Fission in high-energy proton-induced spallation reactions - A progress report*

N.G. Nicolis[1], A. Asimakopoulou[2] and G.A. Souliotis[2],

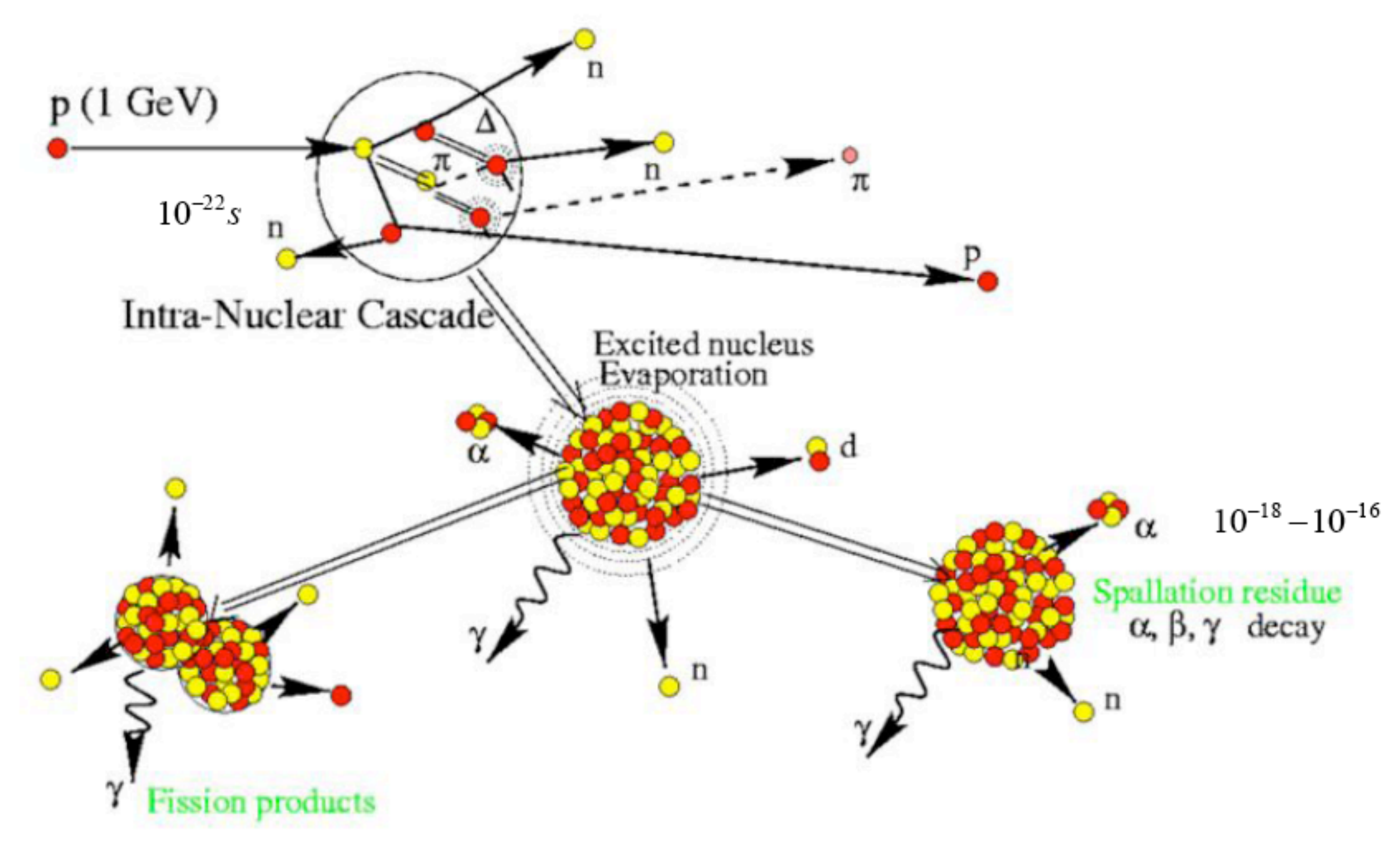
[1]Department of Physics, The University of Ioannina, Ioannina
45110, Greece
[2]Laboratory of Physical Chemistry, Department of Chemistry,
University of Athens, Athens, Greece

* Presented at the 4th Workshop of the Hellenic Institute of Nuclear Physics, University of Ioannina, May 5-6, 2017.

Motivation for studying spallation reactions

- Accelerator-driven systems (ADS)
- Transmutation of nuclear waste
- Spallation neutron sources
- Production of rare isotopes
- Interaction of cosmic rays with interstellar bodies (astrophysics)
- Radiation damage in space
- Testing ground for high-energy nuclear reaction models (above 150-200 MeV)

