Nuclear processes in ultrarelativistic collisions

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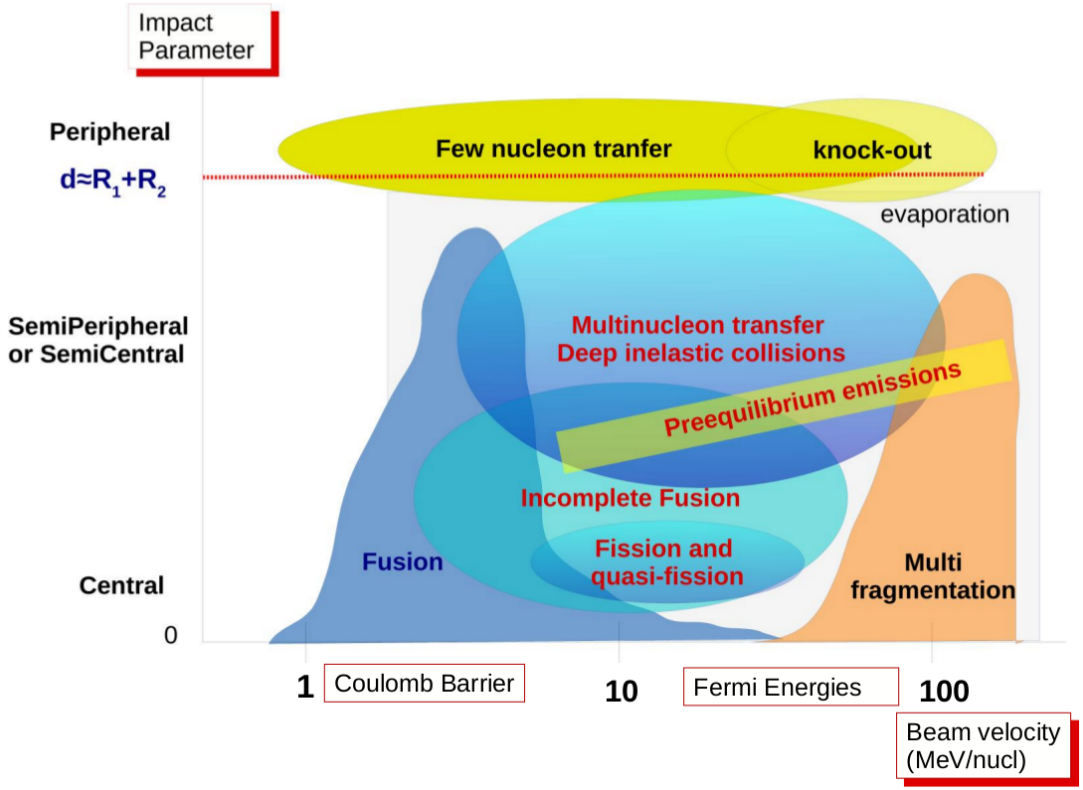
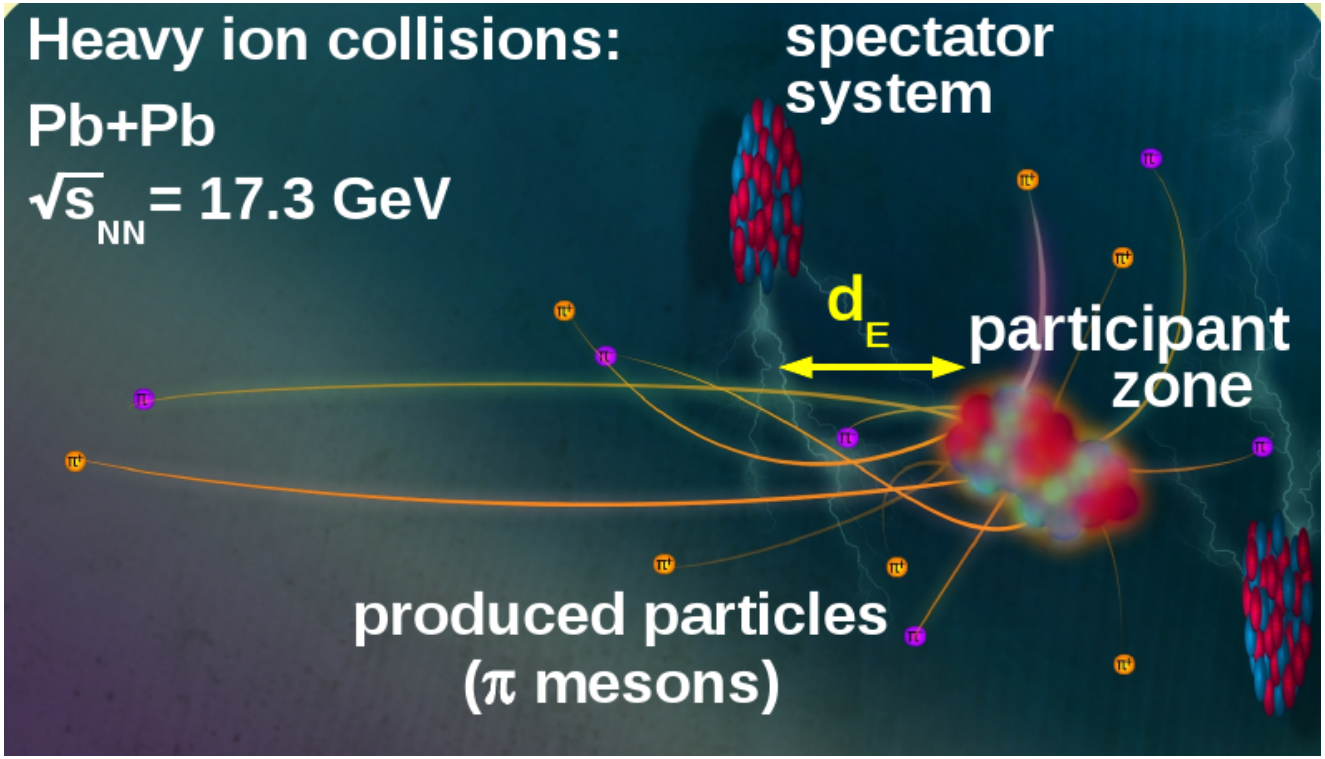
Outline

- 1. Motivation
- 2. Nuclear processes
- a) Abrasion-ablation model (ABRABLA)
- b) Heavy-Ion Phase-Space Exploration (HIPSE)
- c) Fission dynamics (4DLangevin)
- 3. Preliminary results
- 4. Summary



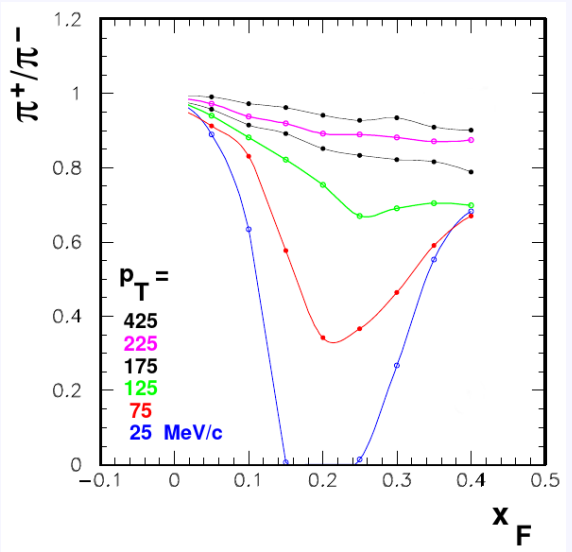
Motivation



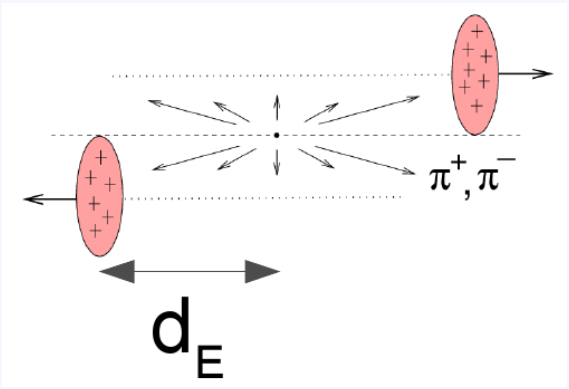
plot by I. Sputowska

- Charged spectators in non-central collisions generate electromagnetic fields
- These modify the trajectories of final state charged particles
- Opposite charges affected oppositely $\rightarrow$ charge asymmetries in distributions of produced particles $\rightarrow$ information on distance d_E and spectator breakup

$R_{spect} = R_0$



Spectator-pion distance



A. Rybicki, A. Szczurek, Phys. Rev. C **75**, 054903 (2007)

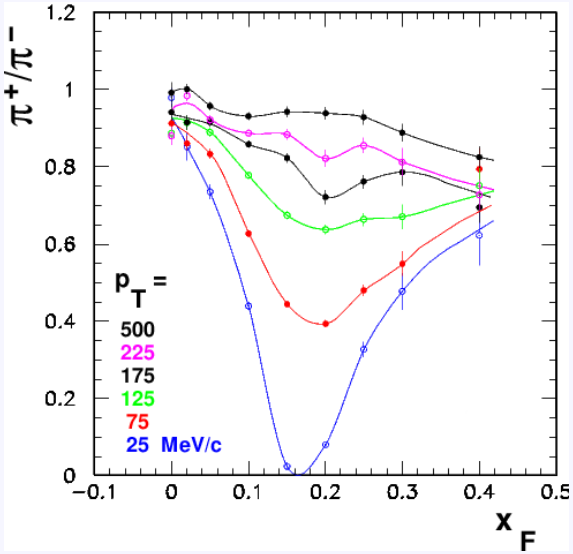
Spectator-pion distance

$$p_T = \sqrt{p_x^2 + p_y^2}$$

$$x_F = \frac{2p_z}{\sqrt{s_{NN}}}$$

Spectator surface expansion was neglected by long time for small systems and/or less peripheral collisions

