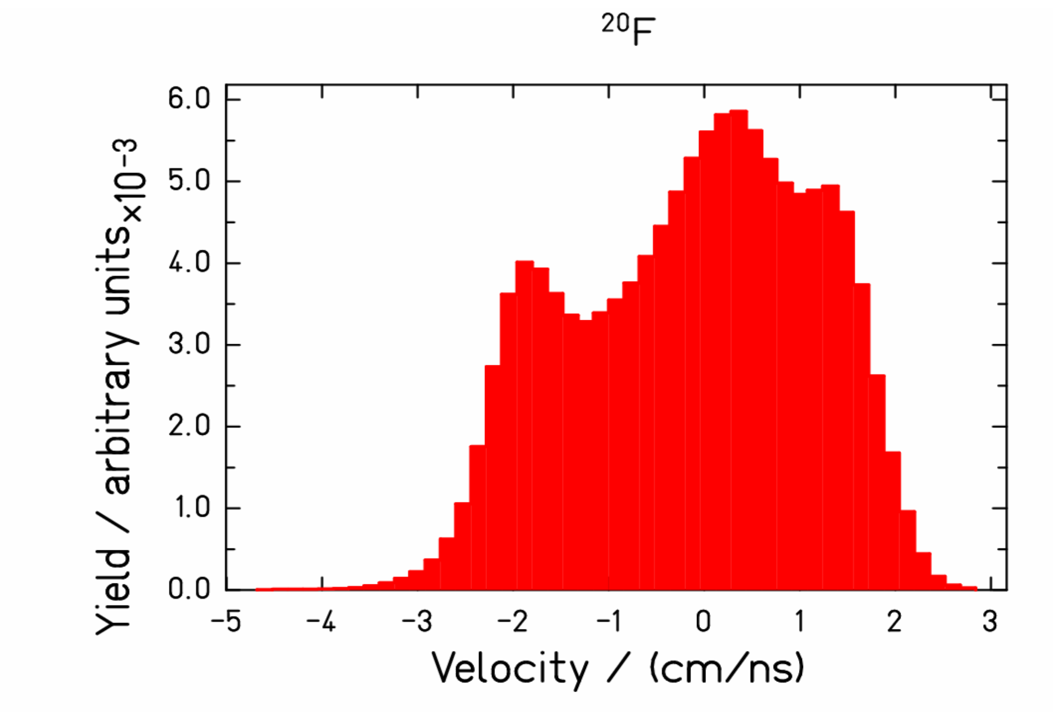
High-mass component: Surviving heavy residue!
Low-mass component: Pre-equ., multifragmentation of binary decay?
Additional information required.

Exp. signature of multifragmentation ?



$^{136}Xe + ^{1}H$
1 A GeV

Longitudinal cuts in velocity

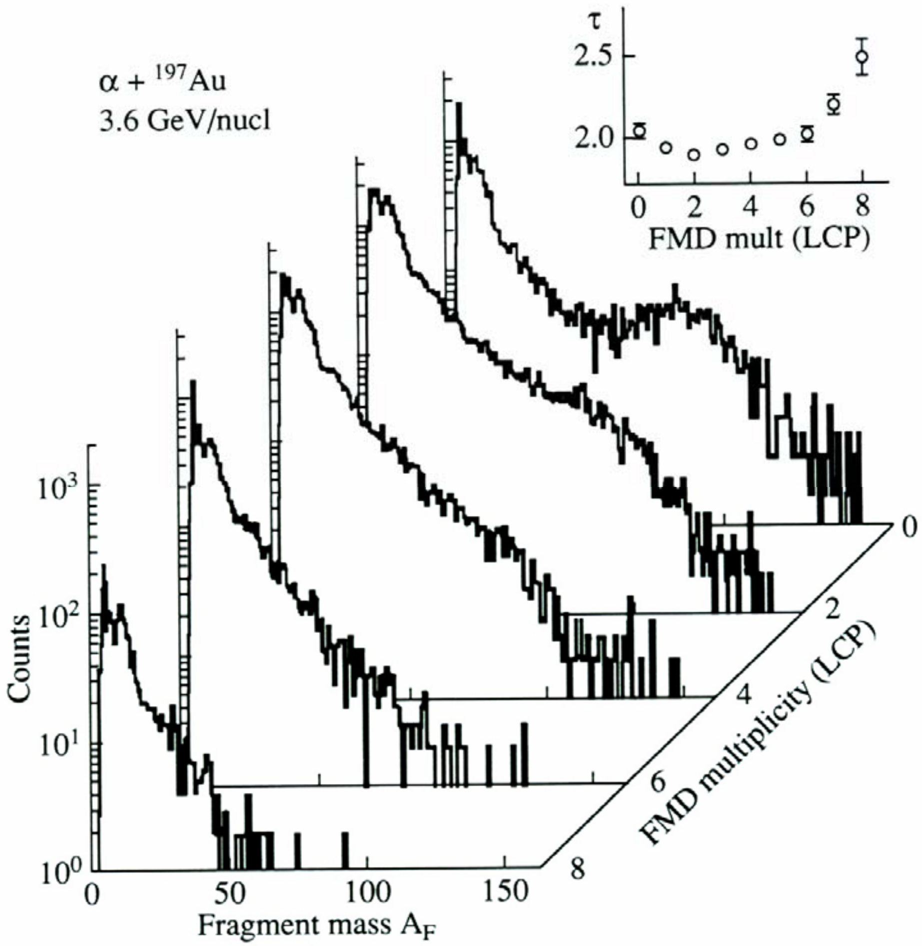


Multifragmentation:
One central component due to expansion of an homogenous source.

Binary decay:
2 separated forward and backward components due to Coulomb repulsion.

PhD, P. Napolitani

Mass distribution: Power law



Multifragmentation in ABLA07:

When $E^* > 3\,A$ MeV, part of the system decomposes into several IMFs.

Size distribution is given by a power law.

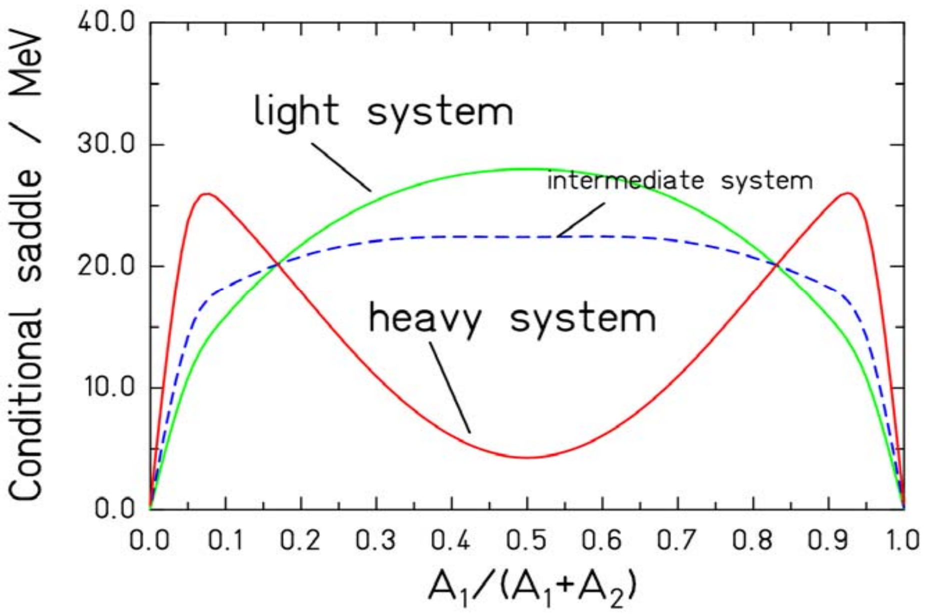
Exponent depends on E^*/A.

V. A. Karnaukov, Phys. Part. Nucl. 37 (2006) 165

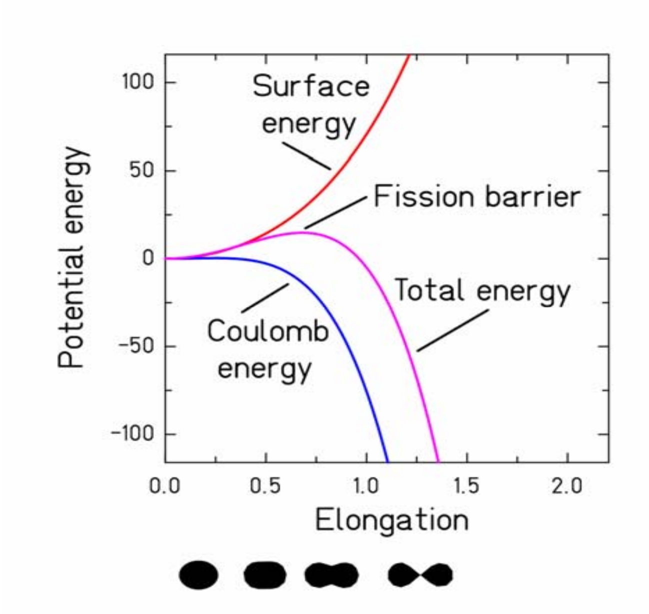
Binary decay

1. Evaporation

Macroscopic features of binary decay



Binary decay over all possible mass splits



Fission barrier of heavy system

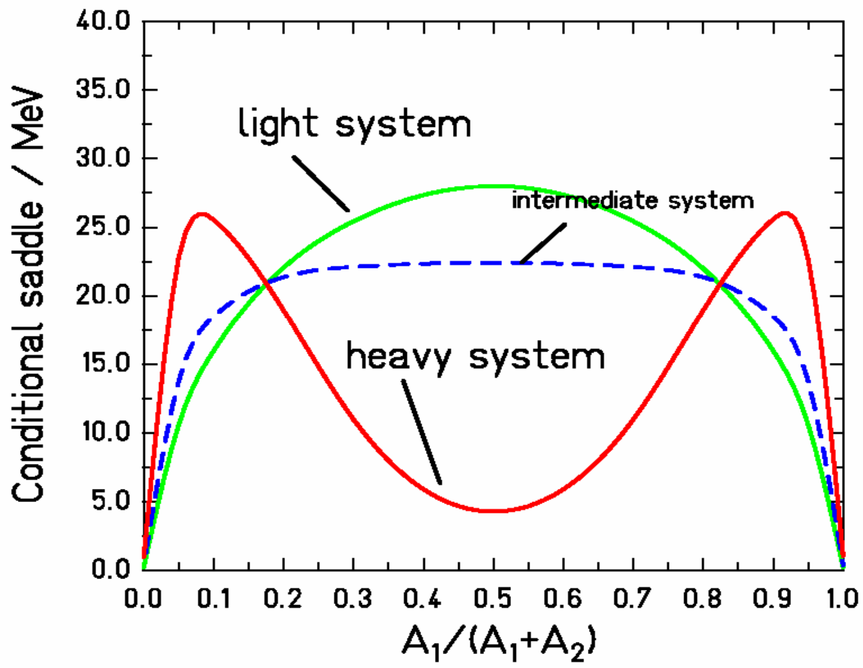
Evaporation and fission are limiting cases of binary decay.

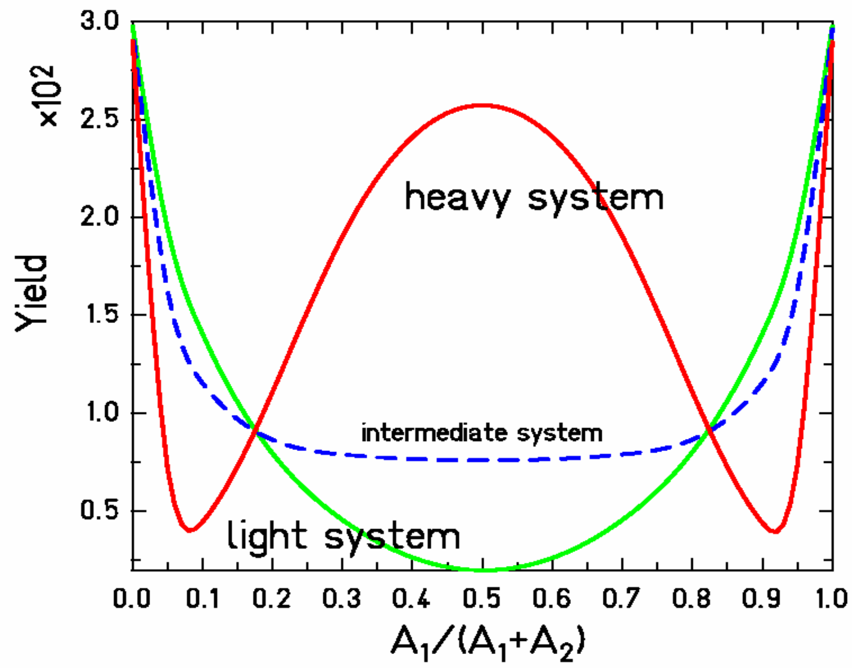
Fission involves more collective phenomena.

IMF emission in ABLA07

• All nuclei below the Businaro-Gallone maximum of the mass-asymmetry dependent barrier are taken into account in the evaporation process ⇒ transition between fission and evaporation picture.

• The barriers are given by the Bass nuclear potential.