The two phases of a proton-induced spallation reaction

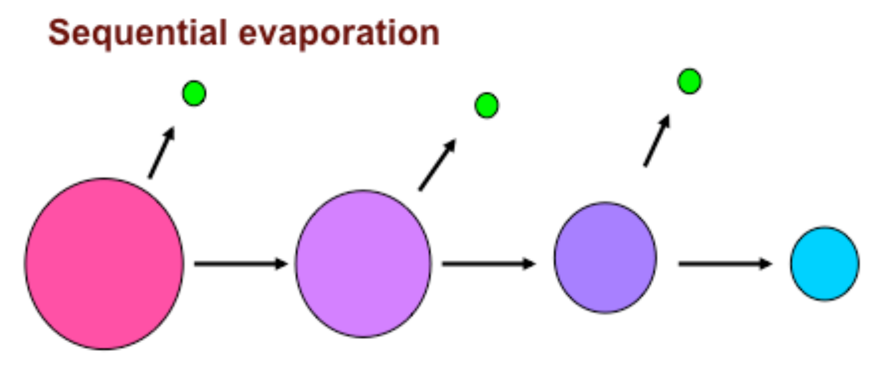


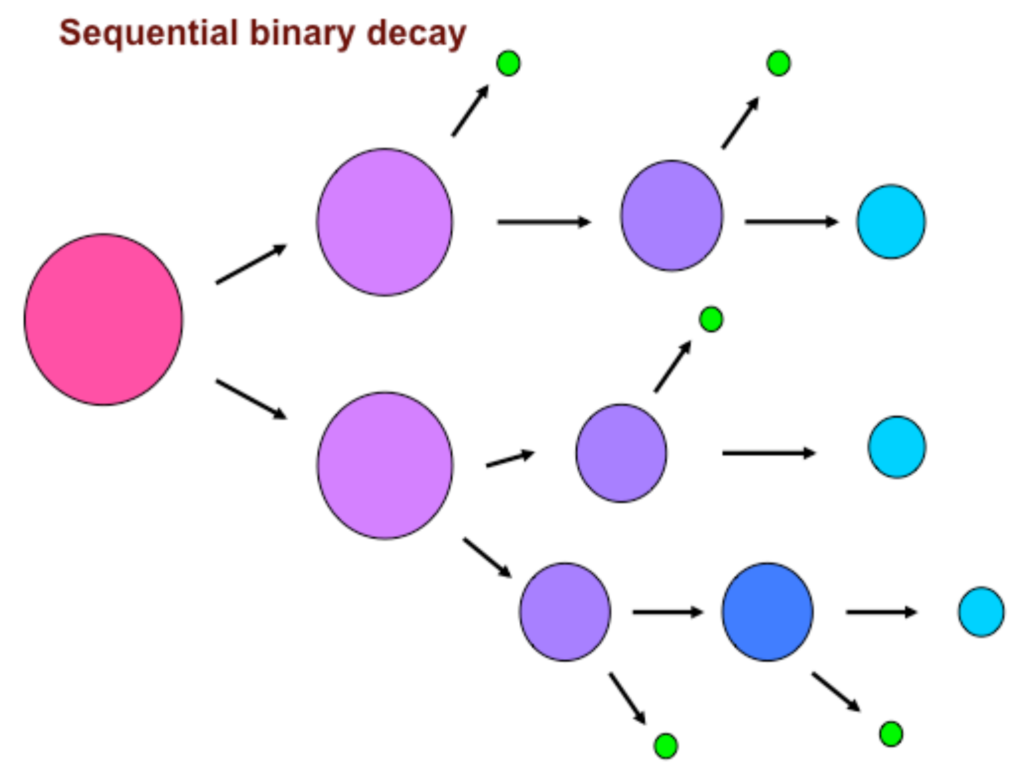
The INC phase (ISABEL code)

- Continuous medium
- Diffuse nuclear surface
- Linear trajectory between collisions
- Free N-N cross sections
- Allows for inelastic N-N collisions
- Collision criterion based on the mean-free-path
- Full Pauli blocking: Interactions resulting in nucleon falling below the Fermi sea are forbidden

Ref: Y. Yariv and Z. Fraenkel, Phys. Rev. C20, 2227 (1979); Phys. Rev. C24, 488 (1981)

The equilibrium decay phase





SMM (Botvina 2008)

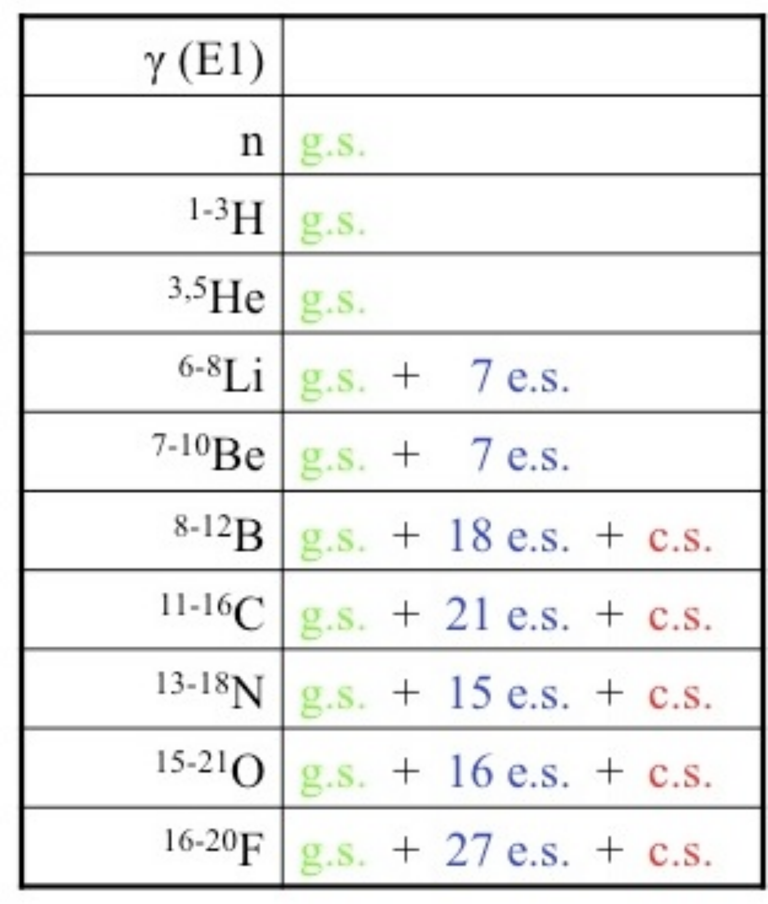
MECO (Nicolis 2008)

The code MECO (Multi-sequential Evaporation COde)