NA49 Pb+Pb at 158 GeV/u



A. Rybicki, Acta Phys. Polon. **B42**, 867 (2011)

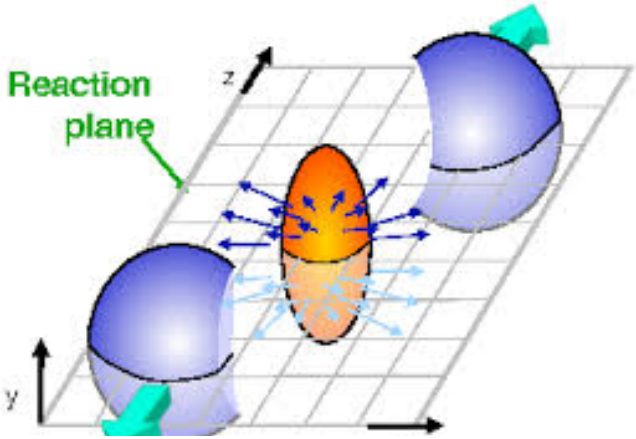
EM effects dependence on spectator charge distribution

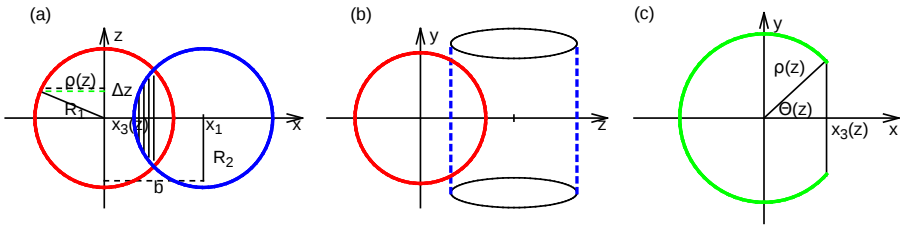
- Shape of the EM distortion is sensitive to the space-time scale of spectator fragmentation
- Allow to get direct information about excitation energy of spectator

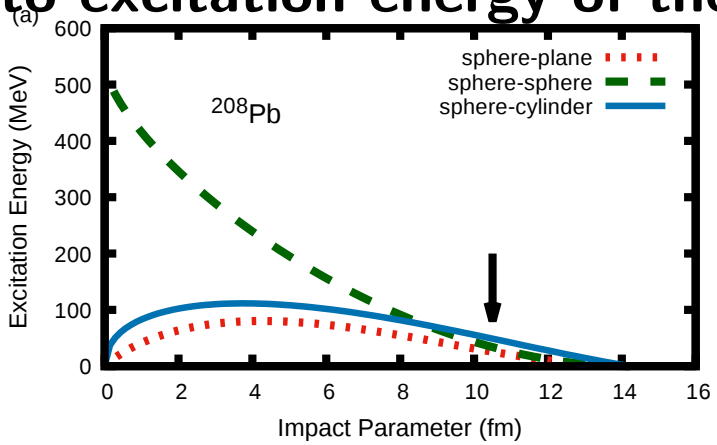
Thanks to A. Marcinek

Pb + Pb Collision - Geometrical Scenarios

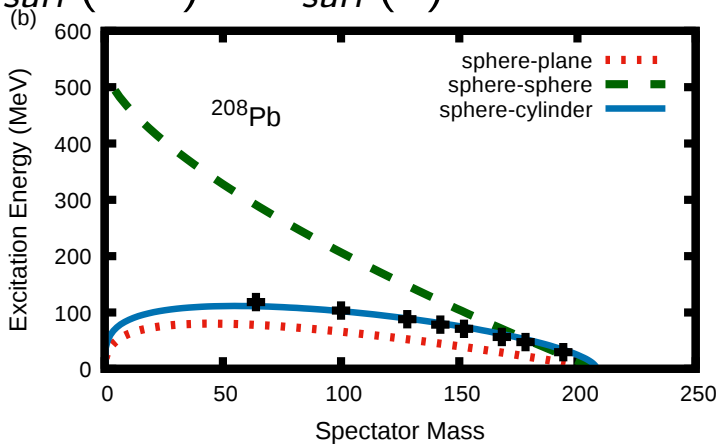
After collision - very deformed shapes of the spectator -
the deformation energy translated to excitation energy of the spectator







$$E_{def} = E_{surf}(def) - E_{surf}(0)$$



K. M., A. Szczurek, P.N. Nadtochy, APPB Proc. Suppl., 10 (2017) 113, arXiv:1708.03716

^{208}Pb + ^{208}Pb at 158 GeV/A SPS CERN

a) Abrasion-ablation model (ABRABLA)

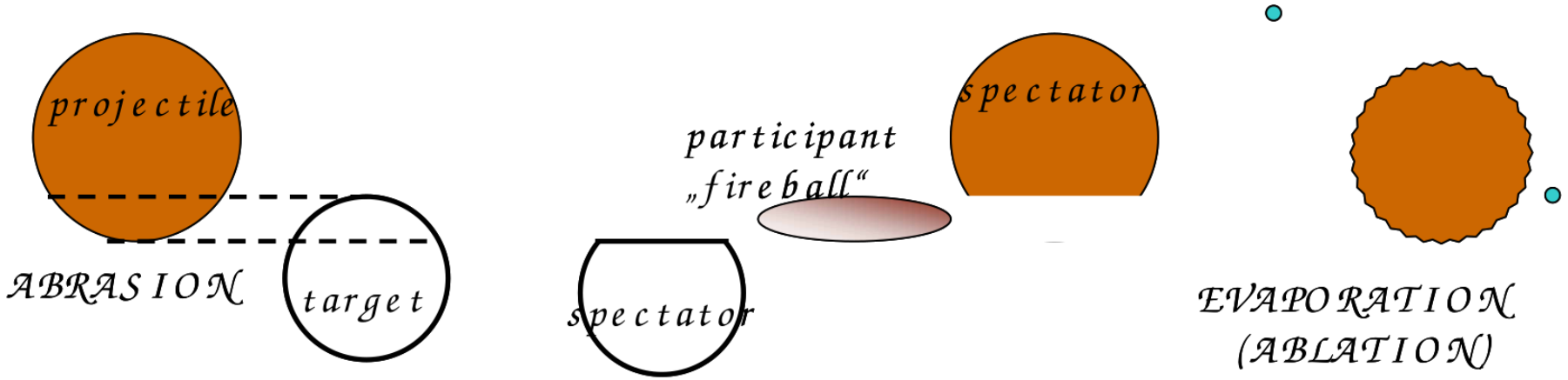


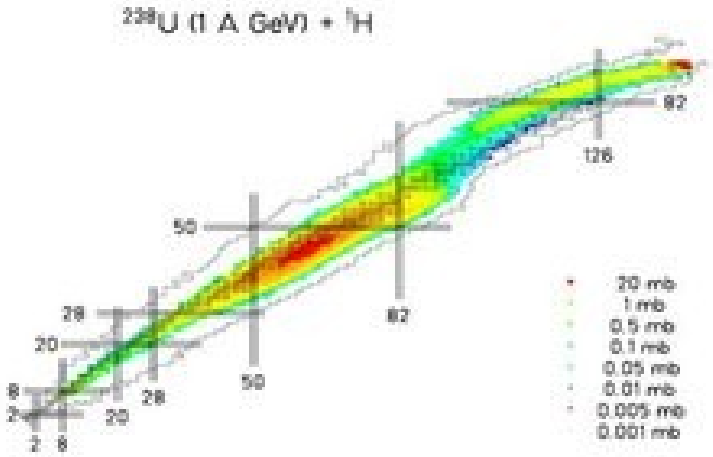
Figure 5.1: Schematic drawing of the abrasion-evaporation process, used to describe peripheral nucleus-nucleus collisions at relativistic energies.

J.-J. Gaimard, K.-H. Schmidt Nucl. Phys. A 531 (1991) 709; K.-H. Schmidt, et al Phys. Lett. B 300 (1993) 313; Europhys. Lett. 83 (2008) 32001; arXiv nucl-ex/0711.3967v1

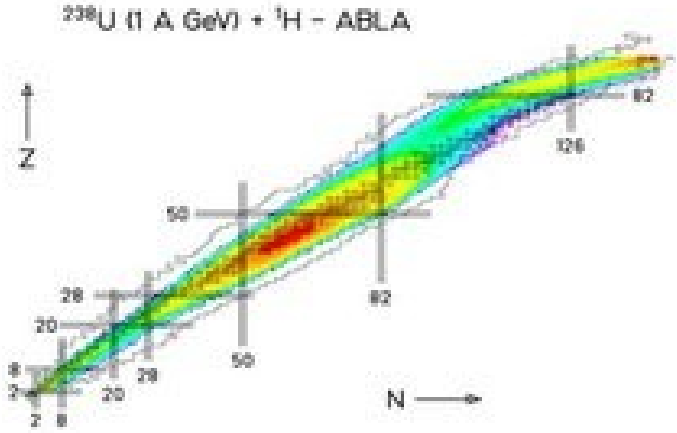
a) Abrasion-ablation model (ABRABLA)