Particle emission widths

Weisskopf-Ewing formalism

$$\Gamma_\nu(E_i) = \frac{2\cdot s_\nu + 1}{2\cdot\pi\cdot\rho(E_i)}\cdot\frac{2\cdot m_\nu}{\pi\cdot\hbar^2}\cdot\int_0^{E_i - S_\nu}\sigma_c(\varepsilon_\nu)\cdot\rho(E_f)\cdot(\varepsilon_\nu - B_\nu)\mathrm{d}E_f$$

- Barriers →
  - calculated with the Bass nuclear potential (deduced from fusion)
- Inverse cross section →
  - influence of the Coulomb barrier
  - energy-dependent inverse cross sections
  - level density with shell and pairing, including excitations of IMFs
  - tunnelling through the barrier (for light charged particles)
- Angular momentum →
  - change in angular momentum due to particle emission included

σ_{inv} in ABLA07

- Particle-decay width in Weisskopf-Ewing approach:

$$\Gamma_\nu(E_i, J_i) = \frac{2 \cdot s_\nu + 1}{2 \cdot \pi \cdot \rho(E_i, J_i)} \cdot \frac{2 \cdot m_\nu}{\pi \cdot \hbar^2} \cdot \int_0^{E_i - S_\nu} \sigma_{inv}(\varepsilon_\nu) \cdot \rho(E_f, J_f) \cdot (\varepsilon_\nu - B_\nu) \mathrm{d}E_f$$

$$\varepsilon_\nu = E_i - S_\nu - E_f$$

- Inverse cross section:

  - Ingoing-wave boundary condition
  - Optical model – $\sum_l (2 \cdot l + 1) \cdot \pi \cdot \lambda\!\!\!^{-2} \cdot T_\nu^l(\varepsilon_\nu)$
  - Parameterization (e.g. NASA)

Ingoing-wave boundary condition

- Analogous to the diffraction of light by a totally absorbing disc or sphere, once the barrier is overcome

$$\sigma_{inv}(\varepsilon_\nu) = \pi \cdot R^2 \cdot \left(1 - \frac{B_\nu}{\varepsilon_\nu}\right), \qquad R = R_{geom} + R_\lambda$$

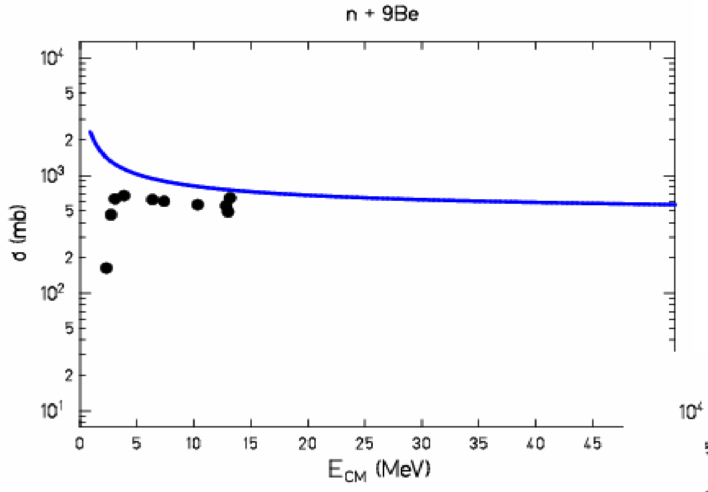
$$R_{geom} = 1.16\, fm \cdot \left(A_1^{1/3} + A_2^{1/3}\right), \quad \text{and} \quad R_\lambda = \sqrt{\frac{\hbar^2}{2 \cdot \mu \cdot \varepsilon_\nu}}$$

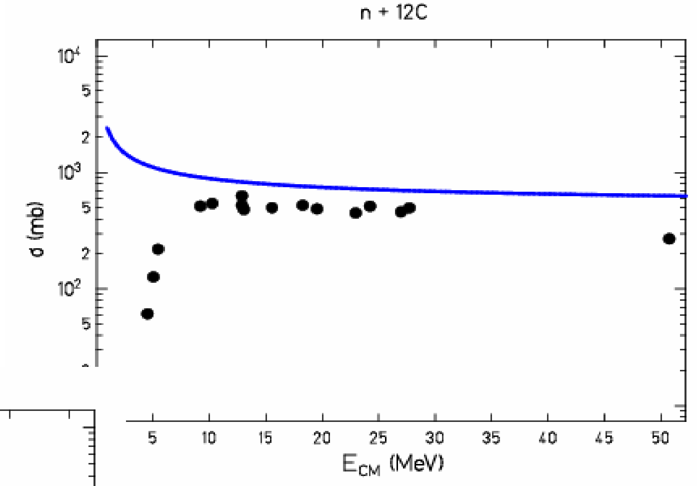
B_ν - Bass model for fusion of two spherical nuclei.

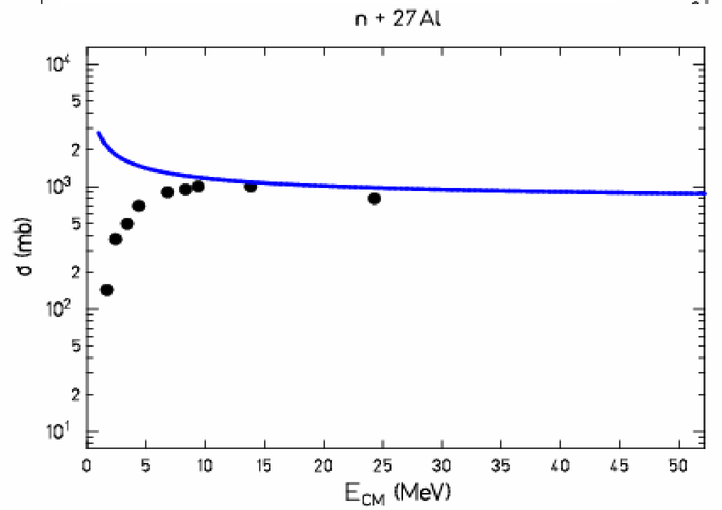
Ingoing-wave boundary condition –> full absorption (inverse of complete fusion).

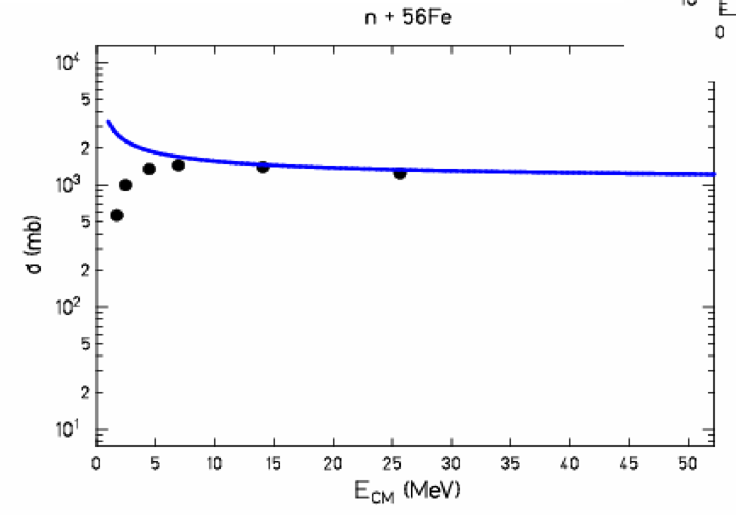
(Enhanced emission for protons, alphas -> due to missing preformation-factor for IMFs? decay of unstable residues?)

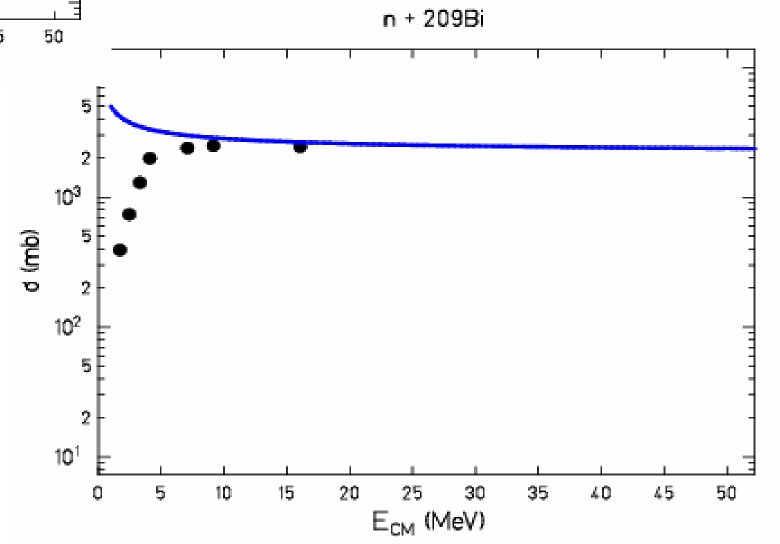
Comparison with data (neutrons)



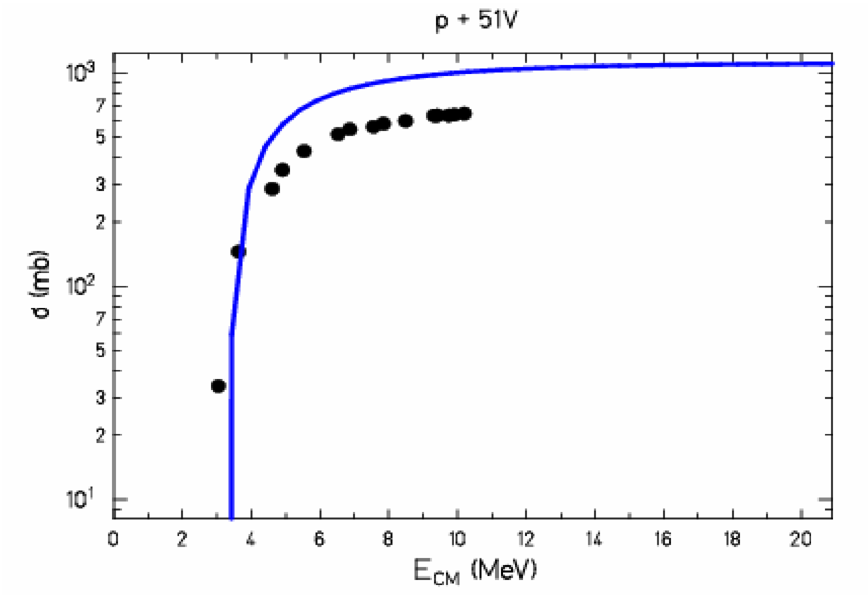


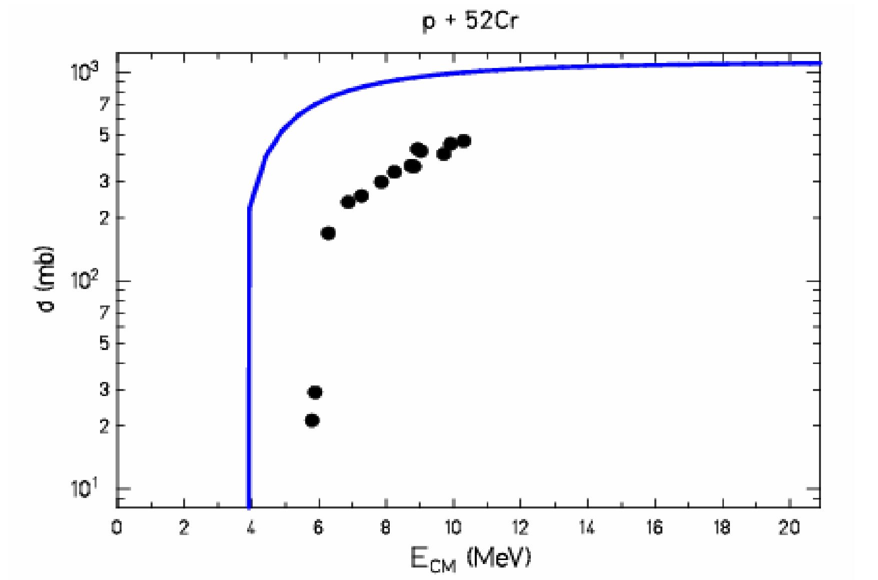


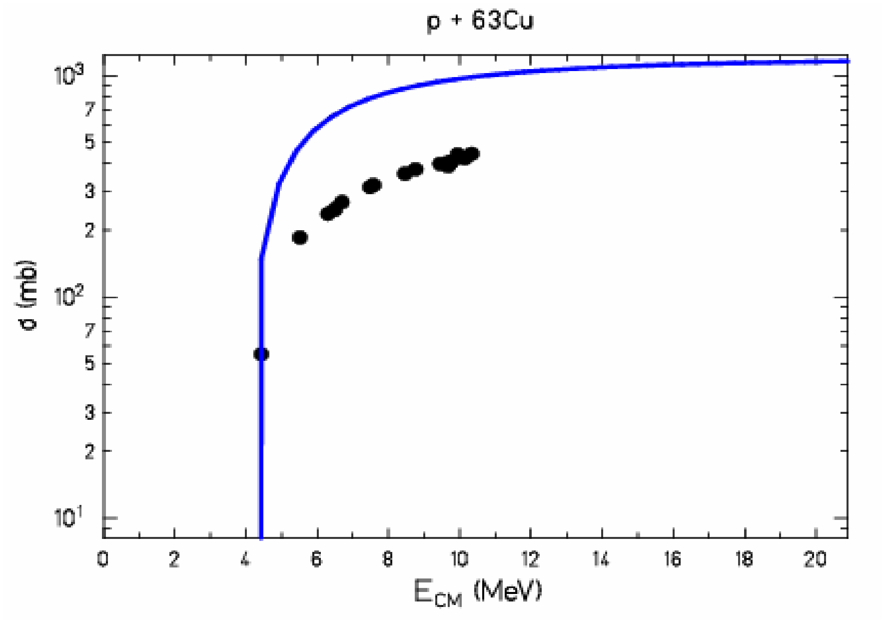


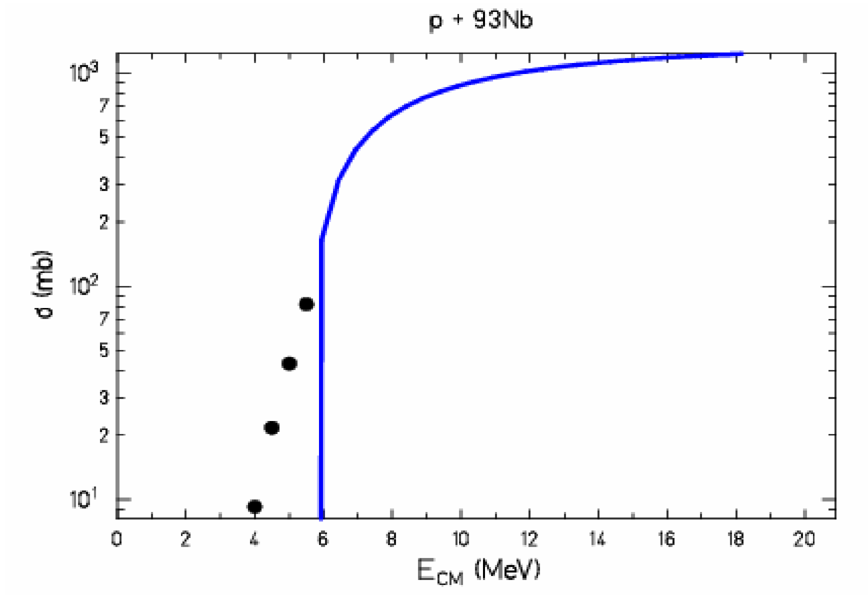


Comparison with data (protons)