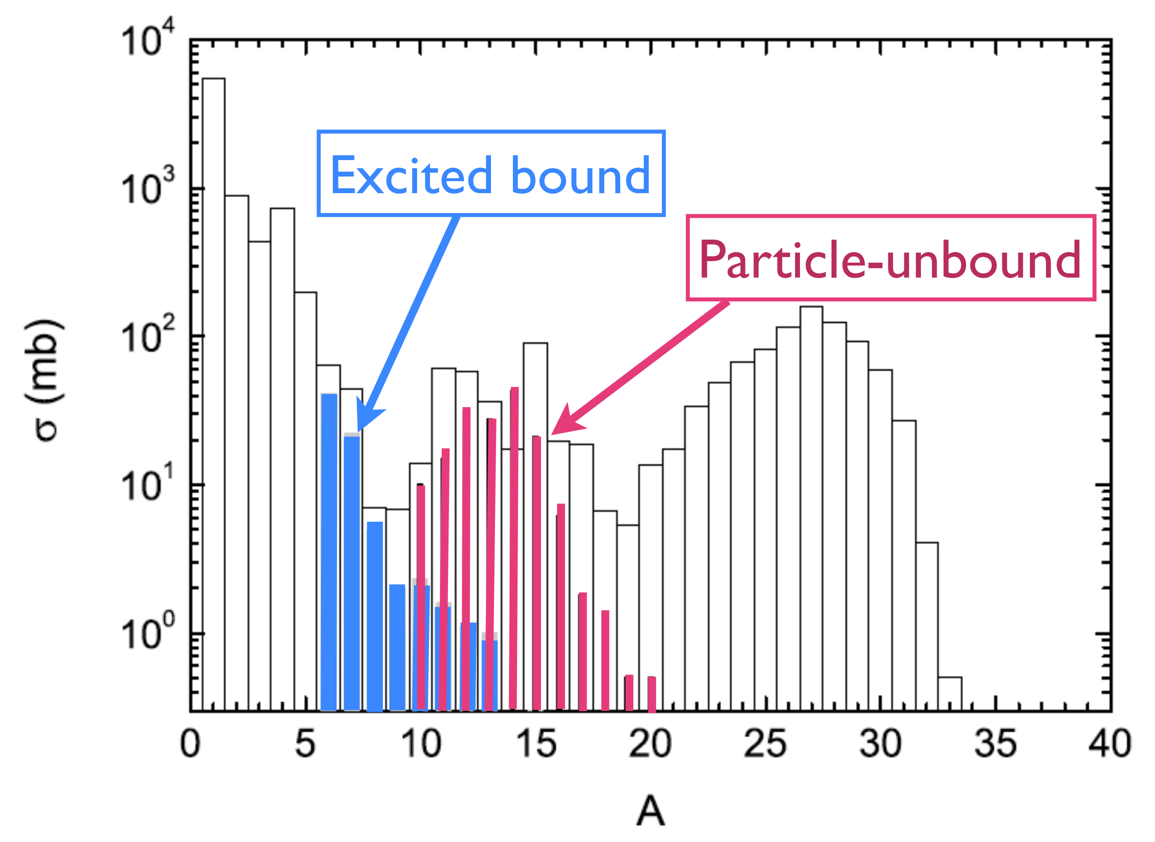
- Monte-Carlo code
- The equilibrium decay of excited nuclei is described as a sequence of binary processes involving emission of fragments in their ground, excited bound and unbound states.
- Any number of user-defined channels can be used.
- Emission of nucleons up to symmetric mass divisions can be used in a generalized Weisskopf evaporation formalism.
- Complete description of reaction systems with an effective fissility below the Businaro-Galone point.

MECO run with 179 decay channels

^{40}Ar* (180 MeV)



γ (E1)	
n	g.s.
$^{1\text{-}3}$H	g.s.
^{3,5}He	g.s.
$^{6\text{-}8}$Li	g.s. + 7 e.s.
$^{7\text{-}10}$Be	g.s. + 7 e.s.
$^{8\text{-}12}$B	g.s. + 18 e.s. + c.s.
$^{11\text{-}16}$C	g.s. + 21 e.s. + c.s.
$^{13\text{-}18}$N	g.s. + 15 e.s. + c.s.
$^{15\text{-}21}$O	g.s. + 16 e.s. + c.s.
$^{16\text{-}20}$F	g.s. + 27 e.s. + c.s.



Ref: N.G.Nicolis, Int. Jour. Mod. Phys. E 17 (2008) 1541-1556.

Fission probability and decay width

Fission probability:

$$P_f = \frac{\Gamma_f}{\sum_j \Gamma_j + \Gamma_f}$$

Decay width for the emission of a particle j (j=n, p, α, ...):
(Weisskopf)

$$\Gamma_j = \frac{(2s_j + 1)m_j}{\pi^2 \rho_c(U_c)} \int_{V_j}^{U_j - B_j} \sigma_{inv}^{j}(E)\rho_j(U_j - B_j - E)E dE$$

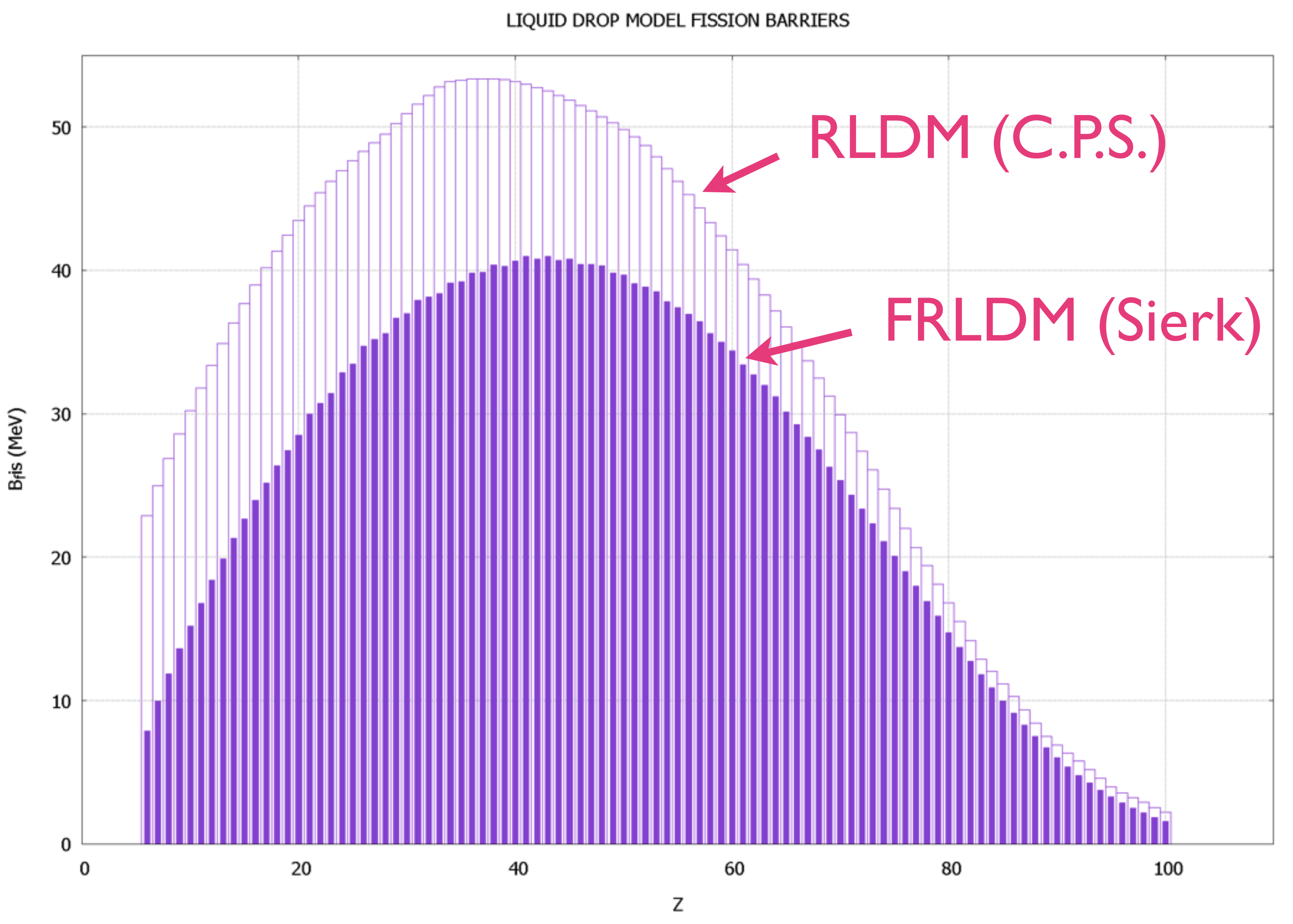
Decay width for fission (transition state theory):