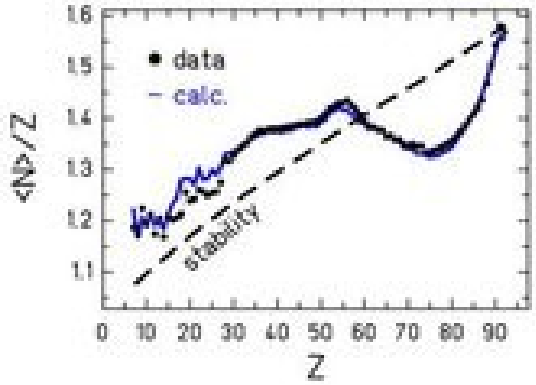
$^{238}U(1AGeV)+^{1}H$

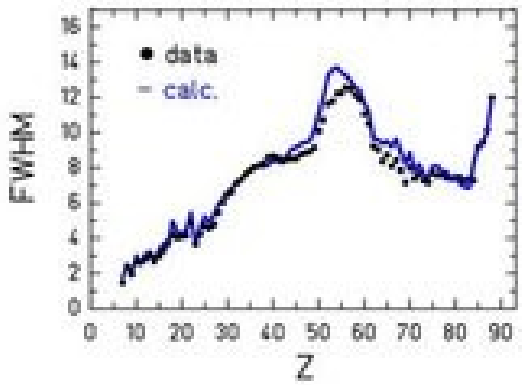
Experimental data:



ABRABLA07:







b) HIPSE dynamical model

Heavy-Ion-Space Exploration (HIPSE) is a phenomenological model dedicated to heavy-ion reactions around Fermi energy. It can be used as an event generator and gives access to partitions before and after statistical decay. D. Lacroix et al. Phys. Rev. C69,054604 (2004)

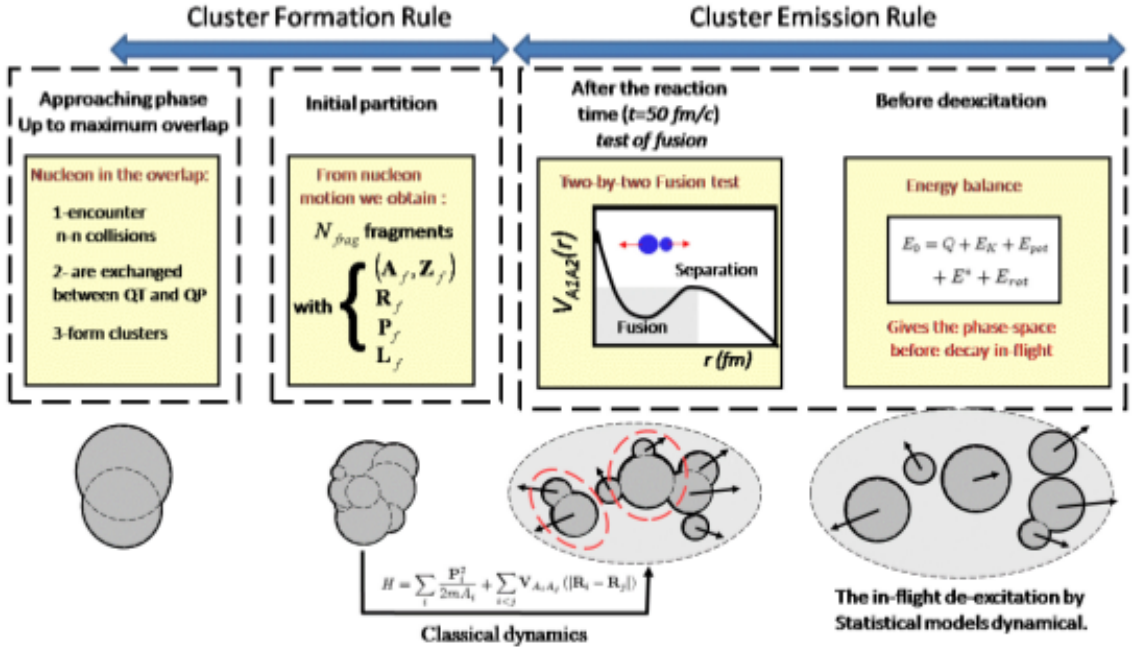
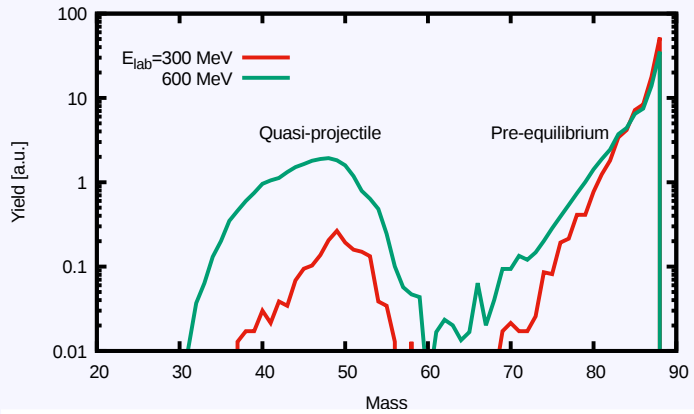
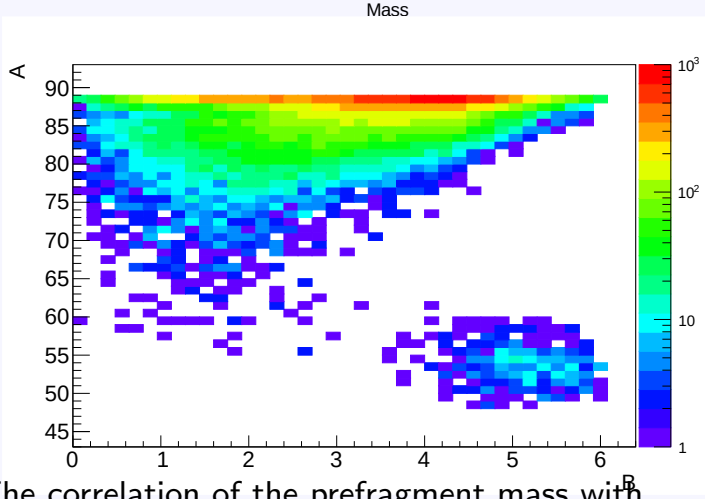


FIG. 38: *Illustration of the different steps to describe nuclear collisions. From left to right are shown: (i) the definition of the participant region after the approaching phase. (ii) the cluster formation. Properties of clusters are directly deduced from properties of nucleons issued from the Thomas-Fermi sampling and eventually distorted by the nucleon-nucleon direct collisions. (iii) Once clusters are formed and after some expansion, a test is made to check if they escape from the attraction of surrounding clusters. If not, the two attracting clusters fuse. (iv) Once the chemical freeze-out is reached, a global energy balance is made to check that the partition is energetically accessible. Then the excitation energy deduced from the energy balance is shared between clusters (v) The in-flight decay is performed. Calculation is stopped once all fragments are cold.*

Entrance channel effect - ^{48}Ti+^{40}Ca→ ^{88}Mo

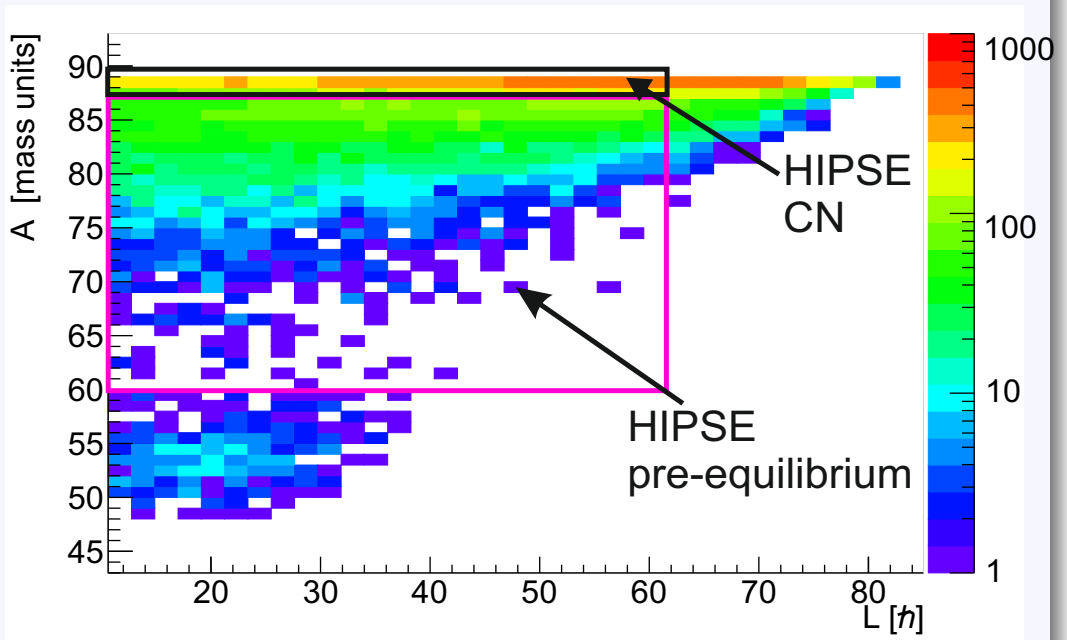
Mass distribution





The correlation of the prefragment mass with the impact parameter in ^{48}Ti(600 MeV)+^{40}Ca.

Outcome from the HIPSE code



Compound nuclei created by HIPSE code. The L_{cut}=64 $\hbar$ marks the spin at which the fission barrier vanishes.