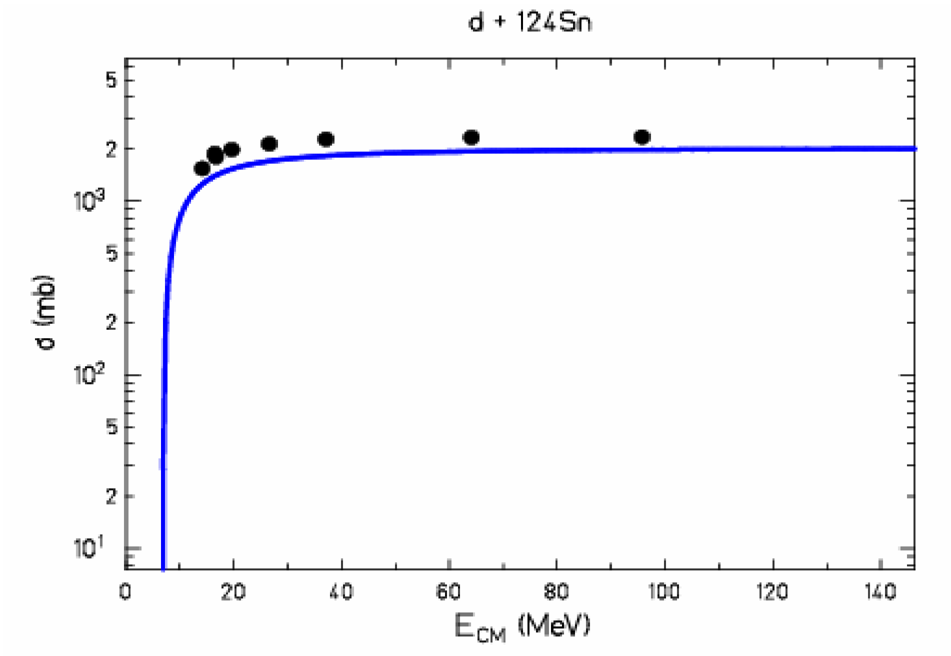


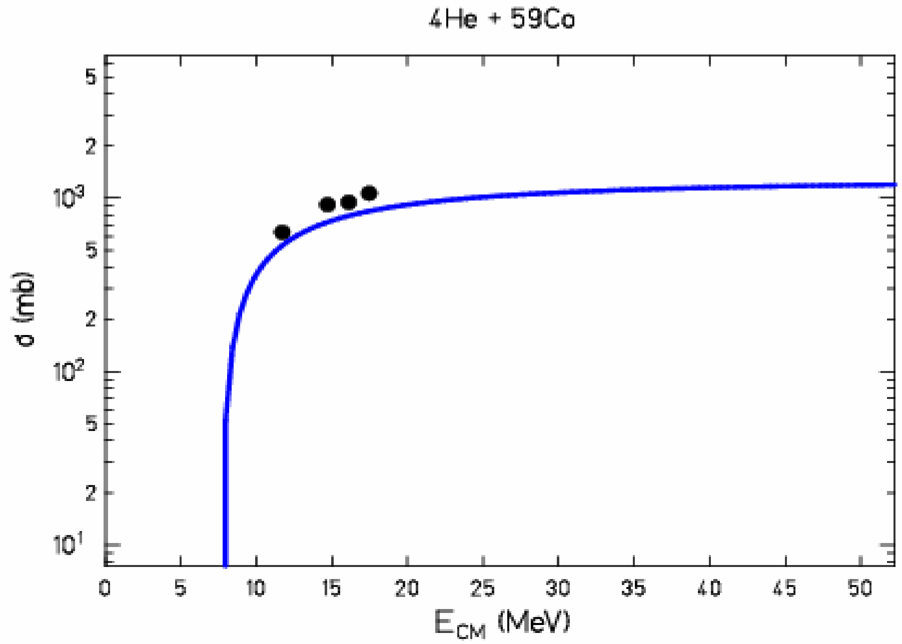






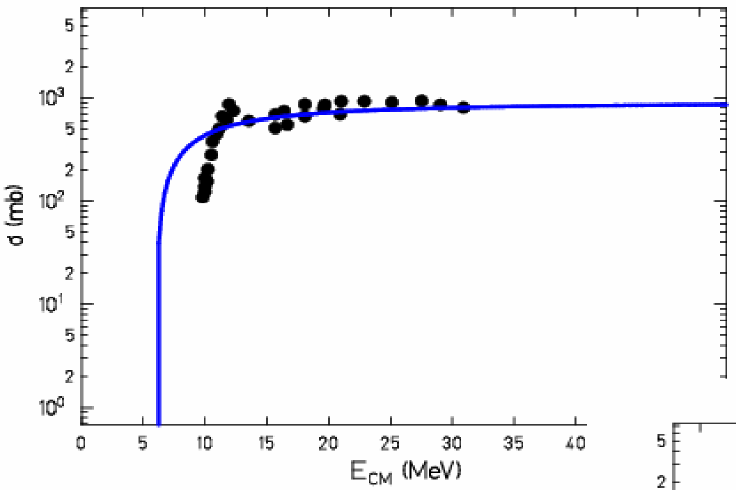
Comparison with data (deuterons, ^{4}He)



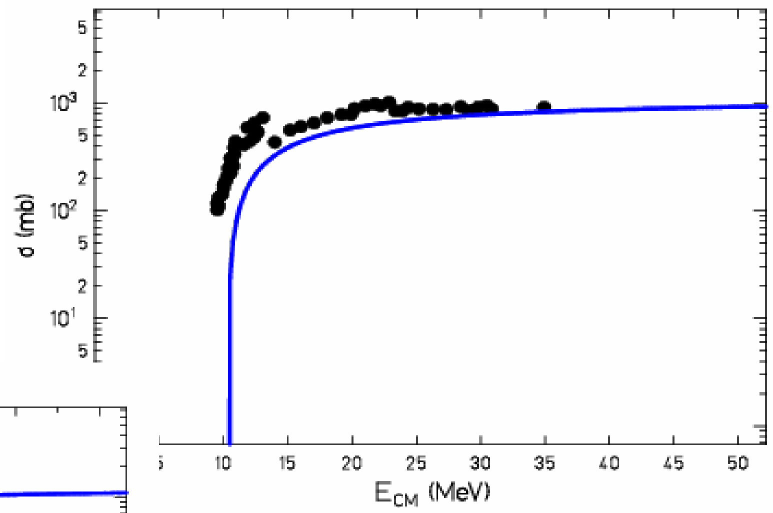


Comparison with data (carbon, oxygen)