$$\Gamma_f = \frac{N_{sad}}{2\pi\rho_c(U_c)}$$

or

$$\Gamma_f = \frac{1}{2\pi\rho_c(U_c)} \int_0^{U_f - B_f} \rho_f(U_f - B_f - E)dE$$

Fission barriers



RLDM (C.P.S.)

FRLDM (Sierk)

Fission delay

The standard theory of fission underestimates the measured pre-fission neutron multiplicities. A fission delay is needed to account for the slowing effects of nuclear dissipation.

$$\Gamma_f = \Gamma_f^{BW}\left(\sqrt{1+\gamma^2}-\gamma\right)$$

$\left(\sqrt{1+\gamma^2}-\gamma\right)$ is the Kramers reduction factor ($\gamma \sim 5$)

$\gamma = \dfrac{\beta}{2\omega_{sp}}$

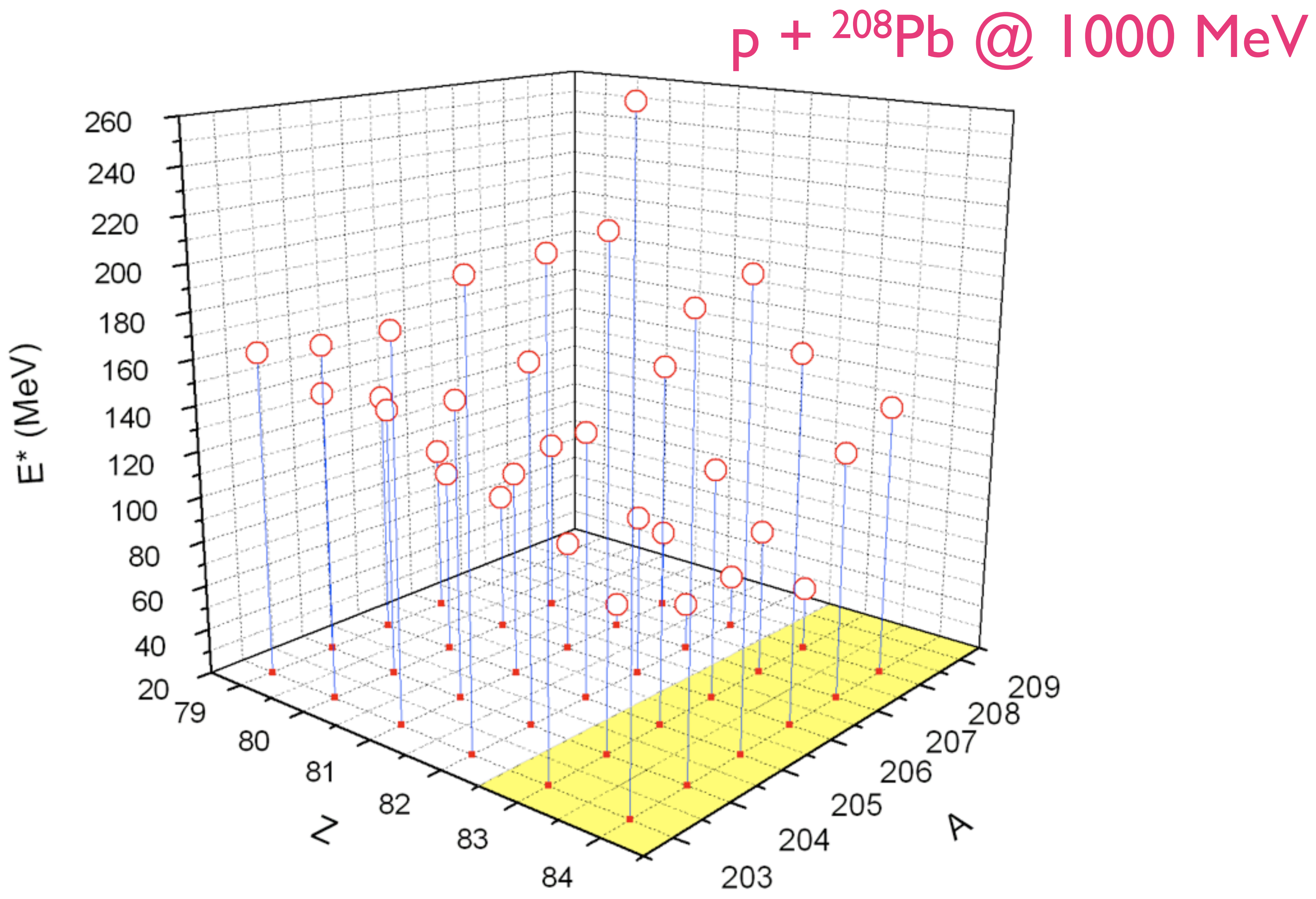
β is the reduced nuclear dissipation coefficient