K.M. et al Acta Phys. Pol. B Proc. Supp. 11, 109 (2018)

Statistical model of compound nucleus decay

GEMINI++ statistical model (R.J. Charity, Phys. Rev. C82,014610 (2010))

- is widely used statistical model code
- adopts a default set of parameters obtained by fitting data from several previous experiments
  - parameters are tuned for heavy nuclei (A>150)
  - there aren't many experimental data to fix parametrs for medium-light nuclei
- tunning parameters of GEMINI++ are:
  - level density
  - Coulomb barrier distribution
  - yrast energy parametrization
  - etc....

M. Ciemała: In the present studies, the statistical code GEMINI++ with an option allowing to treat explicitly the GDR emission [Ciemala et al. Acta Phys. Pol B44, 611 (2013)] was employed for the first time for such an analysis.

Entrance channel effect

CN- de-excitation

PHYSICAL REVIEW C **91**, 054313 (2015)

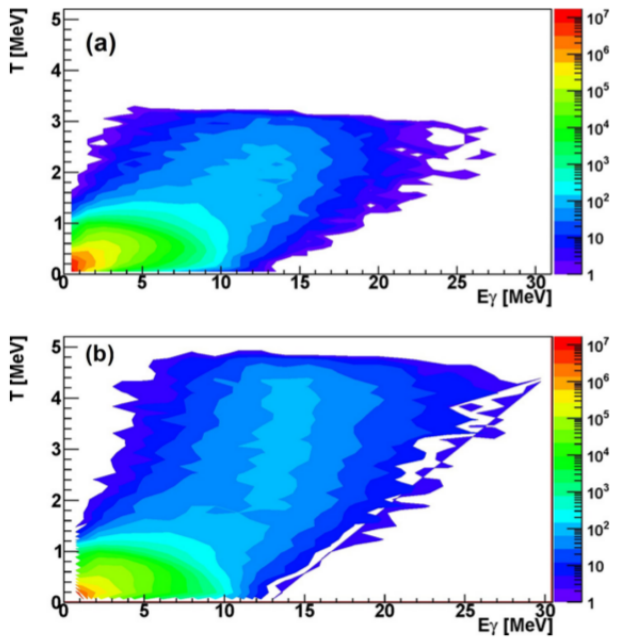
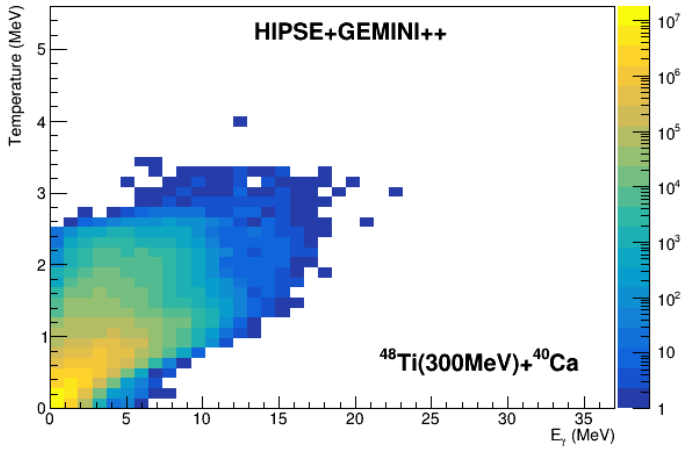
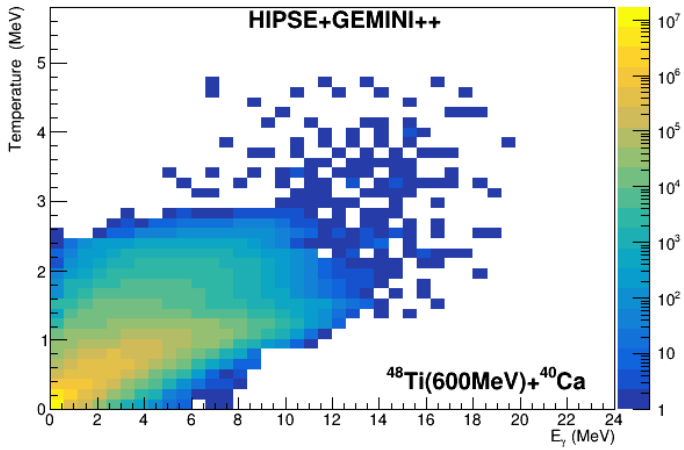


FIG. 11. (Color online) Distribution of the nuclei in the evaporation process as functions of the nuclear temperature reached after the γ decay and the emitted γ-ray energy; calculated with the code GEMINI++ for the data at the beam energies of (a) 300 MeV and (b) 600 MeV.

HIPSE+GEMINI++





CN- de-excitation

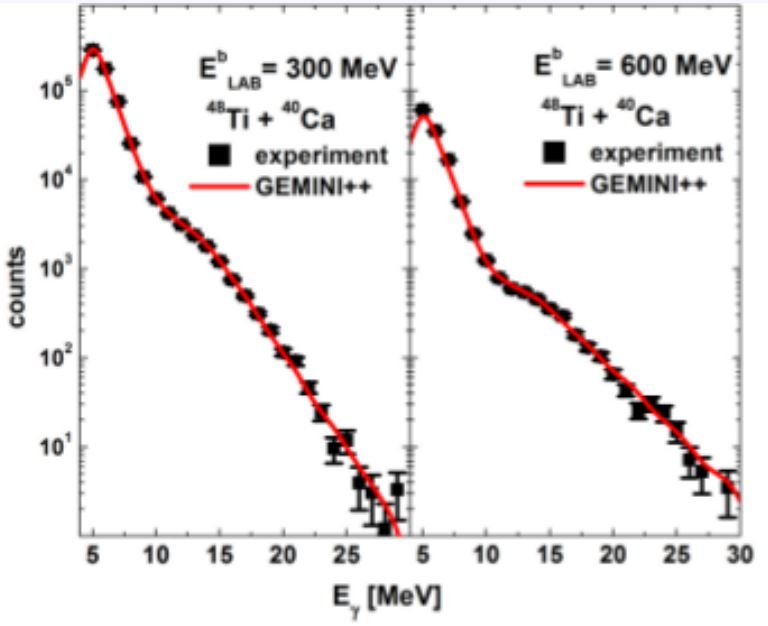
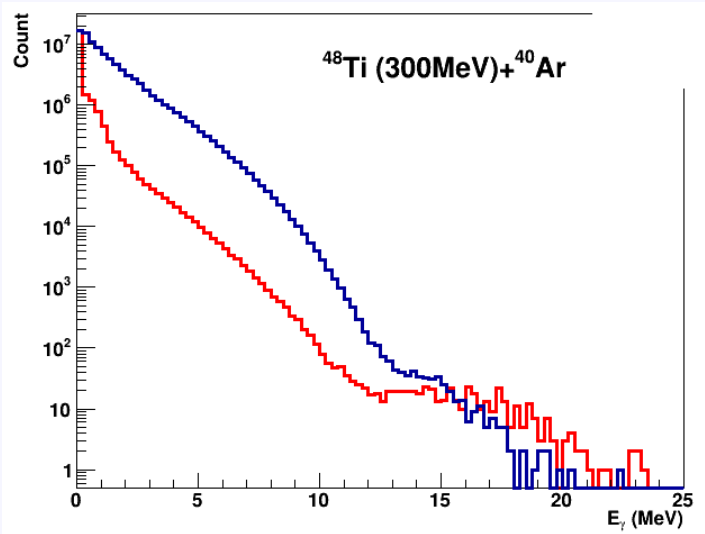


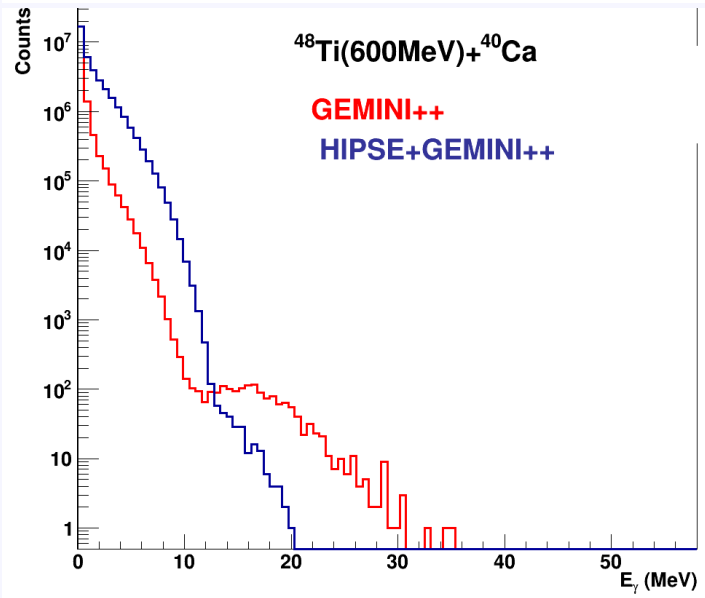
FIG. 9. (Color online) A comparison of the γ-ray spectra from the ^{48}Ti + ^{40}Ca reaction, at the beam energies of 300 MeV and 600 MeV, with the results of the *GEMINI++* fit (see text).

Comparison with exp.

E_b	th (300 MeV)	exp (300 MeV)	th (600 MeV)	exp (600 MeV)
$\langle M_{tot} \rangle$	74.9		55.1	
p_{tot}	4.09	3.8	3.87	5.2
α_{tot}	1.61	1.8	2.18	2.8
d_{tot}	0.24	0.1	0.69	0.4

HIPSE+GEMINI++





c) Fission dynamics - Stochastic Approach

Dynamical effect

- path from equilibrium to scission slowed-down by the nuclear viscosity
- description of the time evolution of the collective variables like the evolution of Brownian particle that interacts stochastically with a "heat bath".
- excess of prescission particles
- all the parameters of the two dimensional fission fragment distribution and their dependence on various parameters of compound nucleus

Observables

- Pre- and post-scission particle multiplicity and energy spectra
- Mass, charge, angular distributions of the fragments
- Total Kinetic Energy distribution
- Isotopic distribution, $\langle N/Z \rangle$....