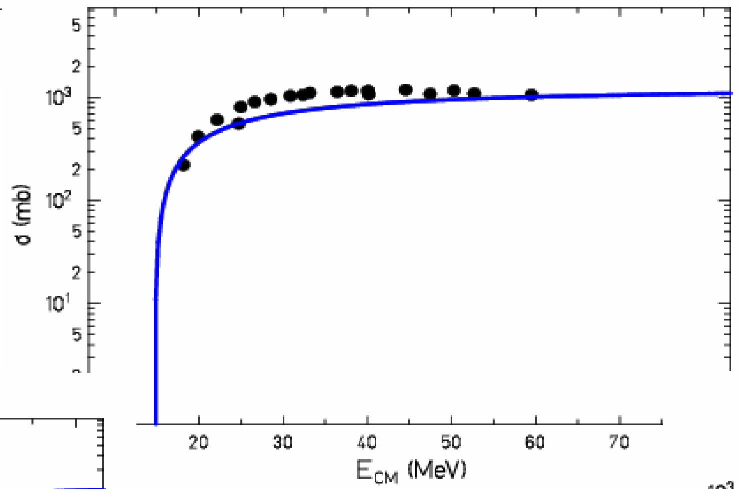
12C+12C fusion cross section



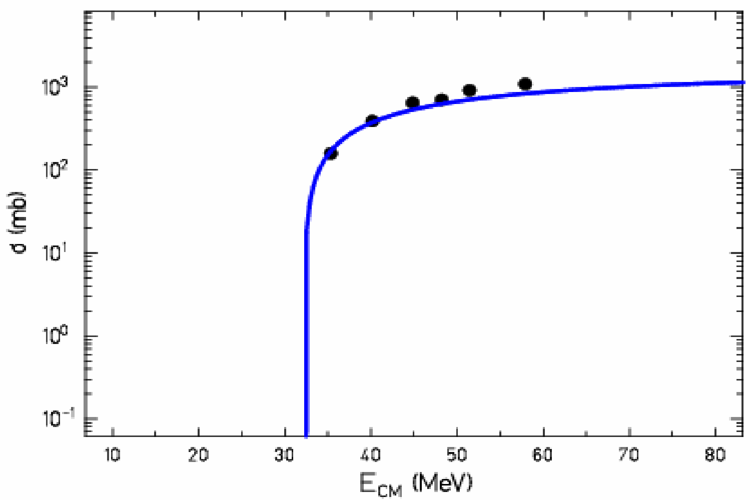
16O+16O fusion cross section



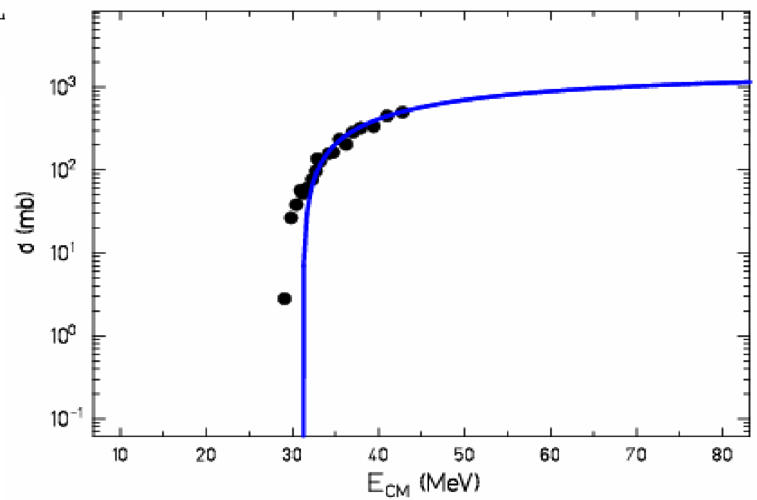
16O+26Mg fusion cross section



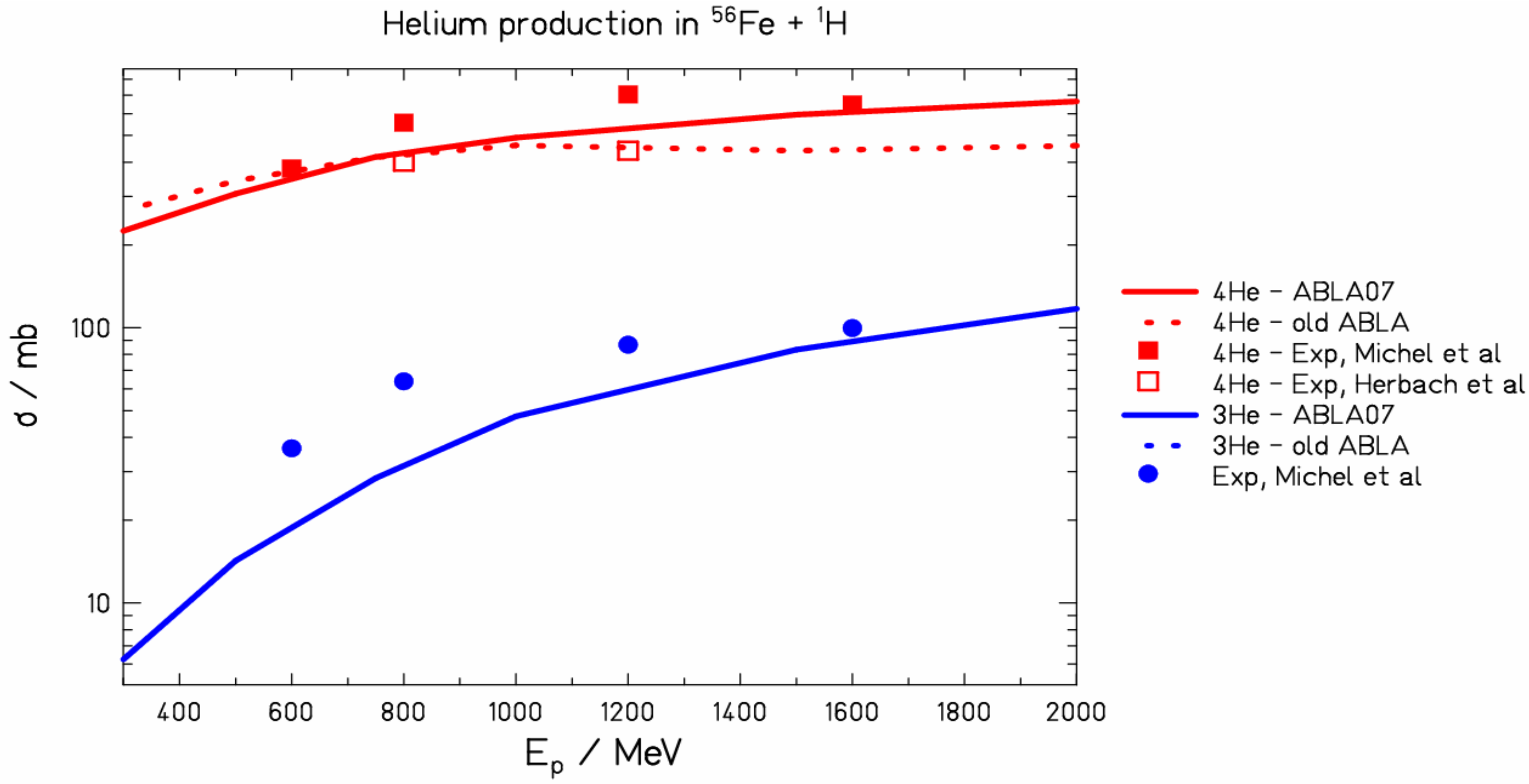
16O+65Cu fusion cross section



18O+58Ni fusion cross section

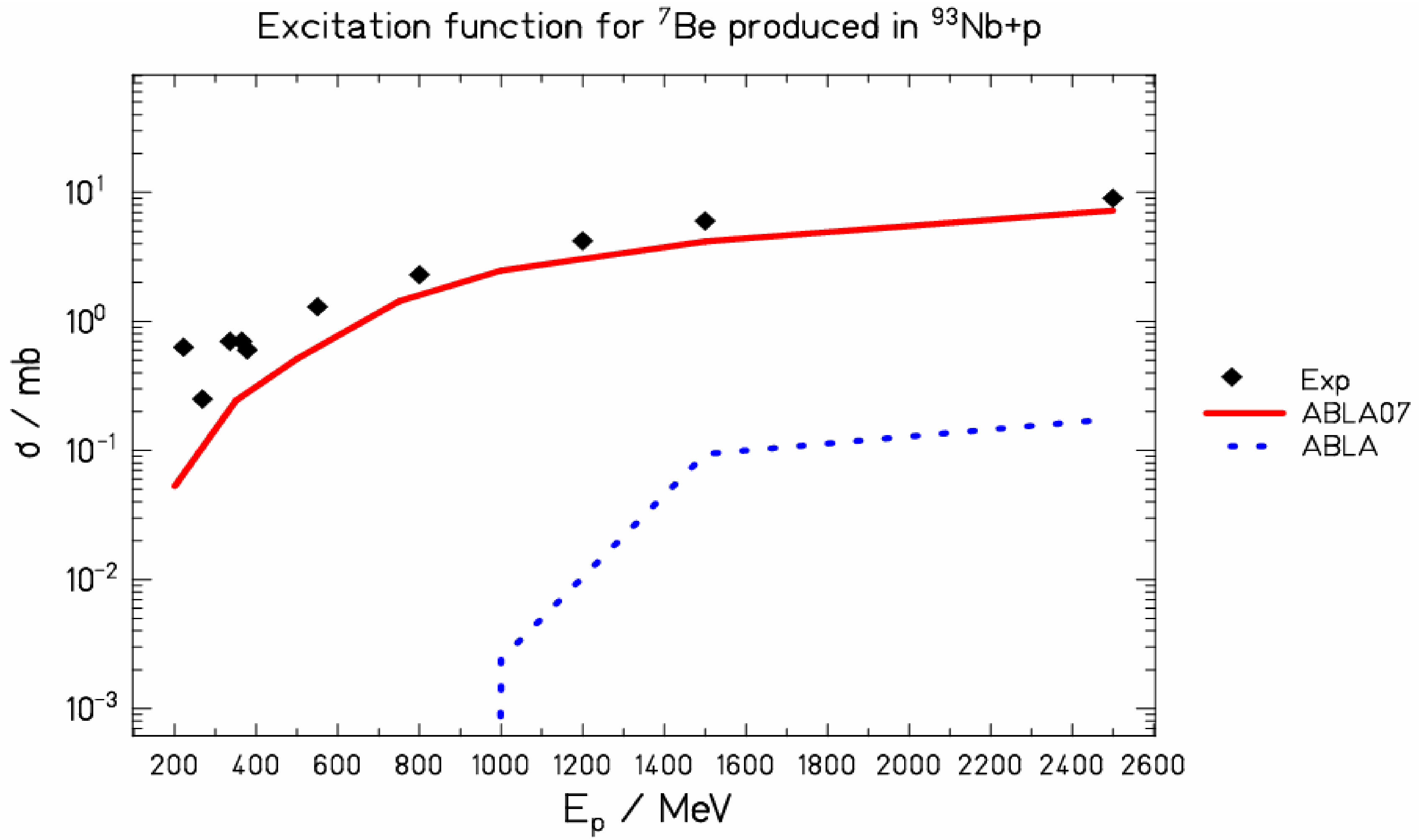


Production of helium

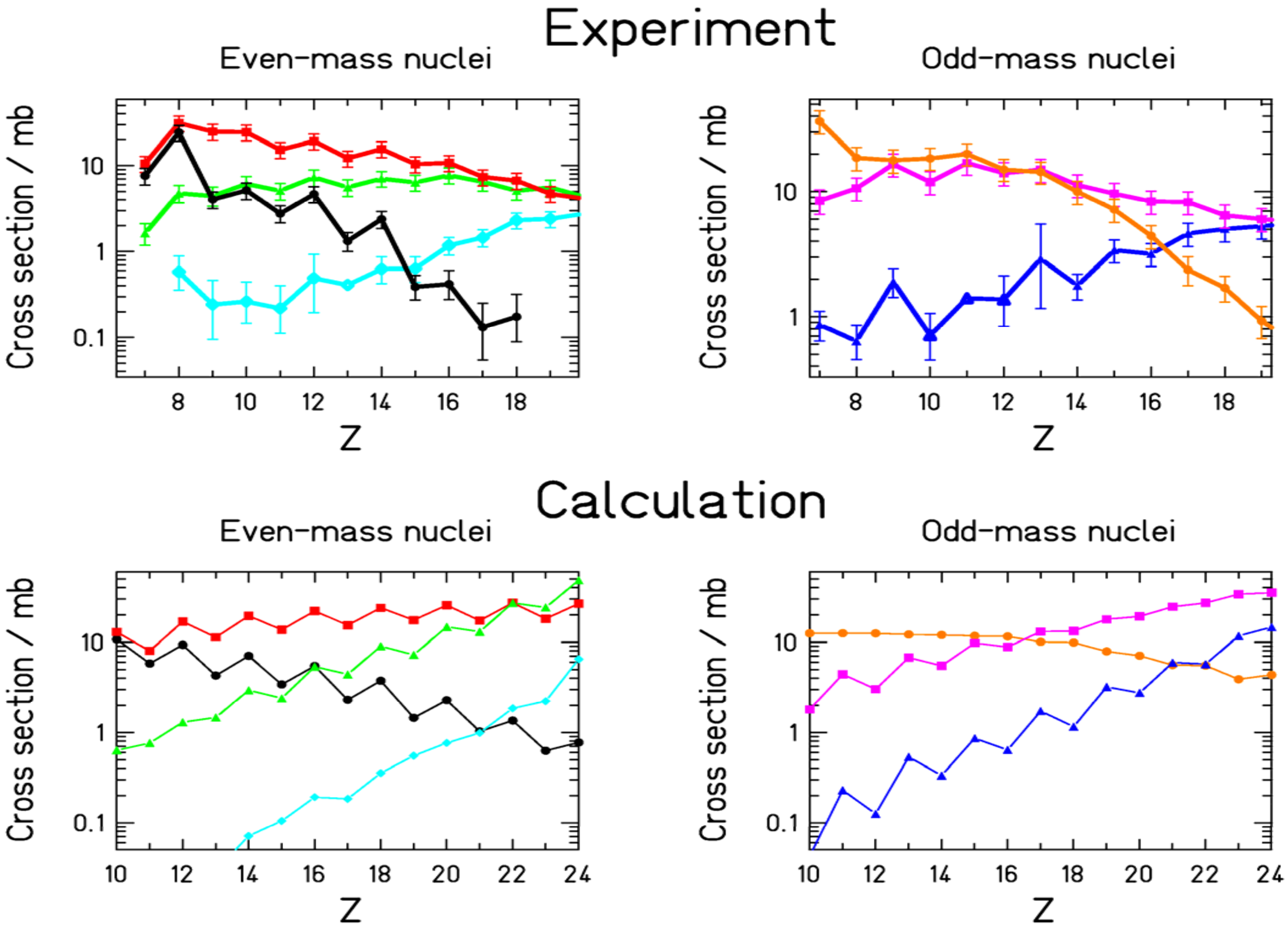


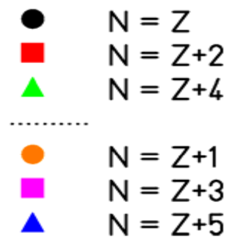
Data: R. Michel et al., NIM B 103,
C. M. Herbach et al., Proc SARE-5 meeting, 2000

Production of ^{7}Be



Odd-even structure in yields of light nuclei



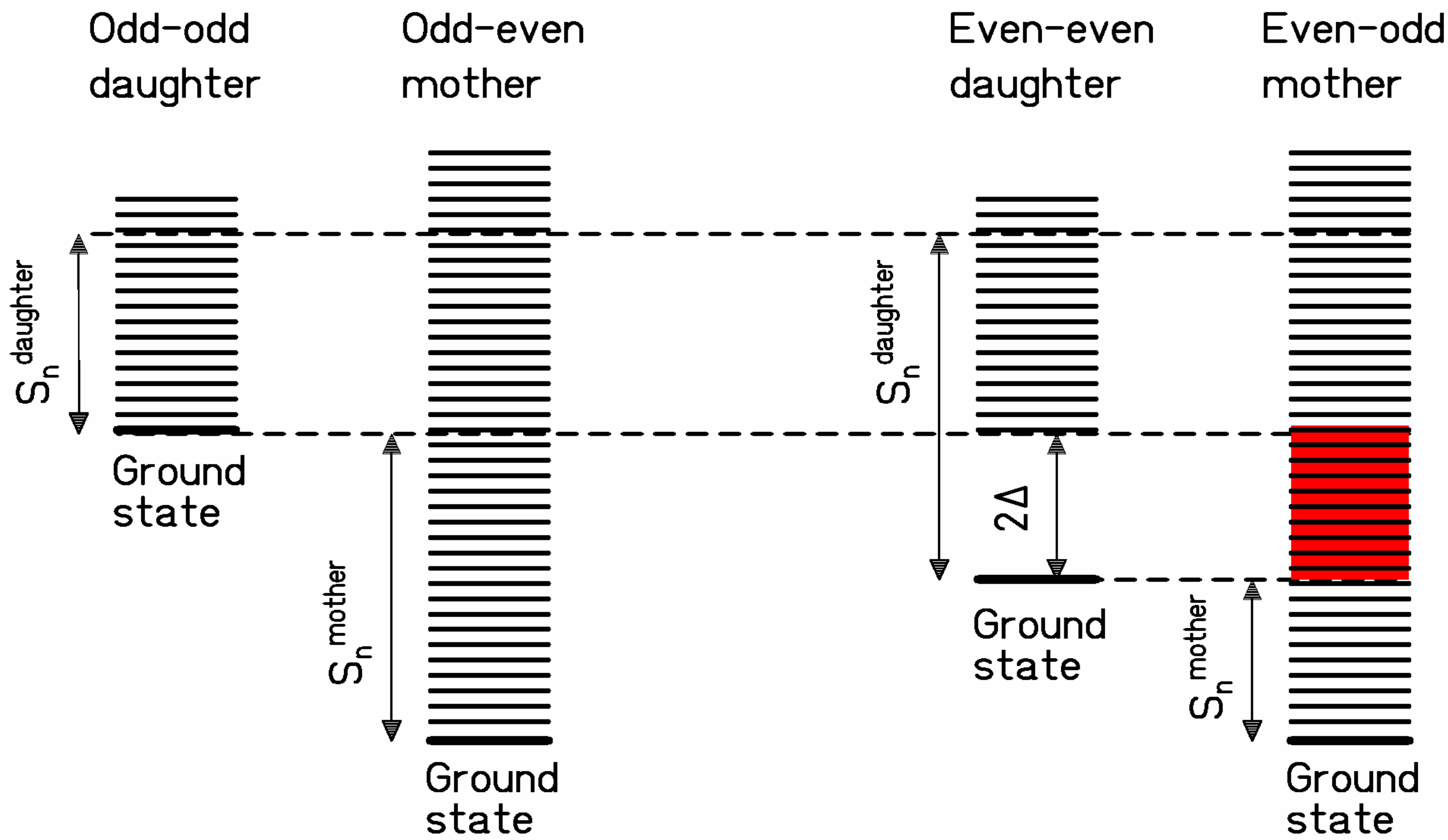


^{238}U+Ti

1 A GeV

M.V. Ricciardi

Detailed consideration on particle-gamma competition needed



Summary: Evaporation in ABLA07

- Emission of nucleons, LCPs, IMFs, continuous coverage up to Businaro-Gallone maximum
- Particle decay widths and energy spectra:
  - energy-dependent inverse cross sections based on nuclear potential, ingoing-wave boundary condition
  - tunneling
  - thermal expansion of emitting source
  - angular momentum in particle emission (moment expansion, analytical)
- Gamma emission at energies close to the particle threshold (Ignatyuk, 2002)