ω_{sp} is the curvature of the PES at the SP

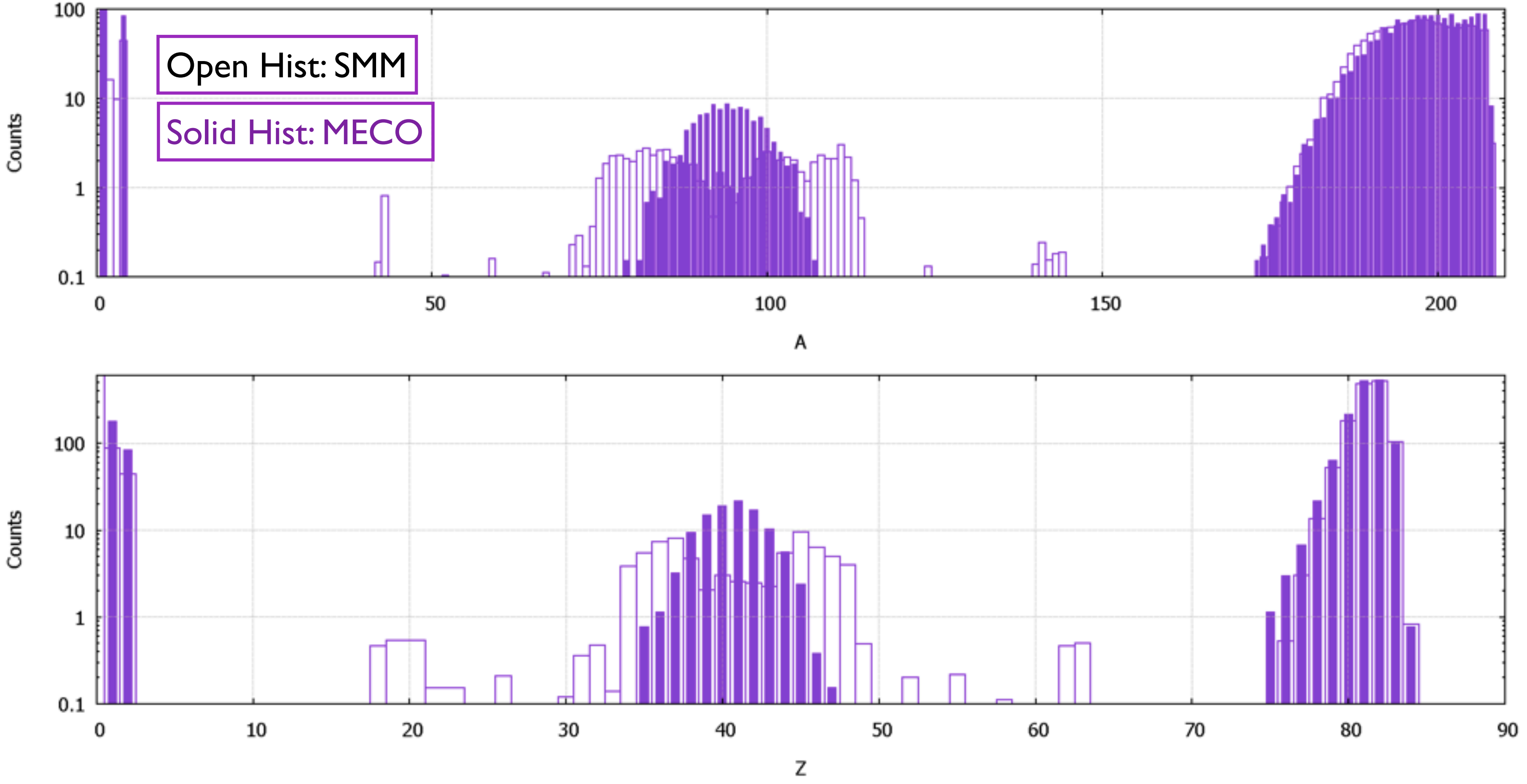
First-order description of fission decay in MECO

- Calculate fission probability.
- If fission occurs, assume a Gaussian profile for the symmetric division with excitation energy dependent variance (G.D. Adeev 1993).
- From the conservation of energy and linear momentum we get the fragment kinetic energies.
- For each fragment, the excitation energy is divided in proportion to the fragment mass.
- Then, the particle decay of each fragment is followed.