Limitations

- Wide domain in compound nucleus mass (from 50 to 250)
- Excitation energy $E^{\star}$ (from 30 to 250MeV)
- Angular momentum L (from 0 to 100 $\hbar$)

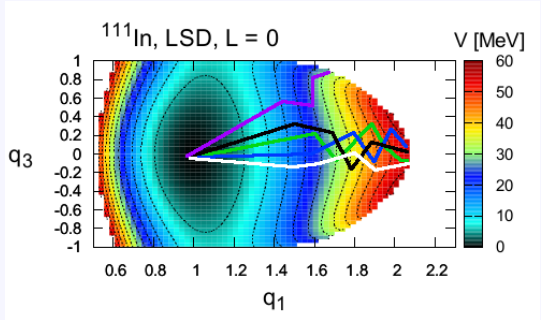
c) Fission dynamics - Stochastic Approach

Langevin Equations

are stochastic differential equations describing the time evolution of a subset of the degrees of freedom. These degrees of freedom typically are collective (macroscopic) variables changing only slowly in comparison to the other (microscopic) variables of the system. The fast (microscopic) variables are responsible for the stochastic nature of the Langevin equation.

$$\frac{dq_i}{dt} = \sum_j [M^{-1}(\vec{q})]_{ij} p_j$$

$$\frac{dp_i}{dt} = -\frac{1}{2}\sum_{j,k} \frac{d[M^{-1}(\vec{q})]_{jk}}{dq_i} p_j p_k - \frac{dF(\vec{q},K)}{dq_i} - \sum_{j,k} \gamma_{ij}(\vec{q})[M^{-1}(\vec{q})]_{jk} p_k + \sum_j g_{ij}(\vec{q})\Gamma_j(t)$$



Ingredients

Inertia ($[M^{-1}(\vec{q})]_{ij}$)
Friction ($\gamma_i(t)$) and fluctuation (g_{ik})
Macroscopic potential ($V(\vec{q},K) \rightarrow F(\vec{q},K) = V(\vec{q},K) - a(\vec{q})T^2$)

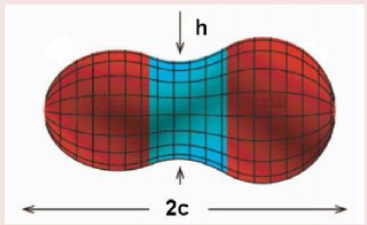
Coupling to the evaporation

Pre and post- scission emission of neutrons, protons, α and γ.

Model Ingredients

Collective coordinates (4D)

- Description of the nuclear shape by elongation, neck and asymmetry – 3 parameters.
- **K** – spin about the fission (symmetry) axis

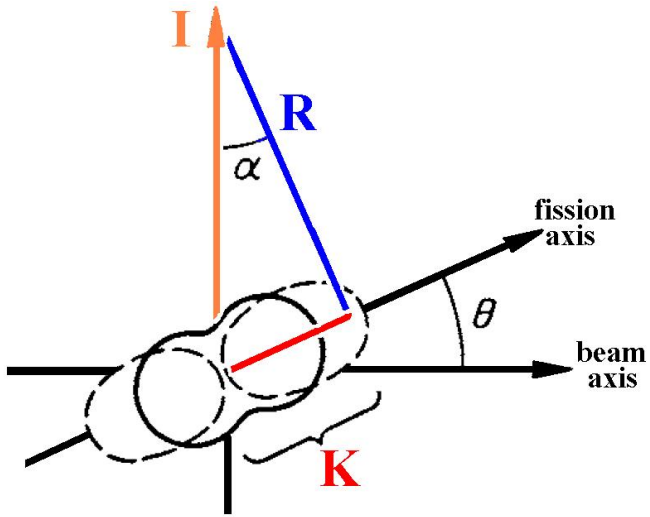


- c - the elongation of the nucleus
- h - constriction coordinate
- α - mass-asymmetry parameter related to the ratio of the masses of nascent fragments

Tilting coordinates - K

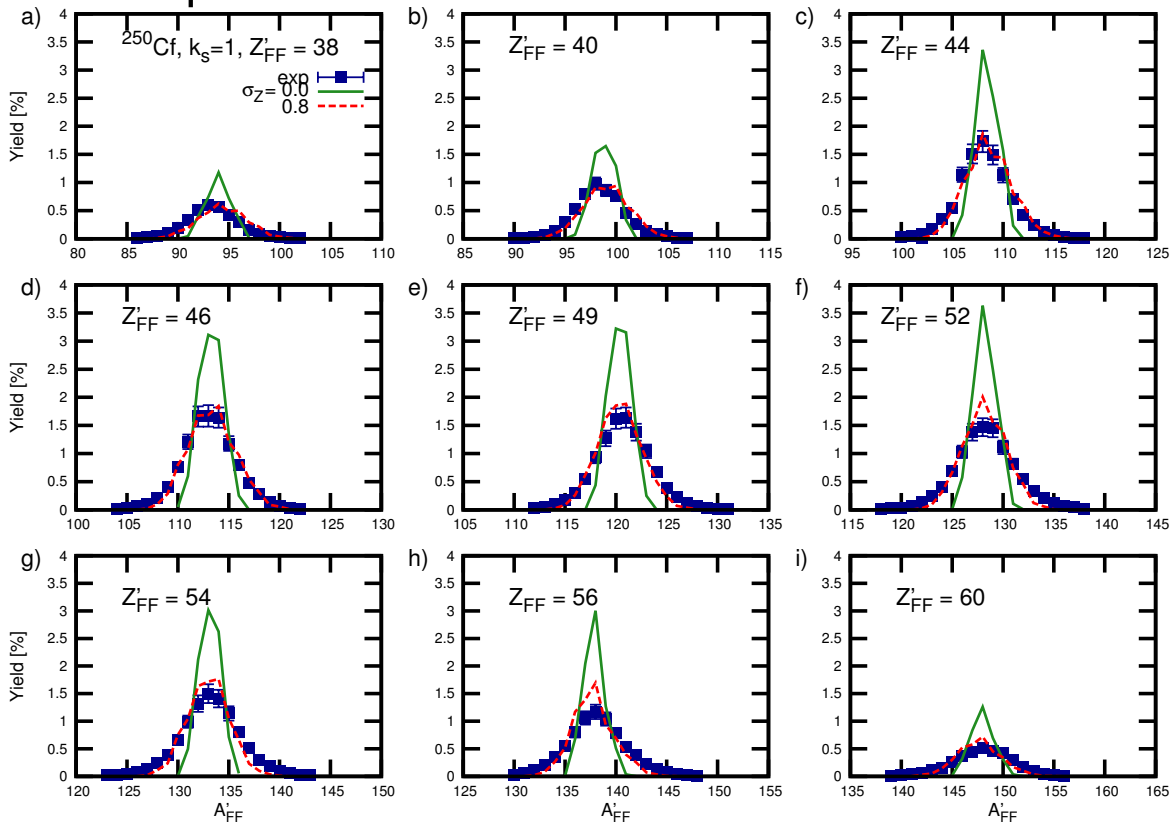
$$\delta \mathbf{K} = -\frac{\gamma_{\mathbf{K}}^2 \mathbf{I}^2}{2} \frac{\partial \mathbf{V}}{\partial \mathbf{K}} \delta \mathbf{t} + \gamma_{\mathbf{K}} \mathbf{I} \psi \sqrt{\mathbf{T} \delta \mathbf{t}}$$

where ψ - random number, γ_K - friction parameter (coupling K with heat bath)– J.P.Leastone,S.G.McCalla,PRC79,044611



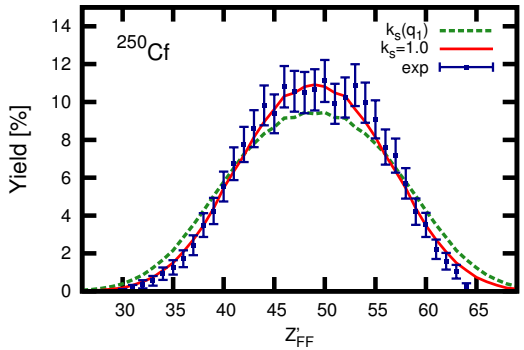
Isotopic Distributions: U + C→Cf (E_{lab}=6.2 AMeV)

The charge variance is necessary to reproduce the isotopic distribution.