Binary decay

2. Fission

Fission-decay width – statistical basis

– Bohr-Wheeler approach (transition-state model)

– Fission barriers from FRLDM (Sierk) + g.s. shell effects, angular-momentum dependent

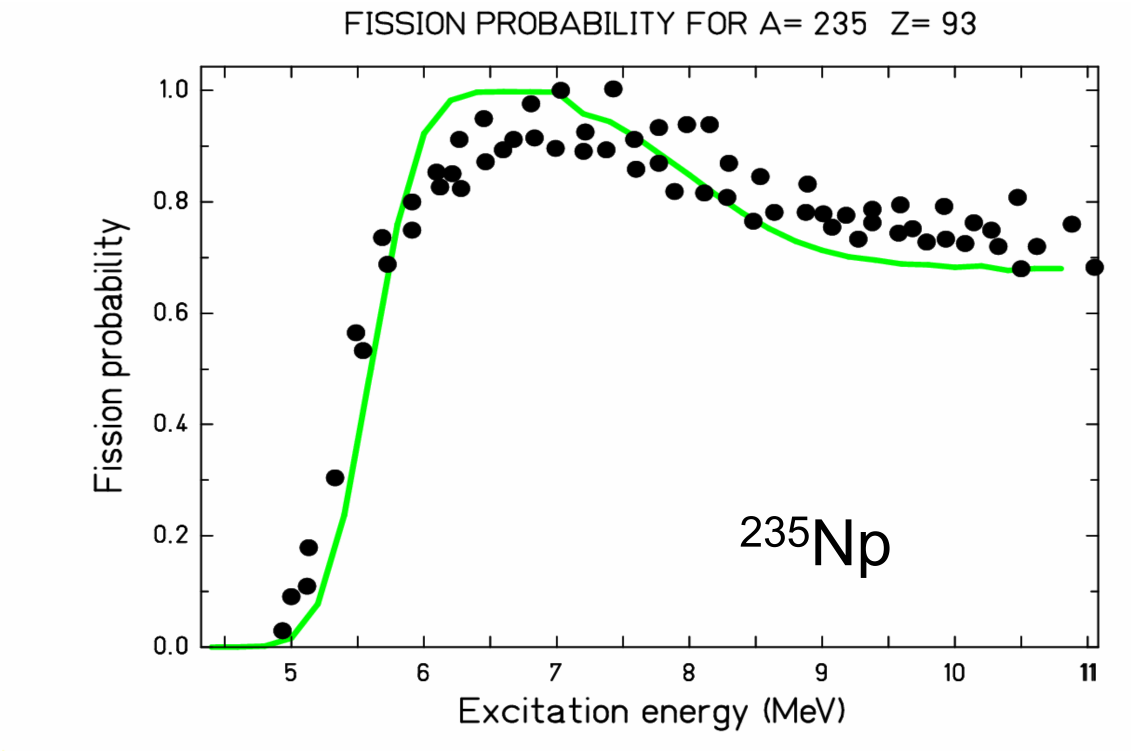
– Macroscopic level density from Ignatyuk (a_f/a_n)

– Shell effects, pairing in level density from Ignatyuk

– Collective enhancement, energy dependent (A. R. Junghans)

Fission cross sections

Low-energy fission → influence of double-humped structure in fission barriers of actinides and symmetry classes at saddle



● exp data - Gavron et al., PRC13

—— ABLA07

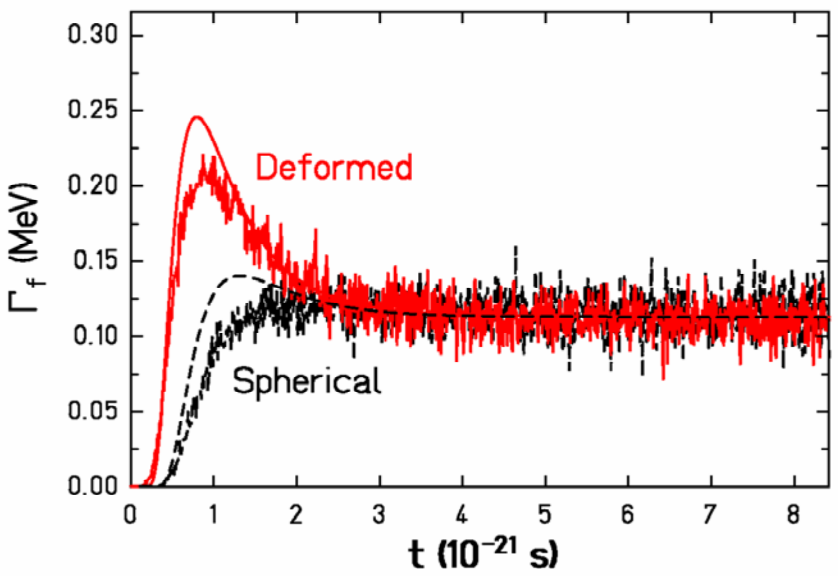
Transient effect

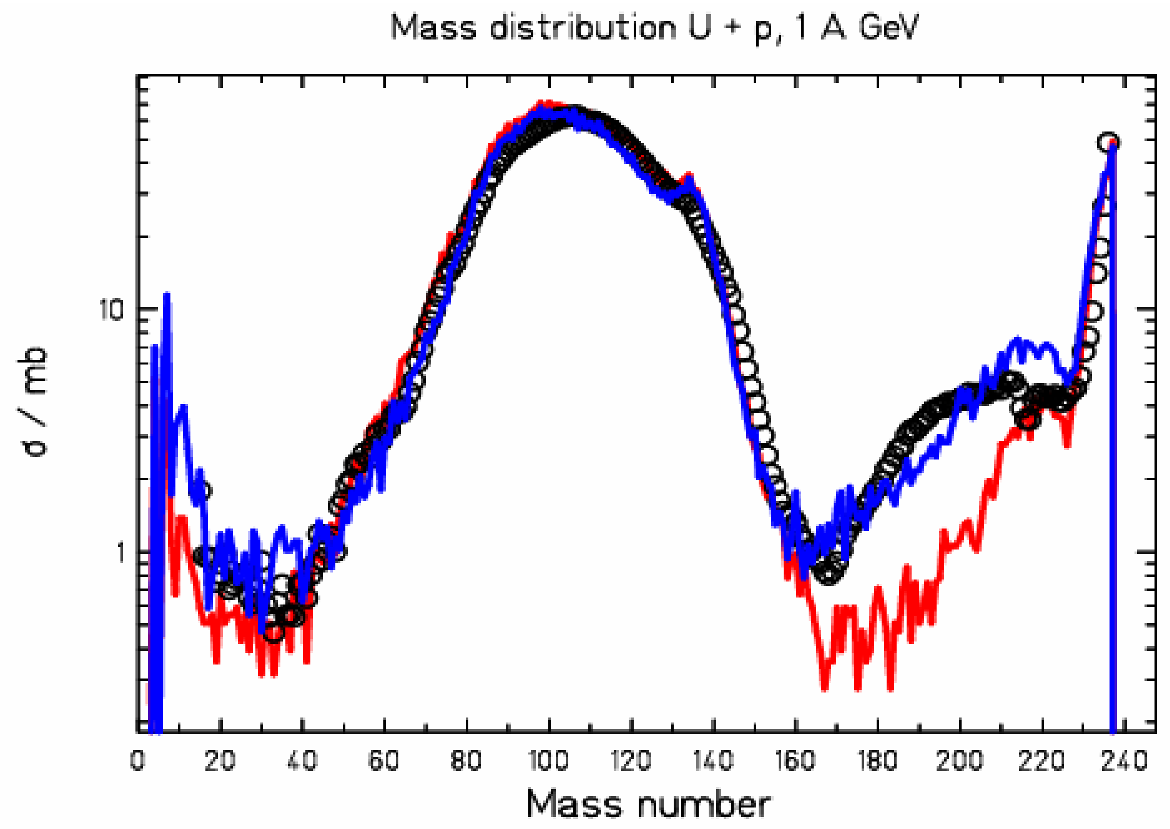
considered by approximated solution of the Fokker-Planck equation

B. Jurado et al, Nucl. Phys. A 747 (2005) 14

Initial deformation considered
(e.g. spallation of ^{238}U)

Time-dependent Γ_f

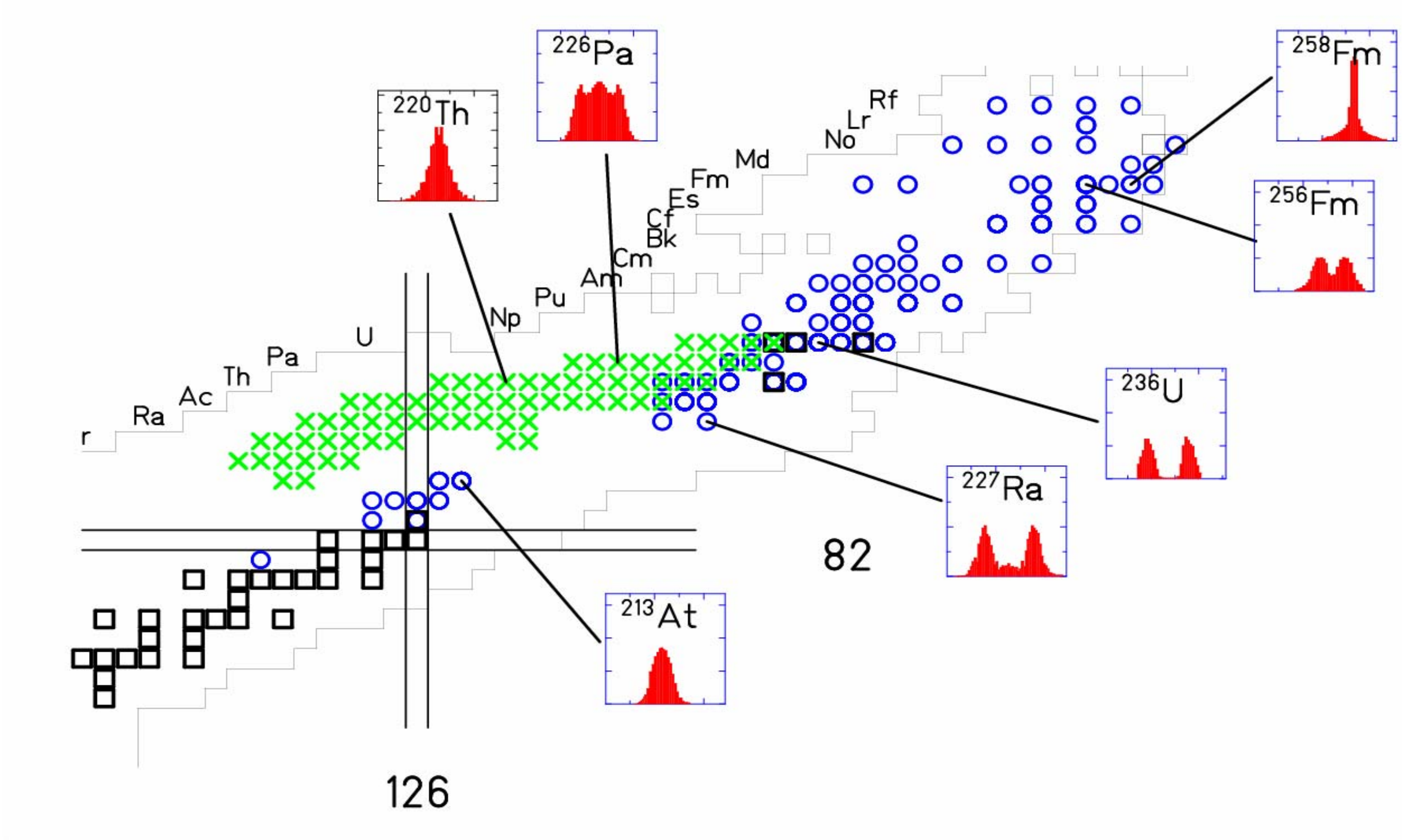




- Dynamical description

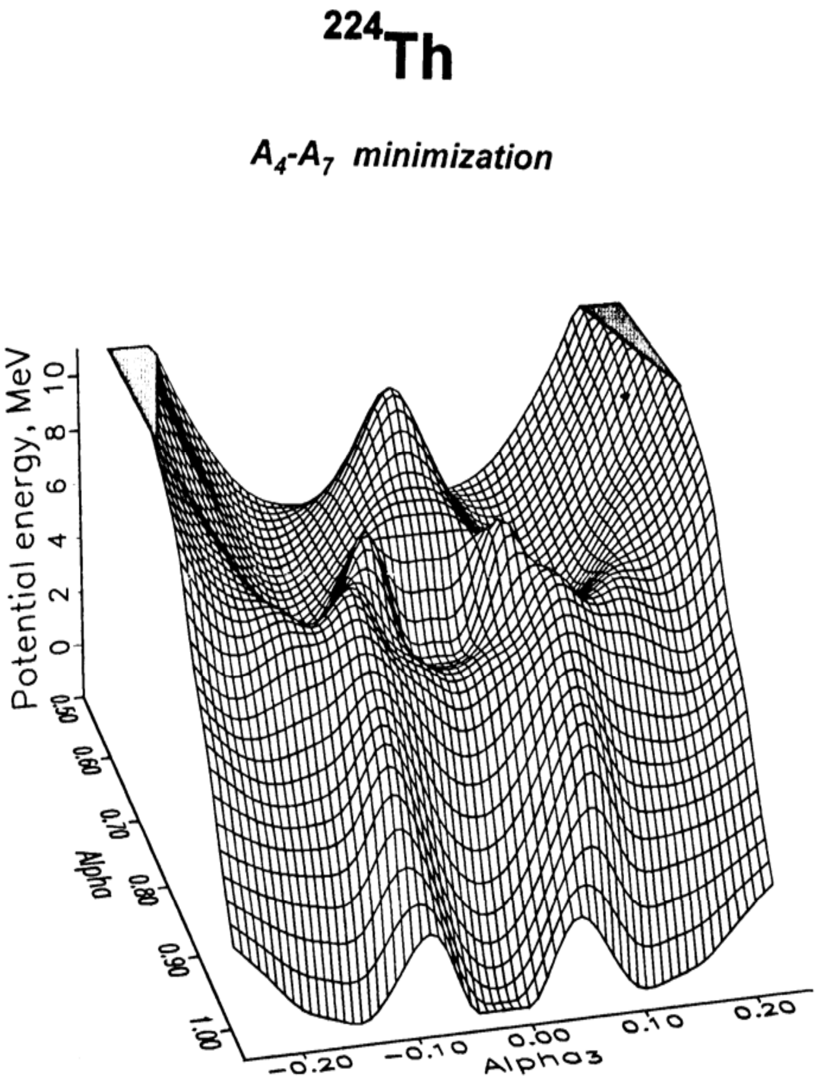
- Statistical description

How to model the fission yields?