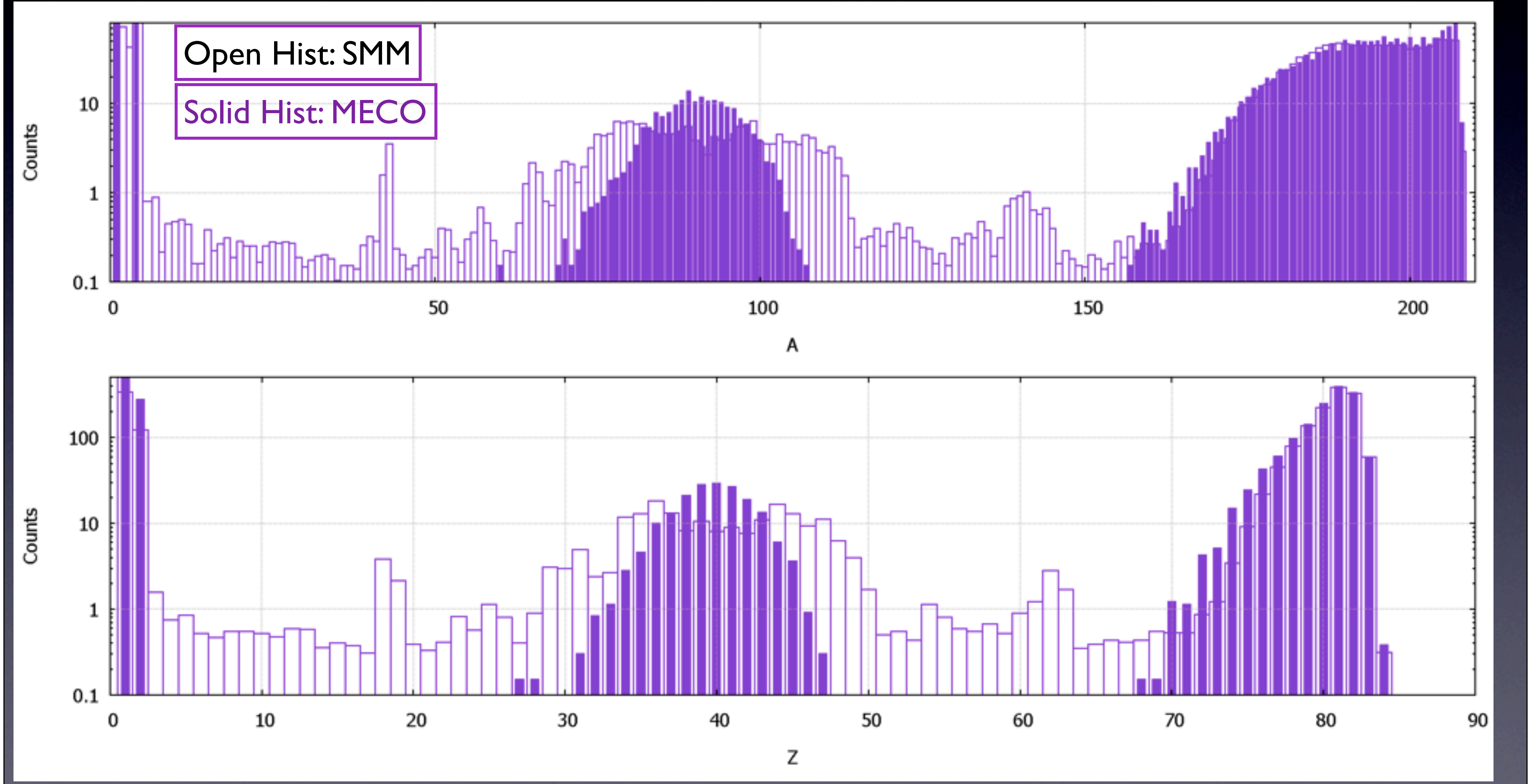
Distribution in A and Z of the average excitation energy predicted by INC



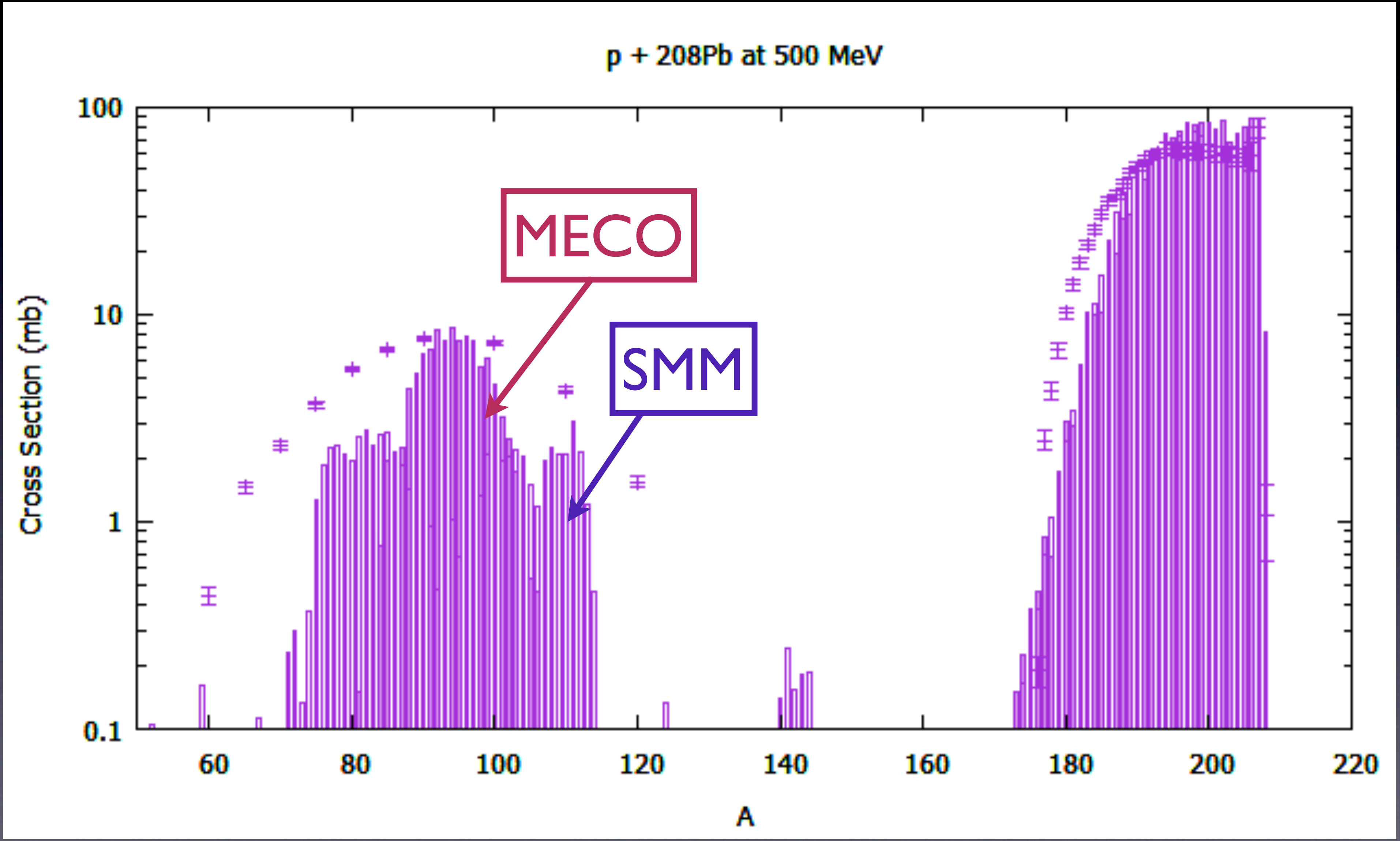
p + ^{208}Pb @ 500MeV
Calculated A and Z distributions with MECO and SMM