K.M., C. Schmitt, P. Nadtochy PRC 91, 041603(R) (2015),

M. Caamano et al. PRC **88**, 024605 (2014)



A finite charge dispersion is necessary to reproduce the isotopic distribution.

$$Z_{FFi}^{UCD} = \frac{A_{FFi} Z_{fiss}}{A_{fiss}}$$

$$Z_{FFi}^{NUCD} = Z_{FFi}^{UCD} \pm 1; \pm 2...$$

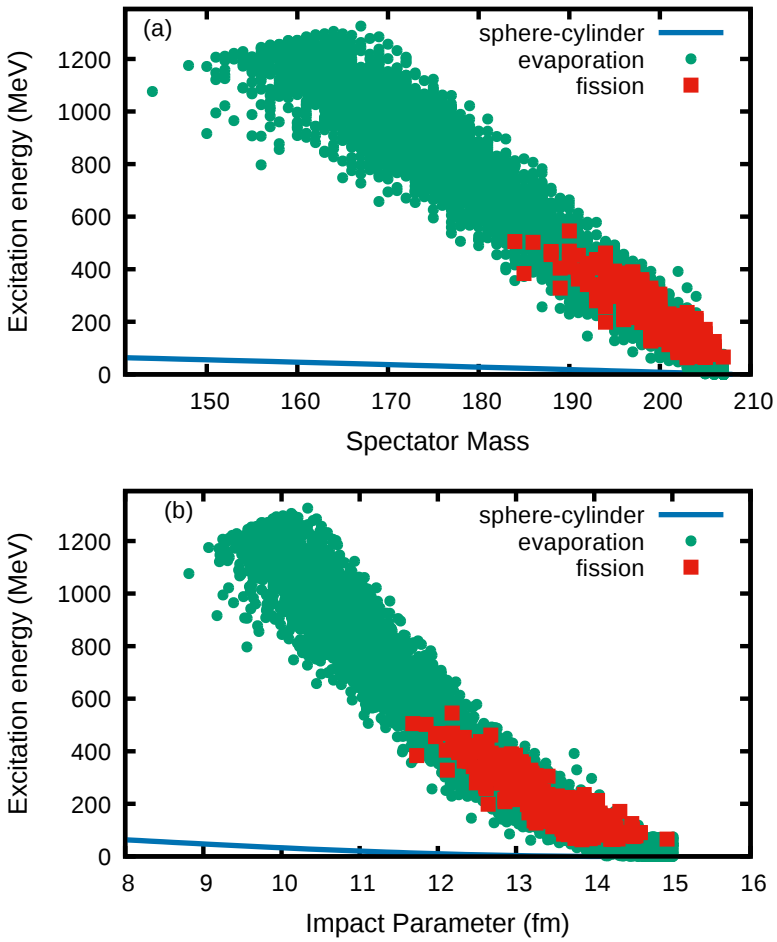
A.V. Karpov, G.D. Adeev Phys.At.Nucl. 65,1596 (2002);

Eur.Phys.J. A 14,169 (2002)

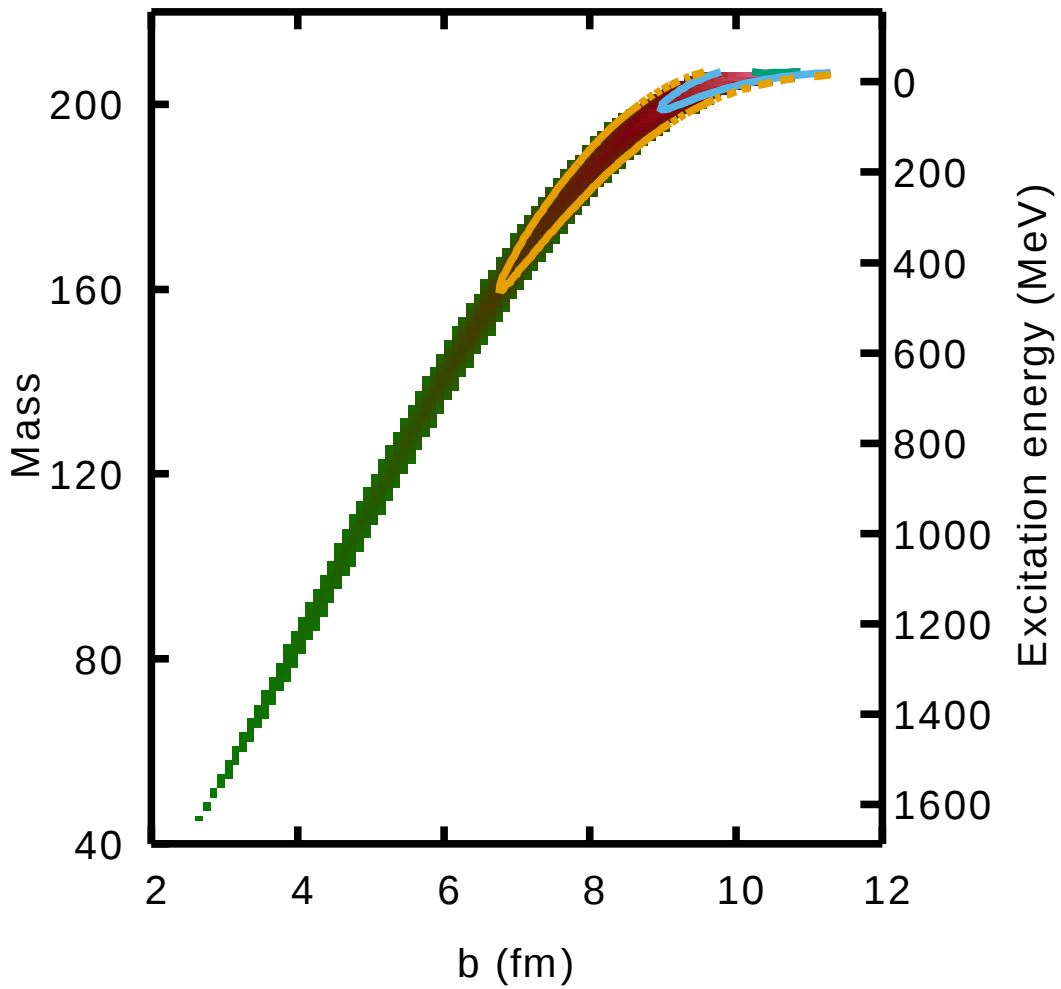
Pb + Pb Collision – Alternative estimations

The spectator mass and excitation energy could be calculated by:

ABRABLA code

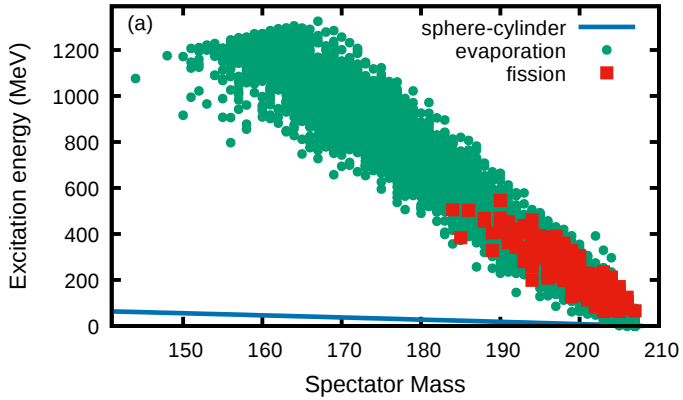


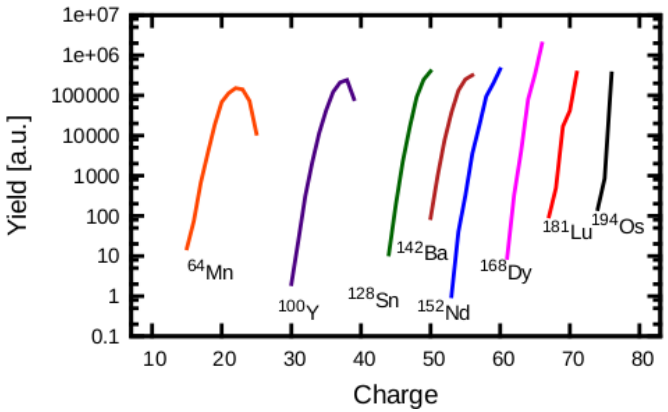
Glauber formula

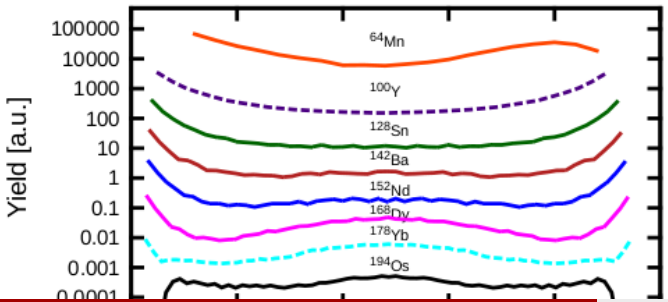


K. M., A. Szczurek, P.N. Nadtochy, arXiv:1708.03716, Phys. Rev. C, 97 (2018) 024604

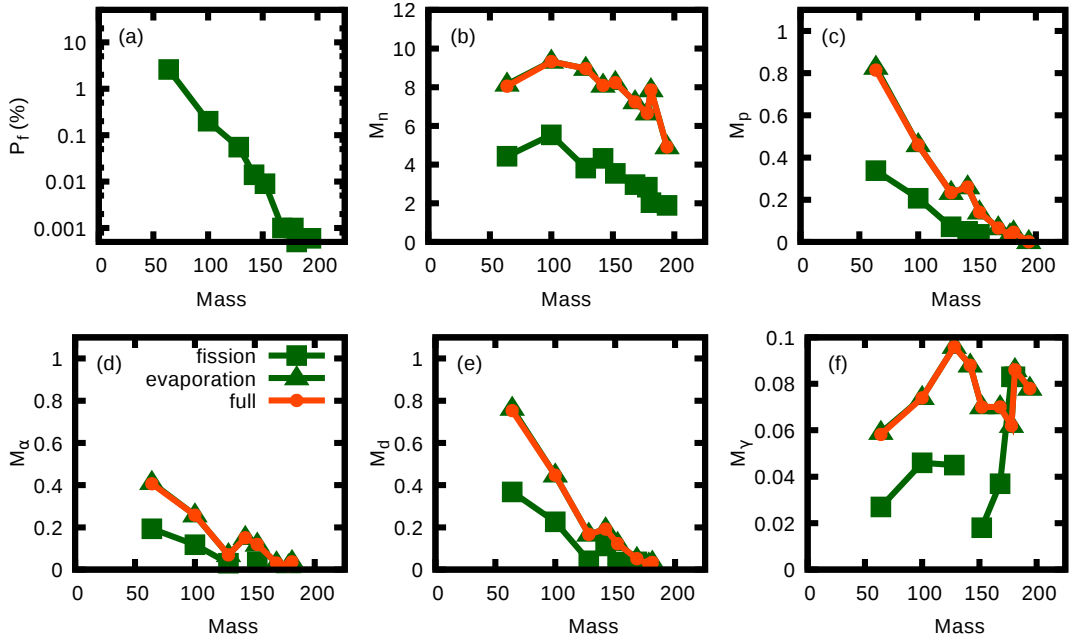
3. Results: Pb + Pb Collision - Dynamic Evolution of Spectator