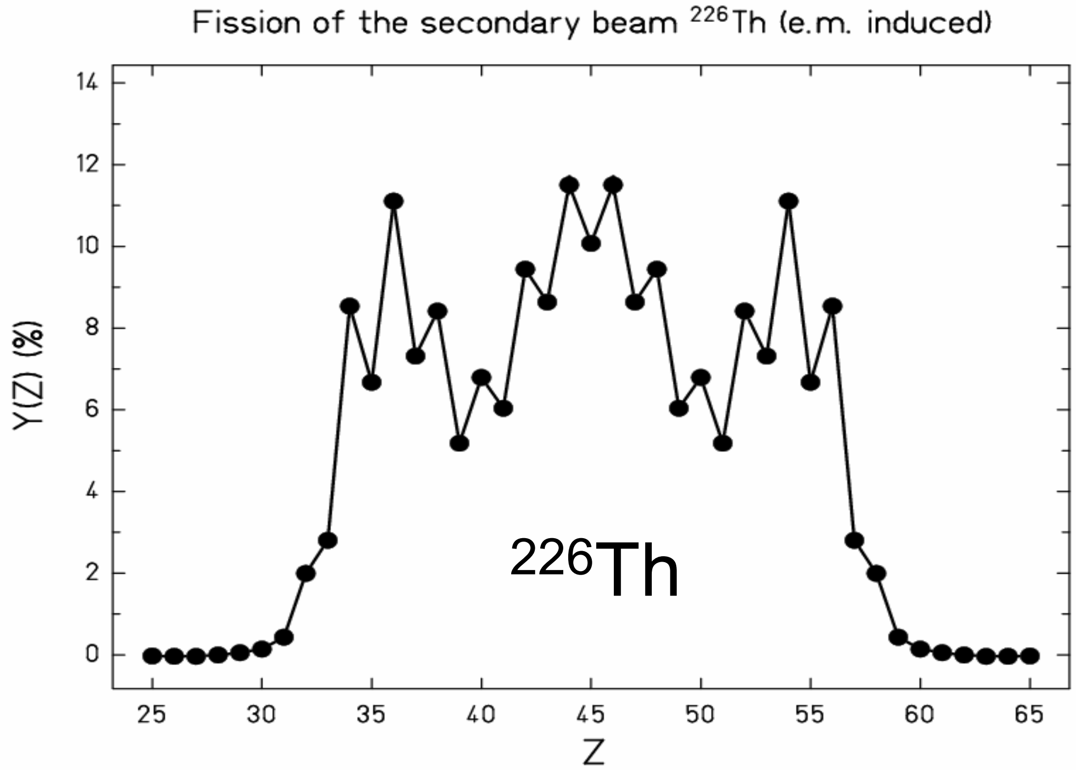


Complexity of multi-modal fission

Fission valleys and fission channels

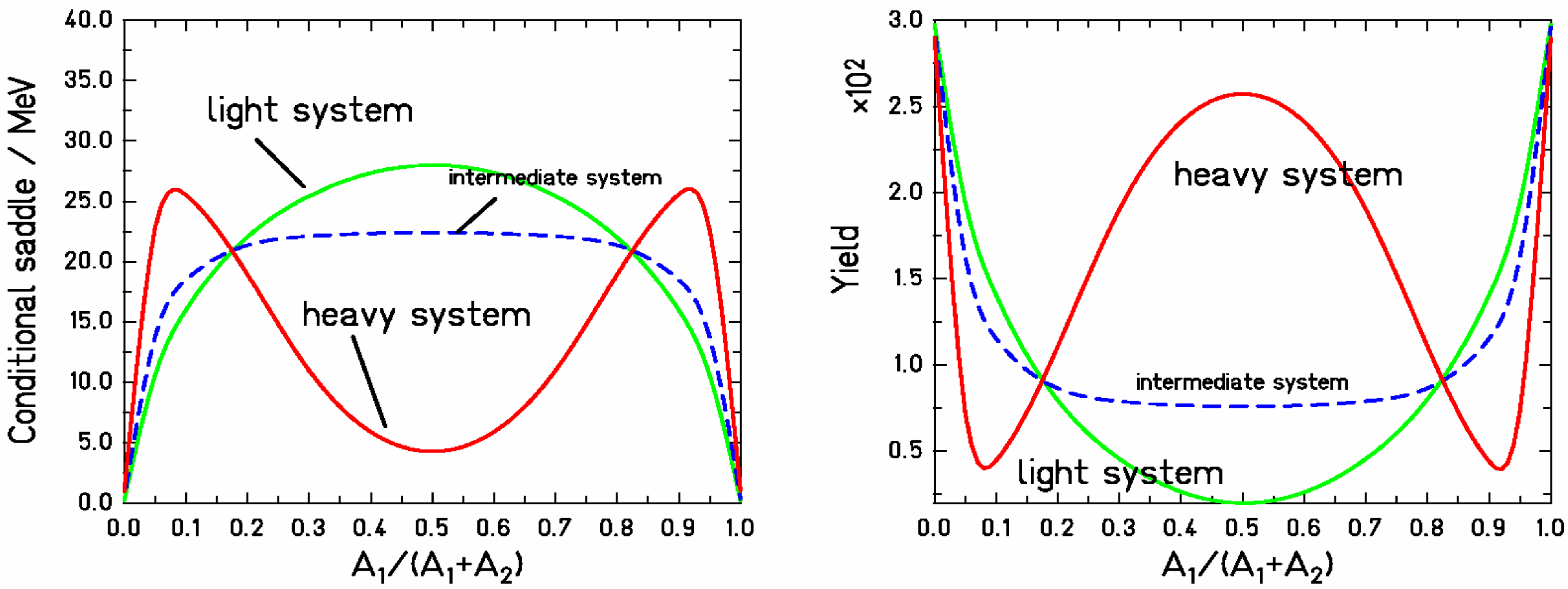


Measured Z yields



Shells of fragments already decisive at outer saddle?!
(Two-centre shell model calculations. Mosel, Schmitt, ...)

Curvature of macroscopic potential and width of mass distribution are related in a statistical approach

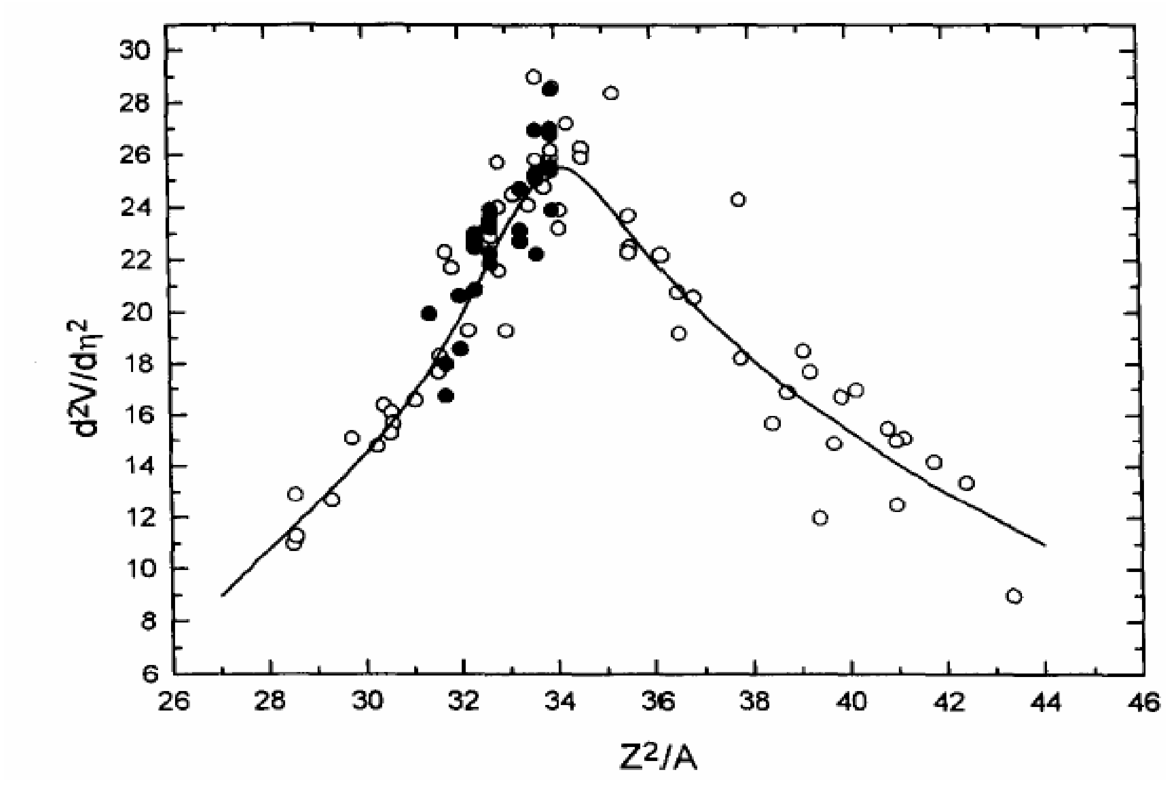


$$d^2V/d\eta^2 \sim T/(\sigma_A^2)$$

Mulgin et al. NPA 640 (1998) 375

Macroscopic potential

Experiment: In cases when shell effects can be disregarded (high E*), the fission-fragment mass distribution of heavy systems is Gaussian.



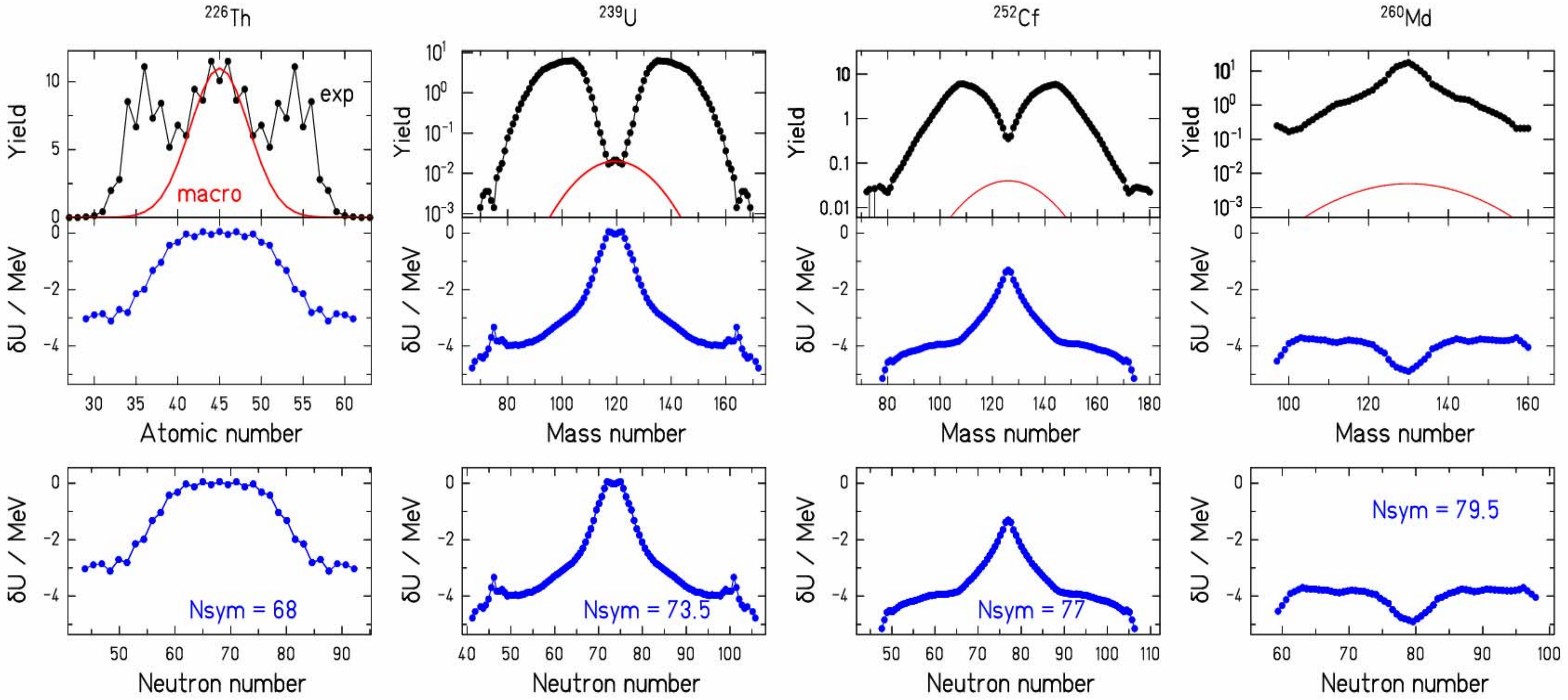
Systematics of second derivative of potential *V* in mass asymmetry *η* deduced from measured width σ_A of fission-fragment mass distributions.

$$d^2V/d\eta^2 \sim T/(\sigma_A^2)$$

← Mulgin et al. NPA 640 (1998) 375

ABLA07 uses this empirical parameterization
for the macroscopic part of a macro-microscopic approach.