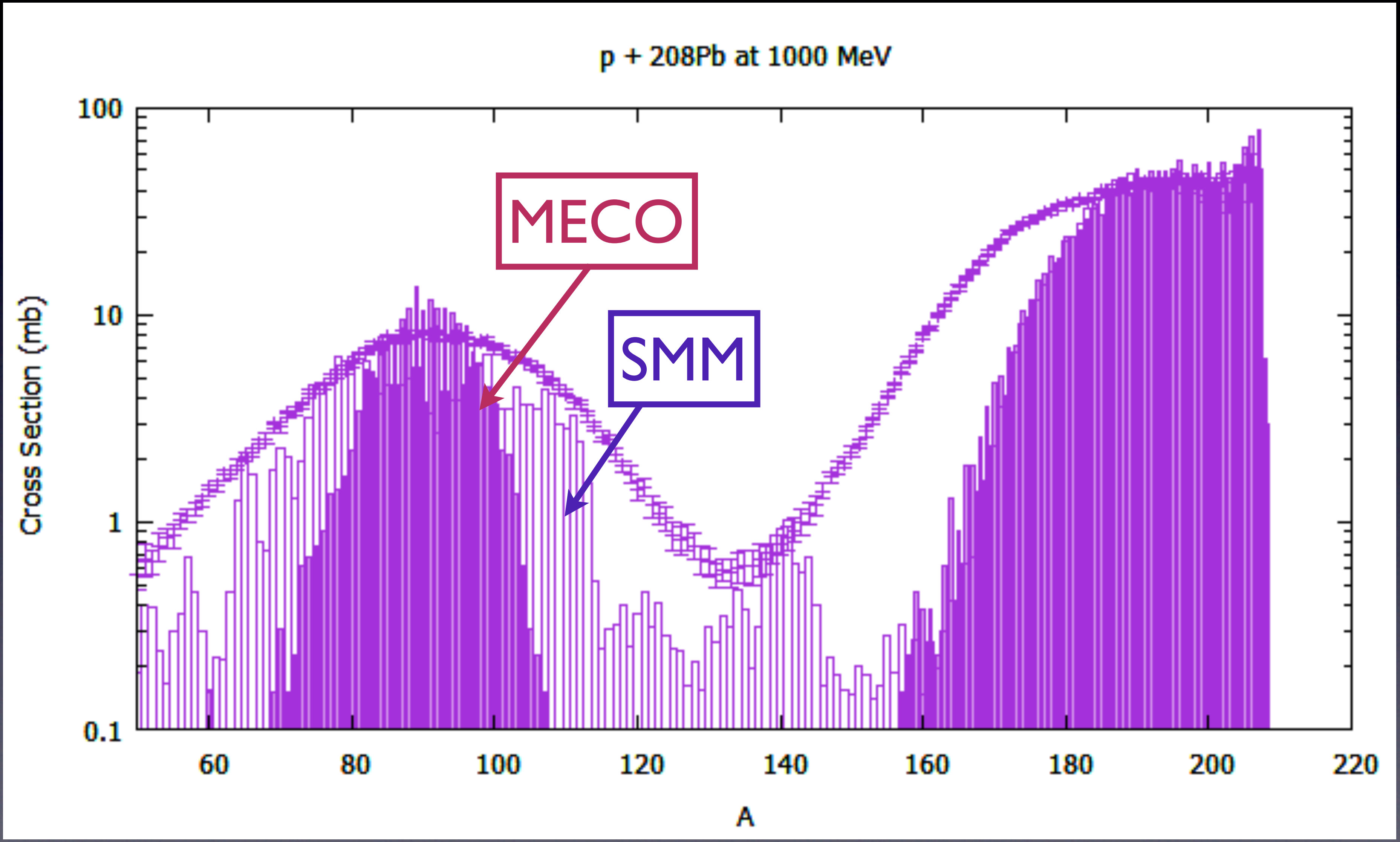
p + ^{208}Pb @ 1000MeV
Calculated A and Z distributions with MECO and SMM



$p+^{208}Pb$ @ 500 MeV
Experimental and calculated mass distributions



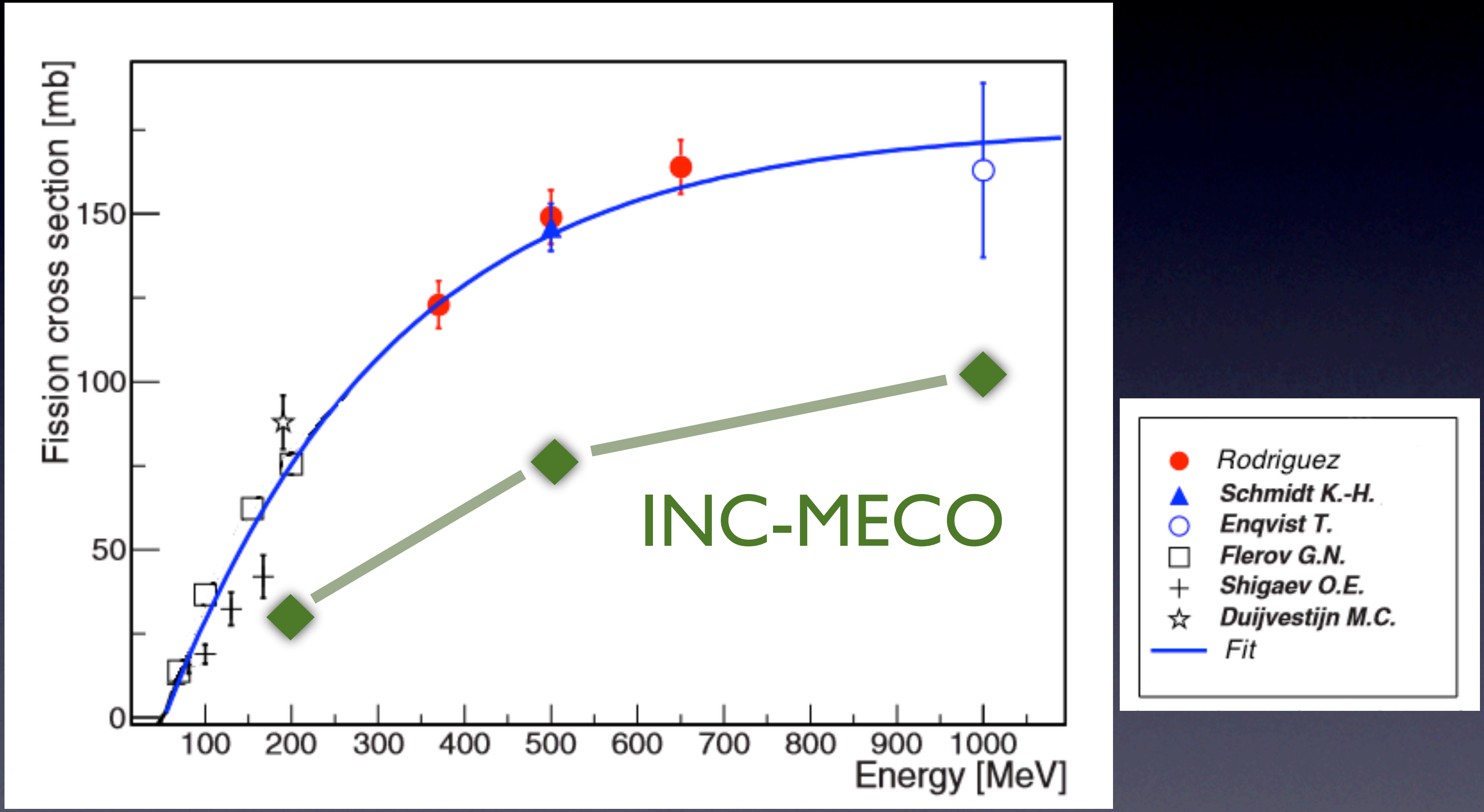
p+^{208}Pb @ 1000 MeV
Experimental and calculated mass distributions