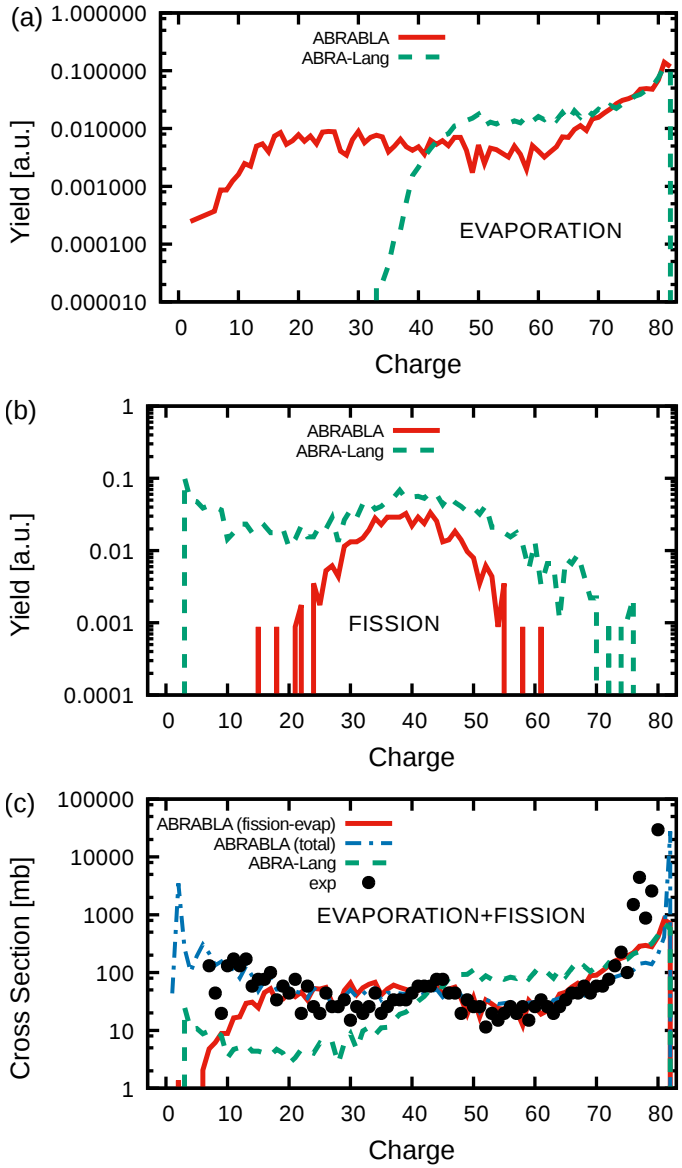
The eight Compound Nuclei have been evaluated in 4D Langevin code to estimate the evaporation and fission channels taking into account the excitation energy predicted with geometrical model (sphere-cylinder).



At high energies the Zero Degree Calorimeters (ZDC) measure neutral particles (RHIC, LHC).
Larger impact parameter (more peripheral collision) – lower fission probability.
K. M., A. Szczurek, P.N. Nadtochy, Phys. Rev. C, 97 (2018) 024604

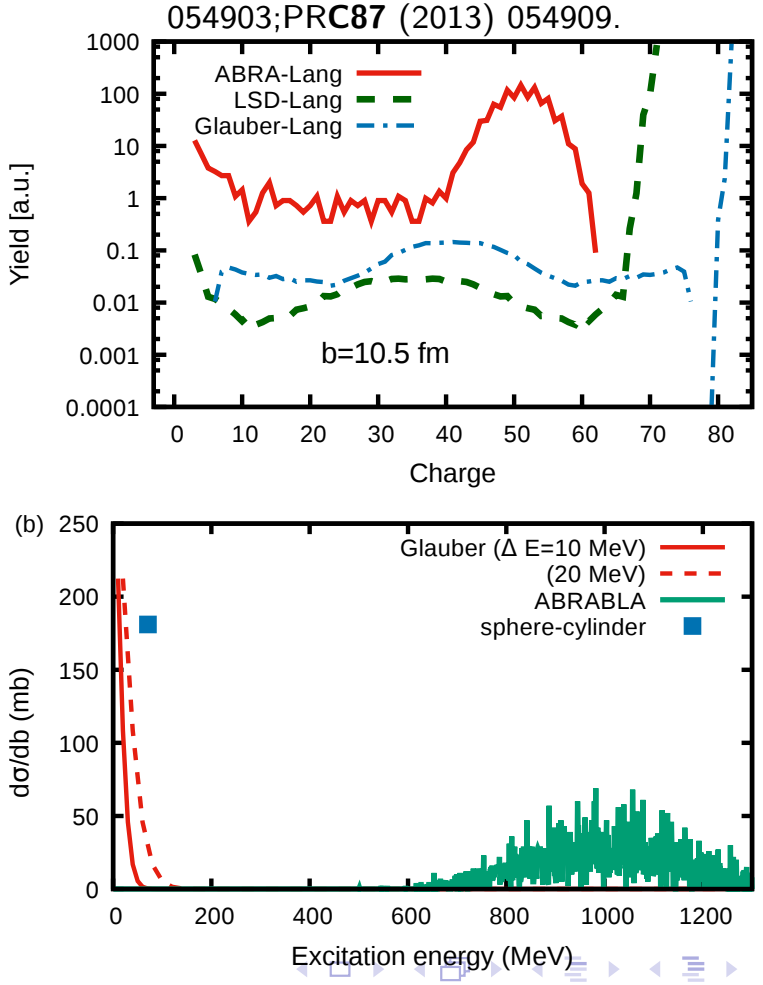
Pb + Pb Collision - Dynamic Evolution of Spectator

ABRA+Langevin



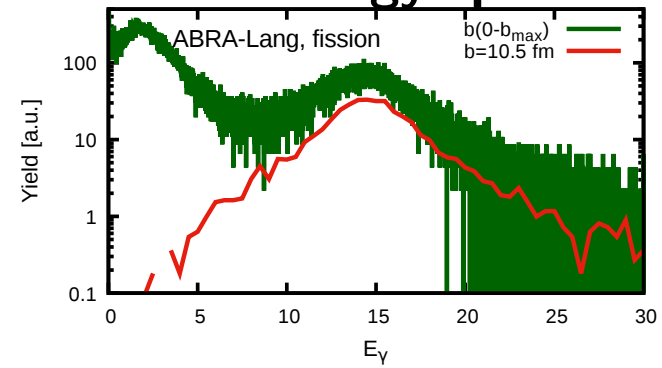
Impact parameter b=10.5 fm

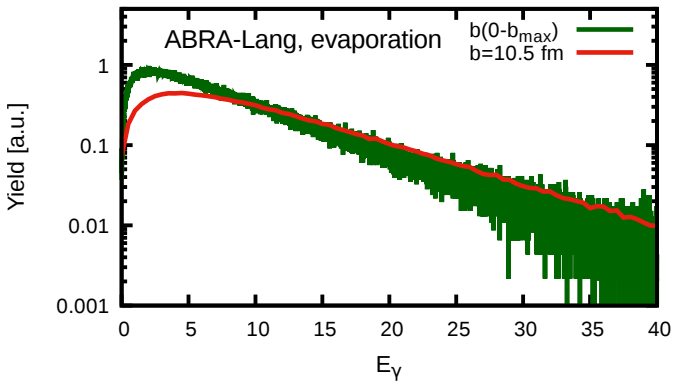
following predictions of A. Rybicki and A. Szczurek, PR**C75** (2007) 054903;PR**C87** (2013) 054909.