Shell effects deduced from fragment yields



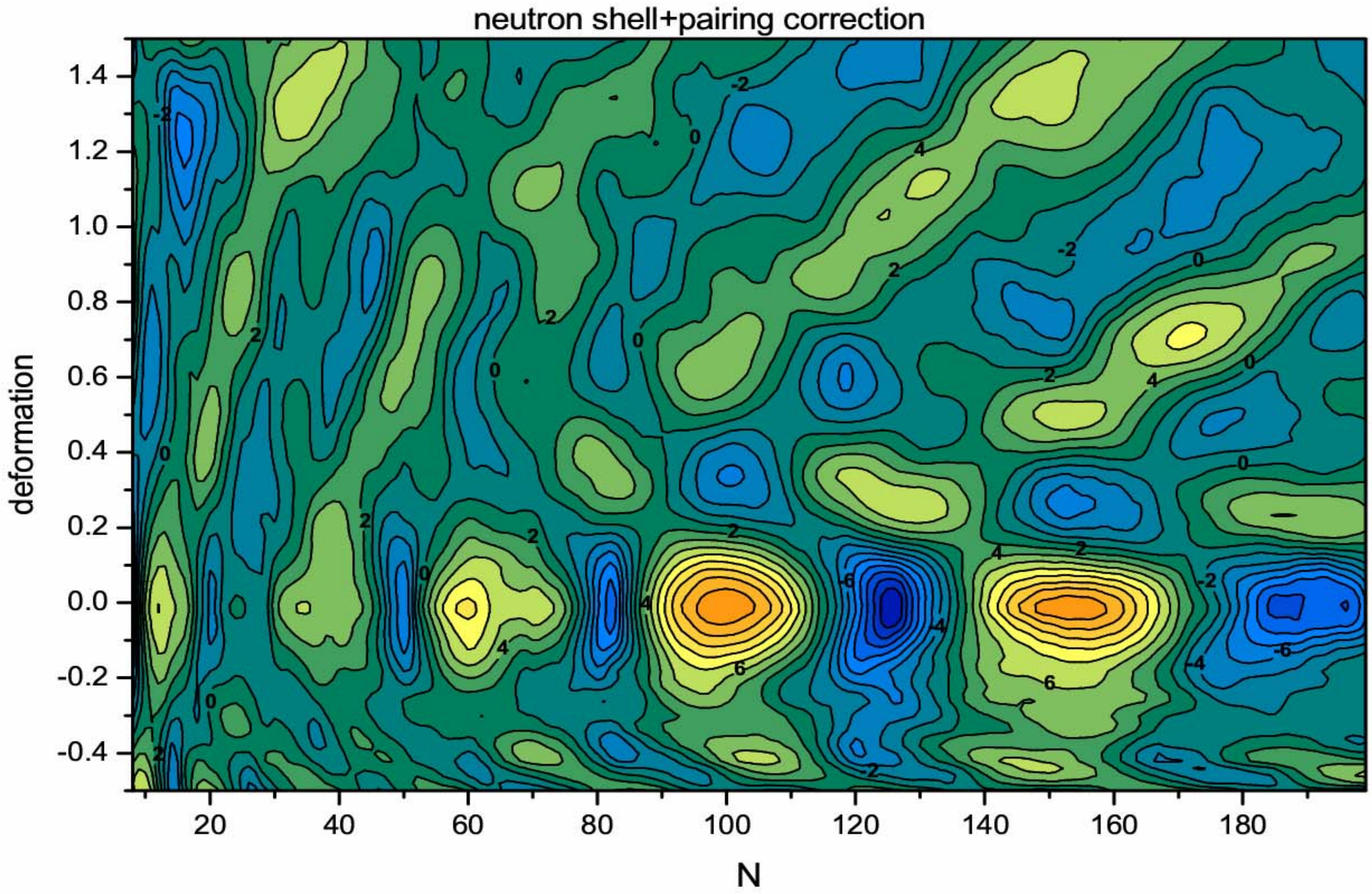
$$\frac{Y_{\exp}}{Y_{\mathrm{macro}}} = \exp\left(-\frac{\delta U}{T_{eff}}\right)$$

Idea introduced by Itkis et al., Sov. J. Nucl. Phys. 43 (1986) 719

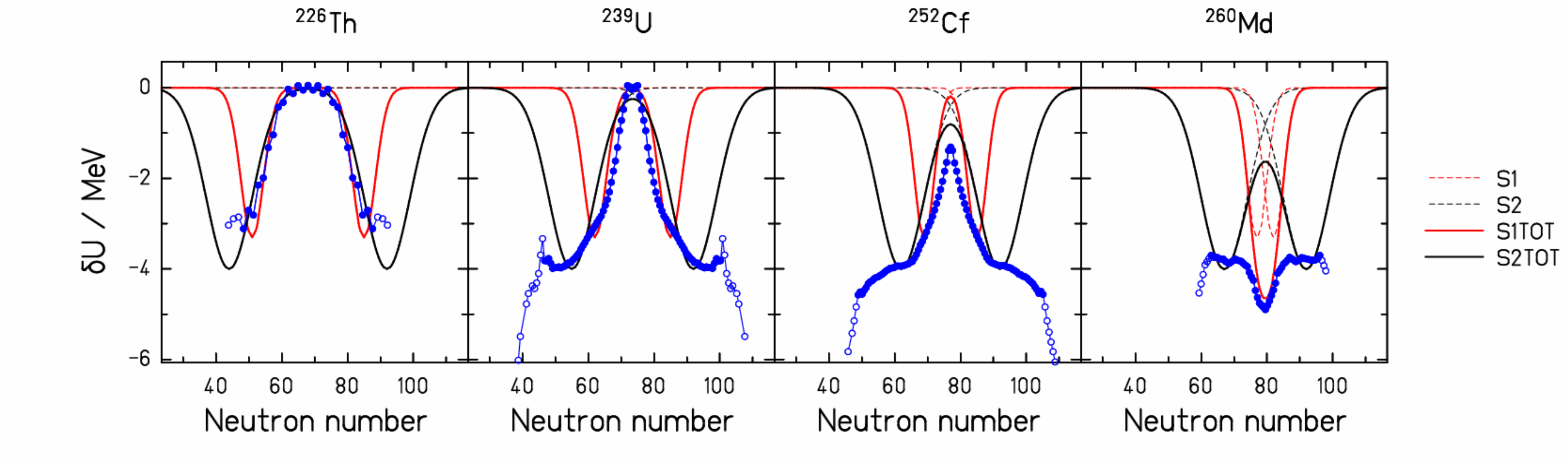
Enhanced yields attributed to shell effects.

Shells in fragments

A. Karpov, 2007



Shell effects attributed to shells in fragments



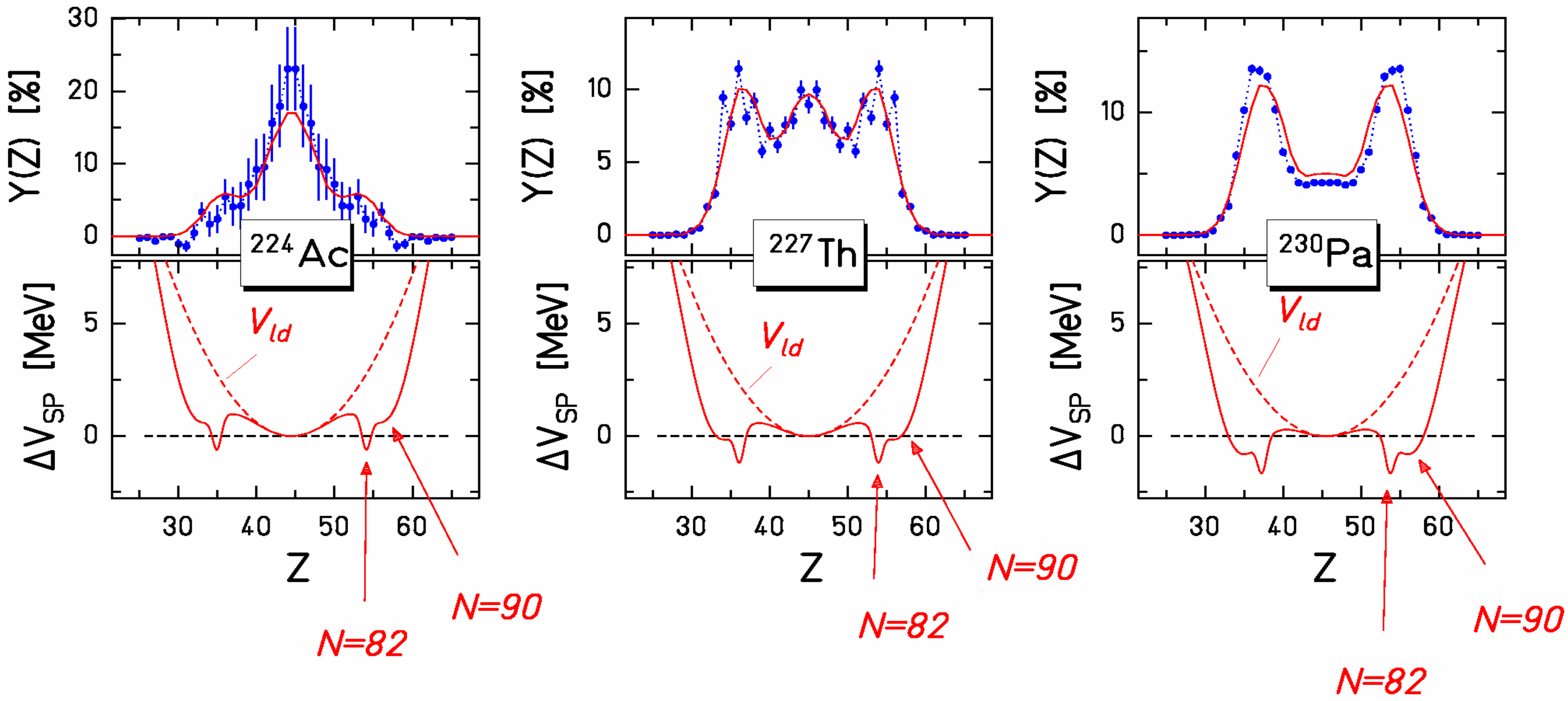
Schematic: only two shells: N = 82 and N = 92

Fission-fragment yields are given by number of levels above the mass-asymmetric potential.

Potential is composed of macroscopic part (CN property) and microscopic part (fragment property).

Powerful separability principle! **(arXiv nucl-ex/0711.3967)**

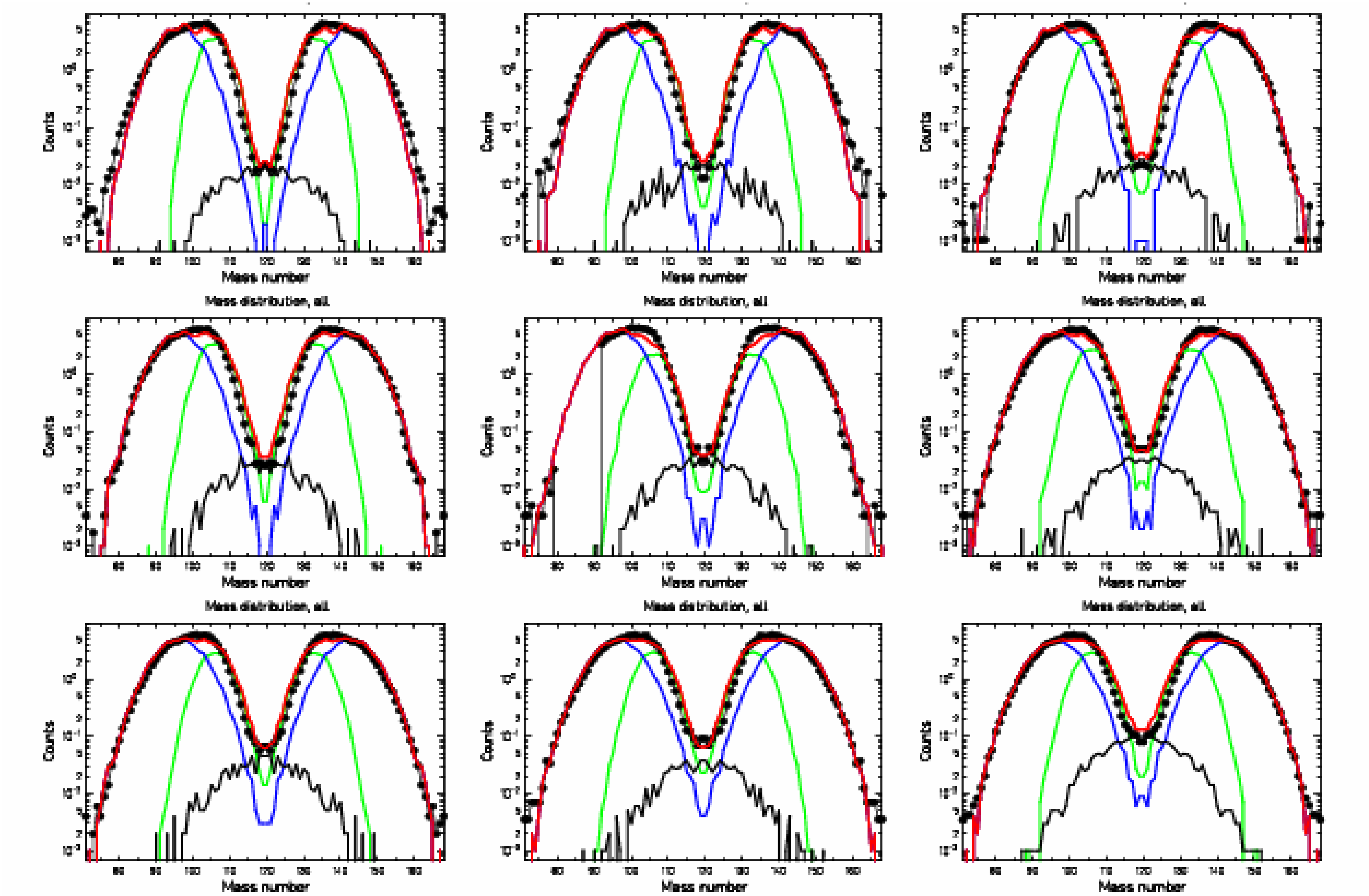
Application: Transition from single-humped to double-humped distributions