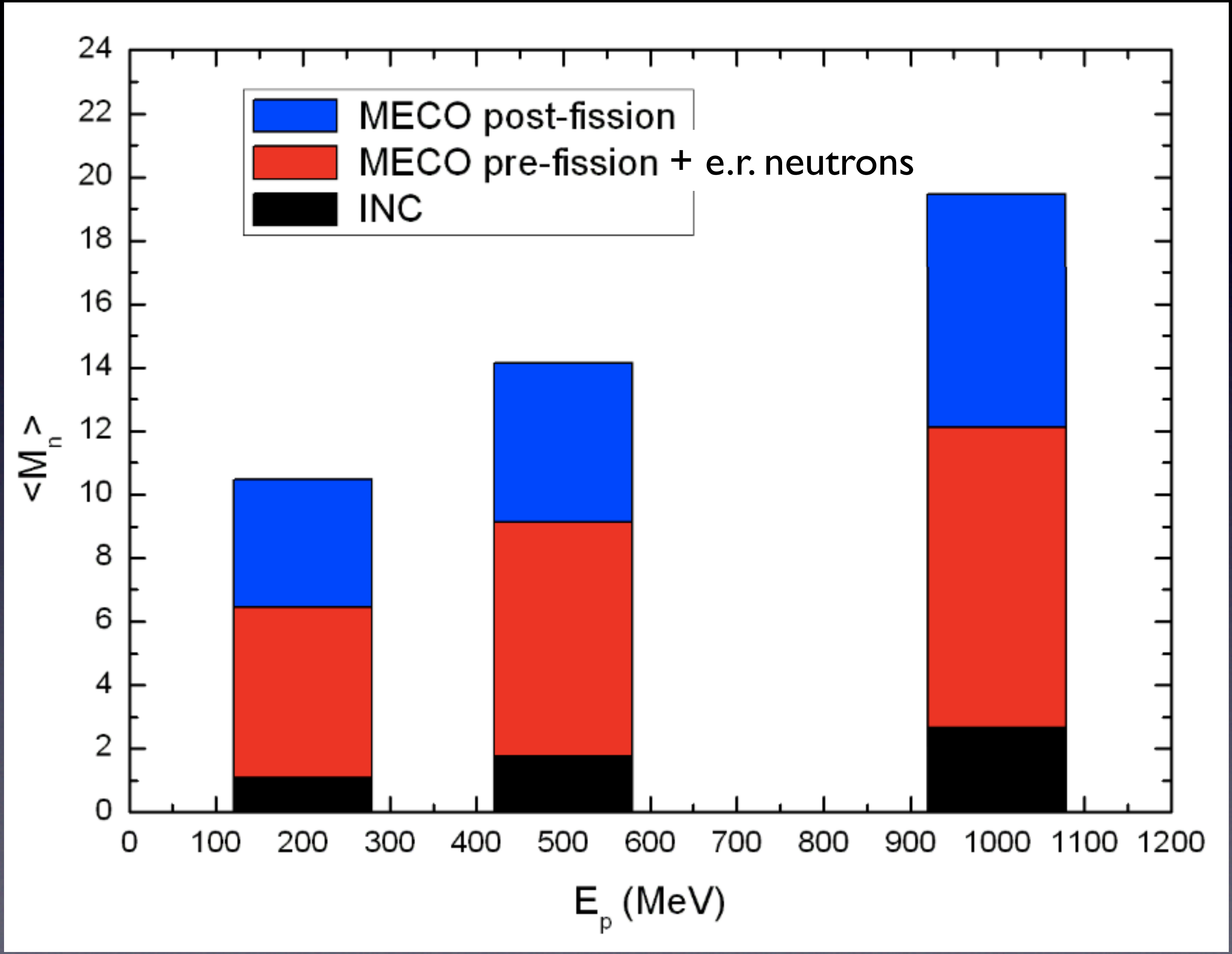
Description of isotopic distributions of evaporation residues

- Agreement between MECO and SMM, in most cases.
- Agreement between experimental data and calculations.
- Examples will be given this afternoon in the talk by Mrs. Aggeliki Asimakopoulou

Fission cross sections for p + ^{208}Pb



Neutron multiplicities



Summary

- We have combined the intranuclear cascade code ISABEL and the sequential binary decay code MECO in an effort to study spallation reactions induced by high-energy protons.
- Preliminary calculations of p+ ^{208}Pb at bombarding energies 200, 500 and 1000MeV were compared with experimental mass distributions, fission cross sections and neutron multiplicities for these reactions.
- For the evaporation residue mass, charge (and isotopic distributions) our calculations with MECO are consistent with the predictions of the SMM code.
- The description of the experimental fission fragment mass distributions requires a careful modeling of the temperature-dependent fission barriers.
- In this direction, additional developments in MECO are in progress.