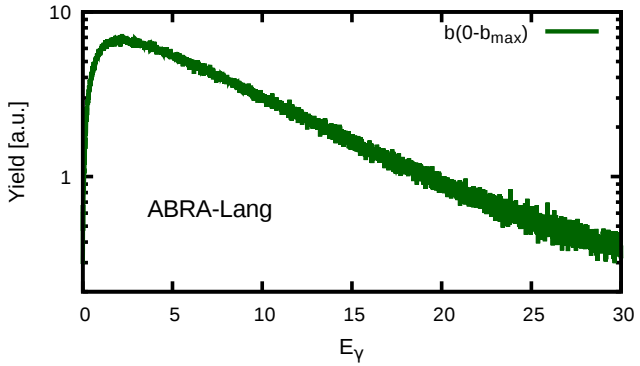


Pb + Pb Collision - Time

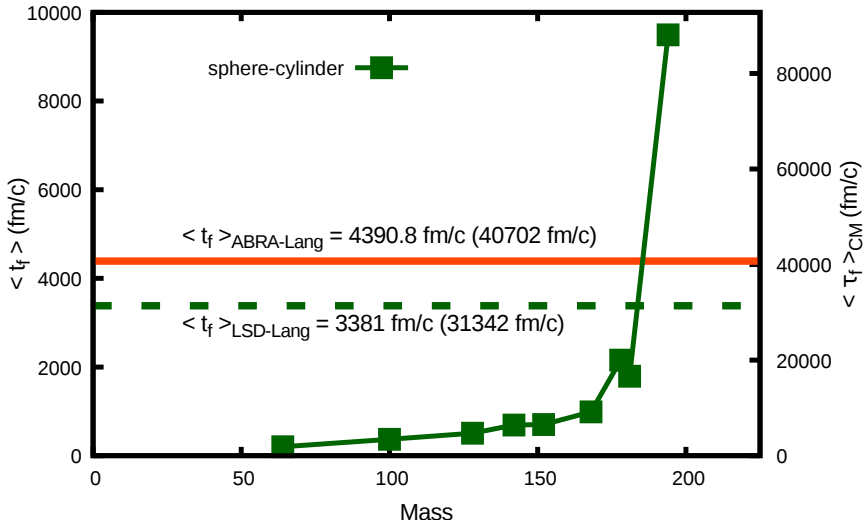
Photon energy spectra

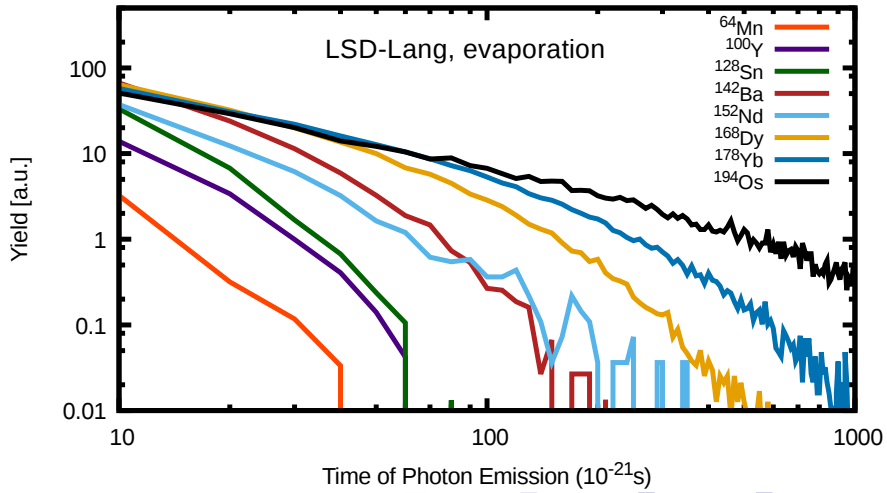






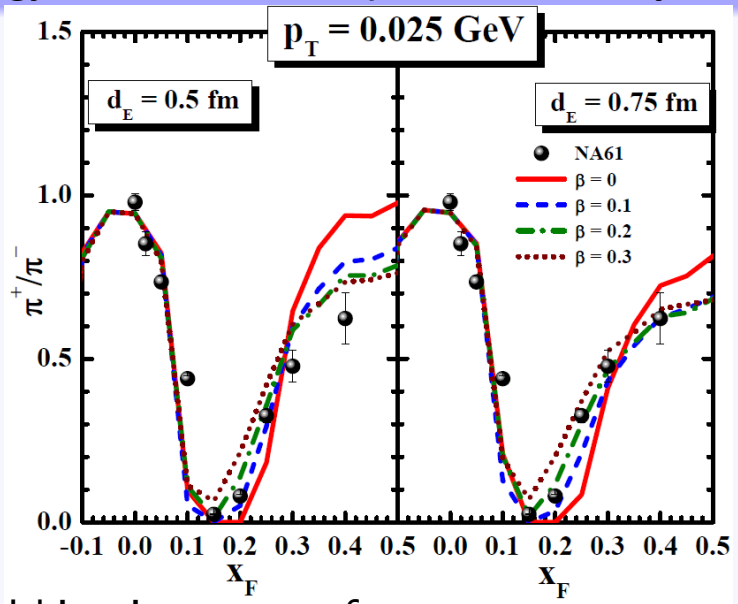
Fission/Photon emission time





Pb + Pb Collision

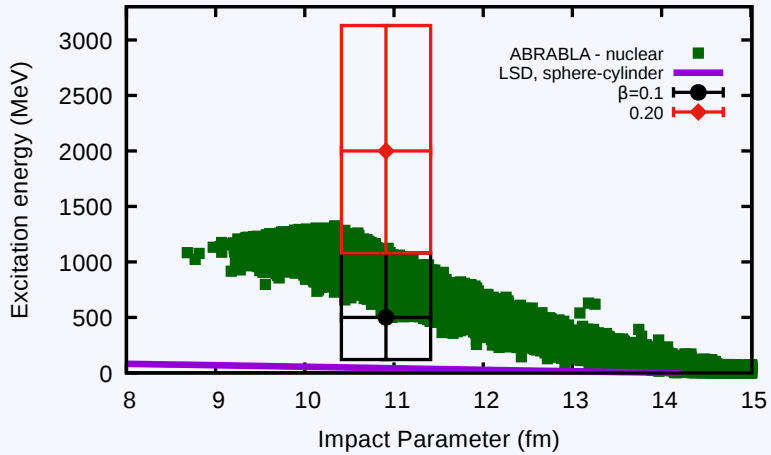
Energy from surface expansion velocity



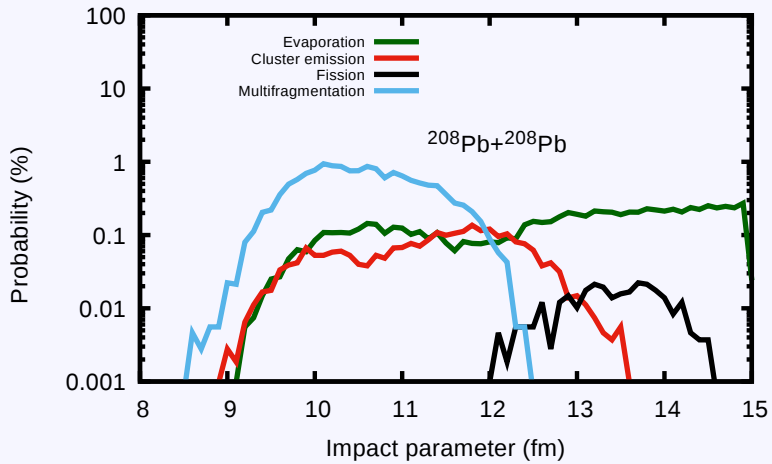
Total kinetic energy of spectator corresponds to β=0.2±0.05 (Calculation done by V. Ozvenchuk)

- EM effects are sensitive to spectator evolution Pb+Pb (in space and time);
- Very different predictions for spectator excitation energy;
- Theoretical tools exist to calculate the corresponding space-time evolution.

Abrasion-Ablation model - energy excitation



Spectator de-excitation processes



Pb + Pb Ultraperipheral Collision

Mass-charge distribution

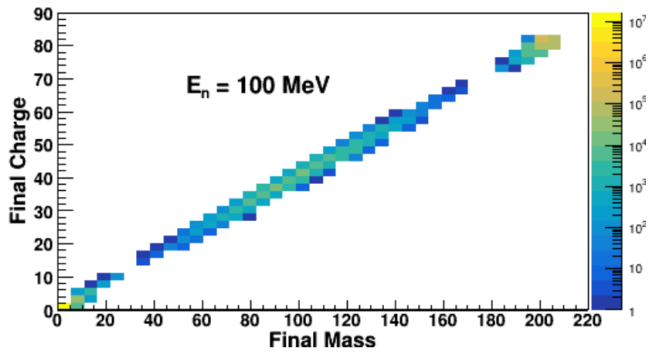


Fig. 4. Final mass-charge distribution of the $n+^{207}\mathrm{Pb} \to A^{*}+X$ at $E_n = 100$ MeV reaction obtained with the HIPSE+GEMINI++ model.

Evaporated particle cross section

Table 1. Total cross sections (in barn) for neutrons and charged particle emission in UPC $^{208}\mathrm{Pb}+^{208}\mathrm{Pb}$ with collision energy $\sqrt{s_{NN}} = 5.02$ TeV calculated with pure GEMINI++, HIPSE+GEMINI++, and EMPIRE. The results for inclusive channels kn and $1pXn$, $1dXn$ and $1\alpha Xn$ are compared with the ALICE data, Refs. [2, 3].

σ [b]	GEMINI++	HIPSE+GEMINI++	EMPIRE	ALICE data
$1n$	90.4	124.1	100.8	108.4 ± 3.9
$2n$	24.9	15.6	25.3	25.0 ± 1.3
$3n$	3.3	4.9	5.9	7.95 ± 0.25
$4n$	2.4	3.6	5.6	5.65 ± 0.33
$5n$	1.5	3.9	3.4	4.54 ± 0.44
n_{tot}	122.6	151.6	152.2	151.5 ± 4.7
$1p$	19.6	28.5	7.1	40.4 ± 1.7
1α	30.7	42.4	64.0	—
$1d$	6.91	5.2	2.7	—
Fission	10.8	18.3	—	—

P. Jucha, M. Klusek-Gawenda, A. Szczurek, M. Ciemala, and K. Mazurek, Phys. Rev. C, 111 (2025) 034901, Acta Phys. Pol. B Proc. Suppl., 18 (2025) 2-A44

More in talk of A. Szczurek.

Summary

- The moddeling of the heavy-ion collisions suffered of the lack of knowledge about time evolution of the spectators and deexcitation channels.
- The presented preliminary calculation estimated the excitation energy of the spectators.
- The dynamic evolution of various spectators produced in peripheral collisions Pb+Pb at 158 GeV/nucleon energies has been investigated.
- The photon energy spectra and emission time are estimated.
- 4D Langevin approach is powerful tool to reproduce existing data and to propose interesting reaction to be done.
- Nuclear processes plays important role in the space-time evolution of the spectator.