$N_{CN}/2 = 67.5$ $N_{CN}/2 = 68.5$ $N_{CN}/2 = 69.5$

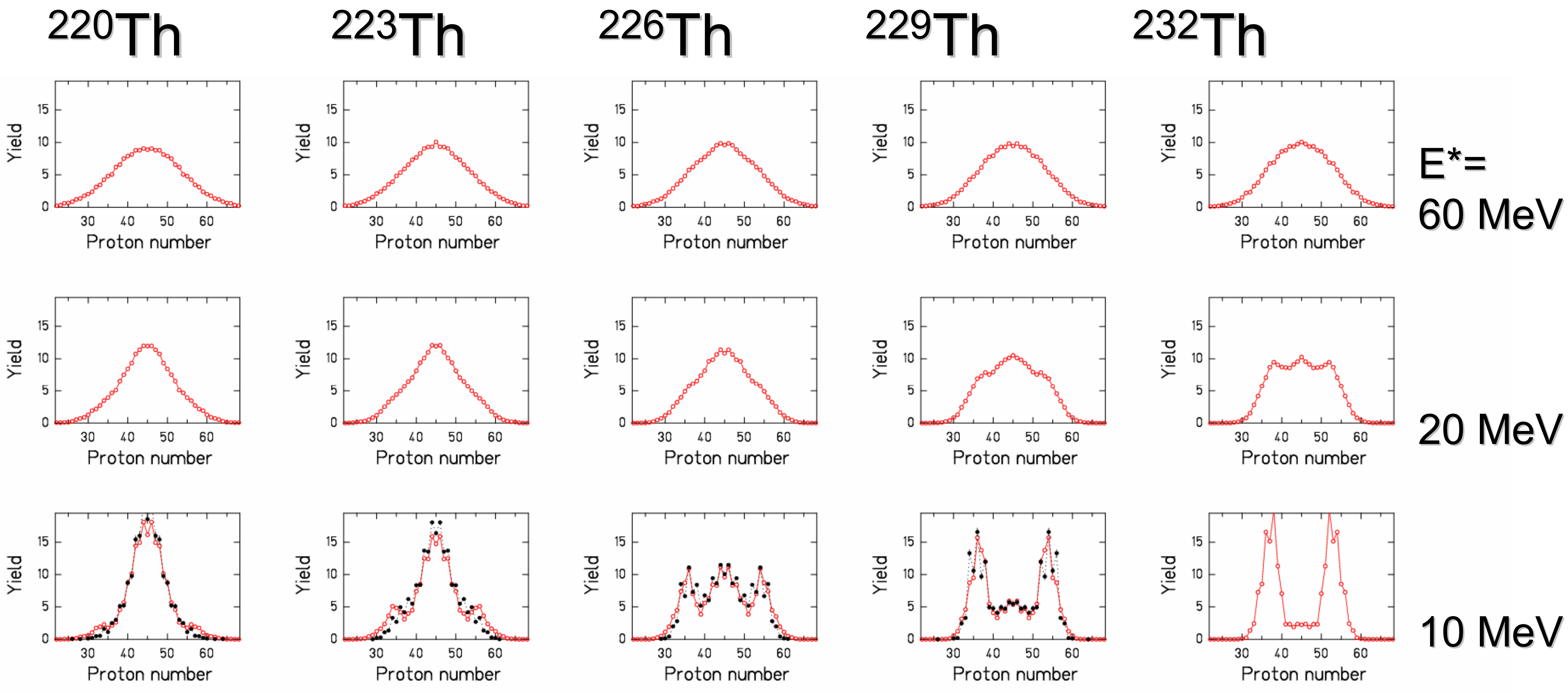
Reason: Moving position of symmetry in neutron number

Comparison with mass distributions
$^{238}U + n$ (1.7 ... 5.5 MeV)



Data: F. Vives et al. NPA 662 (2000) 63

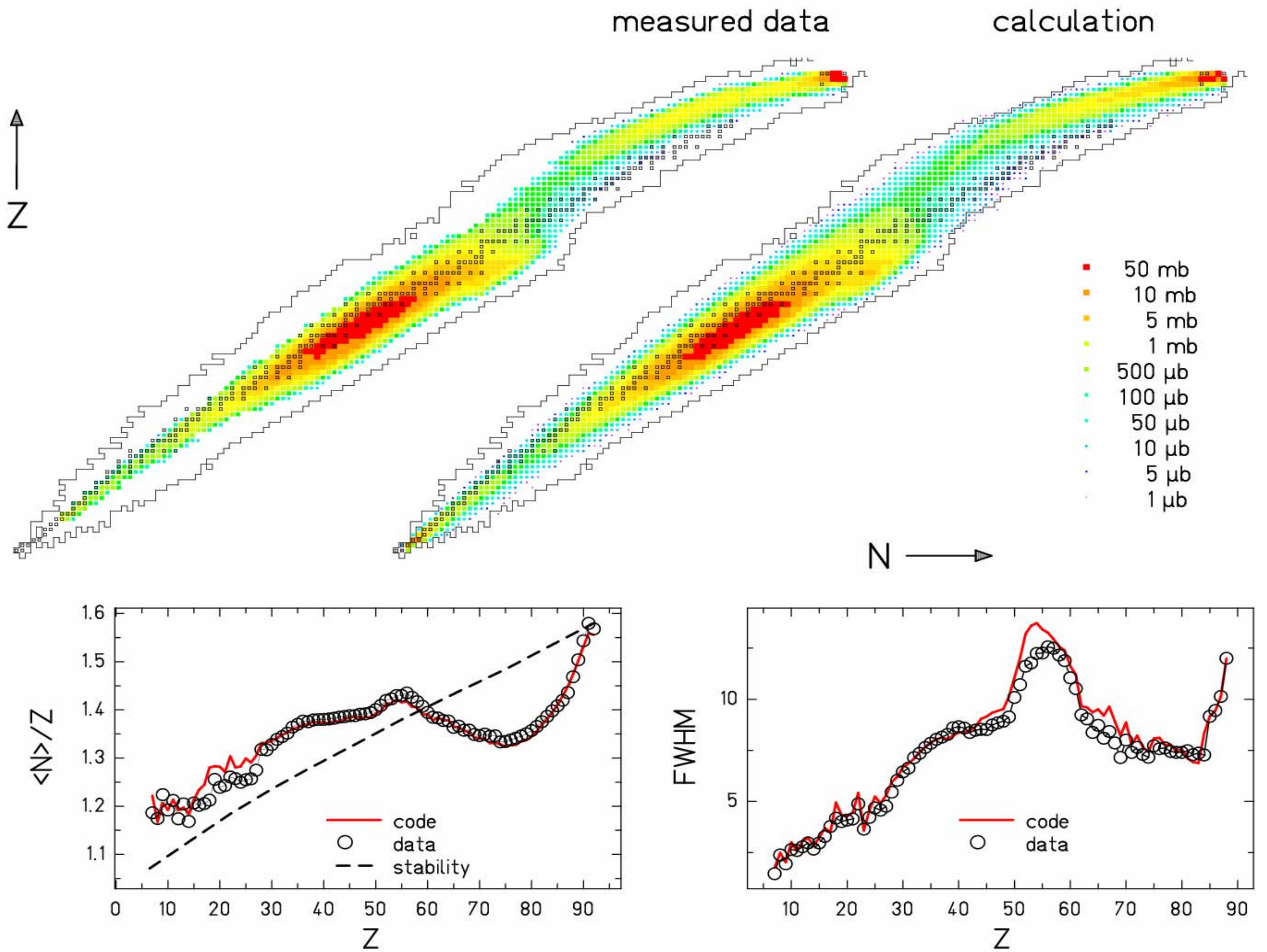
Multimodal fission around ^{226}Th



Black: experimental data (GSI experiment)
Red: model calculations (N=82, Z=50, N=92 shells)

Possible fissionning systems in spallation of ^{238}U!

Spallation ^{238}U (1 A GeV) + ^{1}H

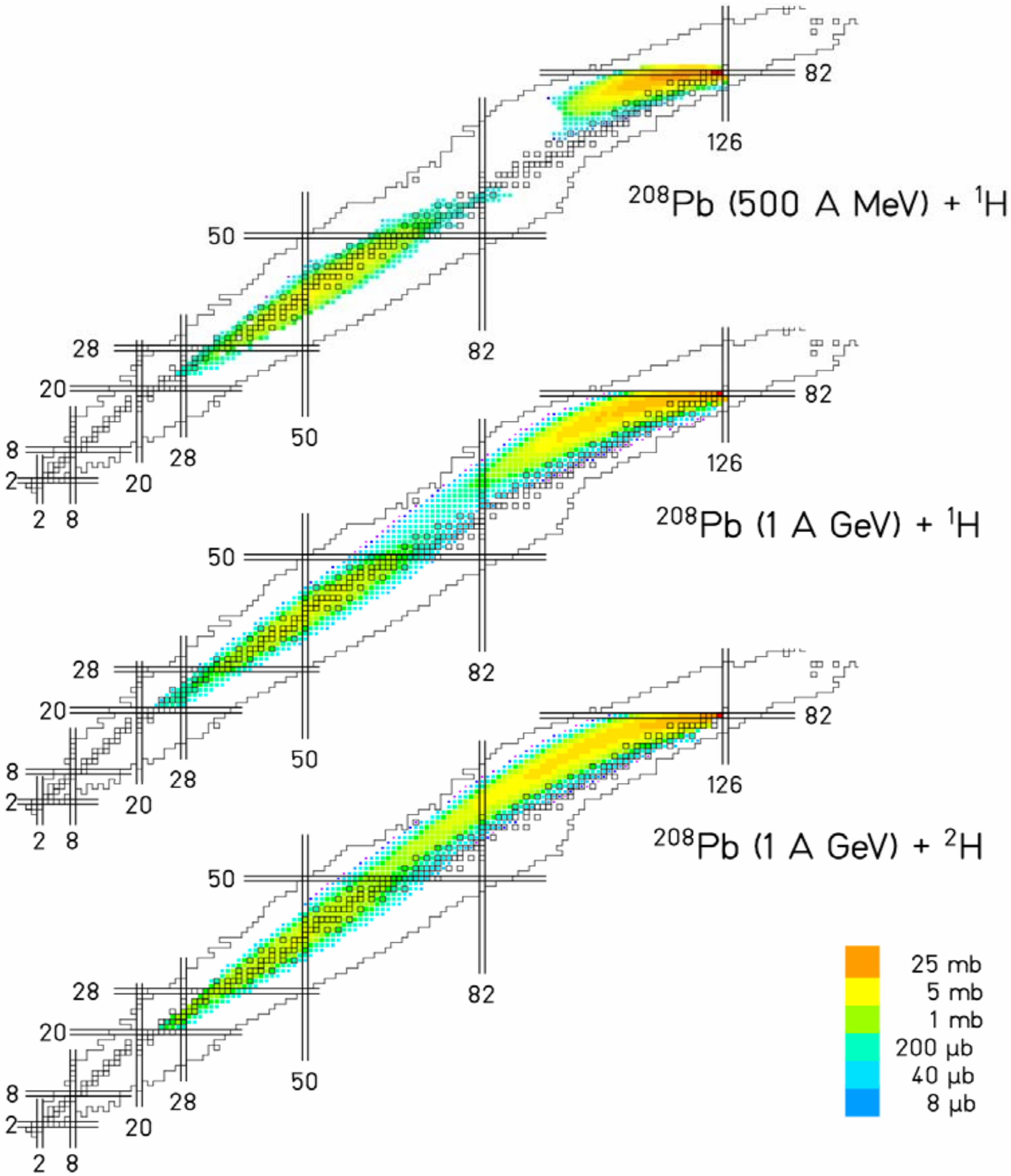


Summary: Fission in ABLA07

- Coverage beyond the Businaro-Gallone maximum
- Influence of nuclear viscosity on the fission decay width:
  - analytical time-dependent approach (B. Jurado et al., 2003)
  - influence of initial conditions
- Symmetry classes and barrier structure
- Particle emission on different stages of the fission process
- Nuclide distributions with statistical macro-microscopic approach (spont. fission .. high E*)
  - Separability principle: Compound-nucleus and fragment properties

Influence of the INC phase

Variation of beam energy



Increase of beam energy leads to higher excitation energies after INC and to larger mass loss in evaporation.

Data:

T. Enqvist et al., NPA 686, 481, NPA 703, 435

B. Fernandez et al., NPA 747, 227

L. Audouin et al., NPA 768, 1

Conclusion

ABLA07

Developed by

A. Kelic, M.V. Ricciardi, K.-H. Schmidt

New features (with moderate increase of computing time):

- Multifragmentation
- CN-decay channels γ, n, p, LCP, IMF, fission (continuous)
  - inverse x-sections from nuclear potential
  - treatment of angular momentum
  - fission transients from Fokker-Planck equation
  - barrier structure in low-energy fission
  - nuclide production in fission with 1 parameter set
    - from spontaneous fission to high E* for all CN
  - evaporation on fission path

Ready to be coupled with INCL 4 (or other INC, or ABRA, or ..)