Role of the spectator system in electromagnetic effects

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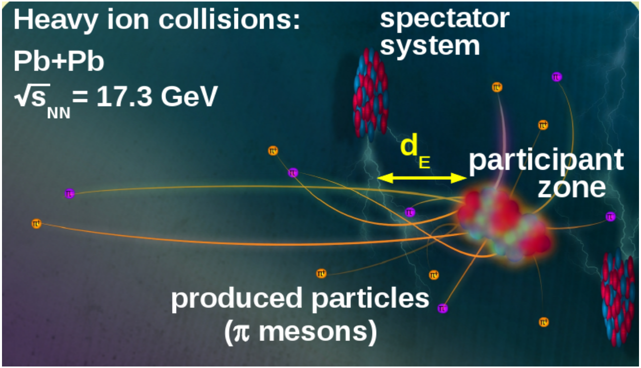
May 24, 2018

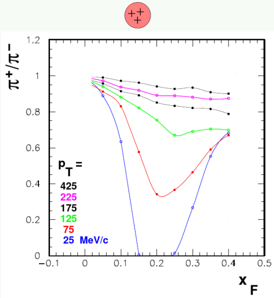
Introduction



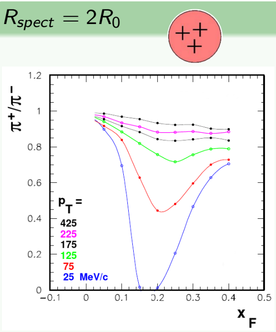
plot by I. Sputowska

- 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

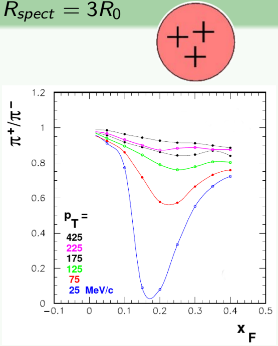
$R_{spect} = R_0$



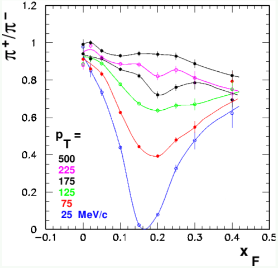
$R_{spect} = 2R_0$



$R_{spect} = 3R_0$



NA49 Pb+Pb at 158 GeV/u



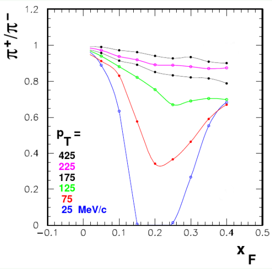
A. Rybicki, Acta Phys. Polon. **B42**, 867 (2011)

EM effects dependence on spectator charge distribution

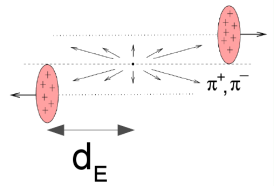
- Shape of the EM distortion is sensitive to the space-time scale of spectator fragmentation
- Allow to get direct information about excitation energy of spectator

Thanks to A. Marcinek

$R_{spect} = R_0$



Spectator-pion distance



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

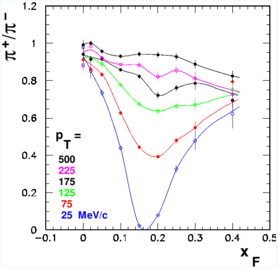
Spectator-pion distance

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

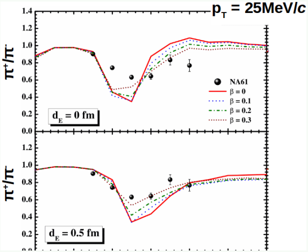
$$x_F = \frac{2p_z}{\sqrt{s_{NN}}}$$

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

NA49 Pb+Pb at 158 GeV/u



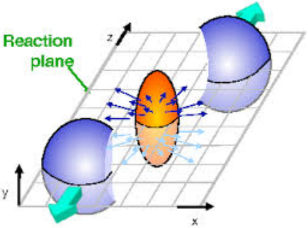
Ar+Sc exp/calculation Thanks to M. Kiełbowicz

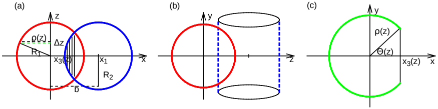


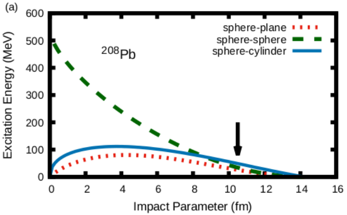
Pb + Pb Collision - Geometrical Scenarios

After collision - very deformed shapes of the spectator -

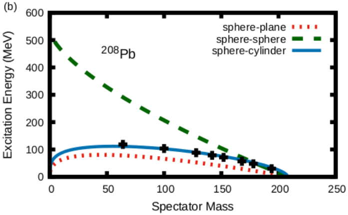
the deformation energy translated to excitation energy of the spectator







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



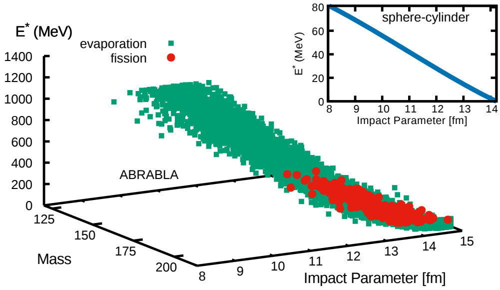
K. M., A. Szczurek, P.N. Nadtochy, APPB Proc. Suppl., 10 (2017) 113, Phys. Rev. C, 97 (2018) 024604

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

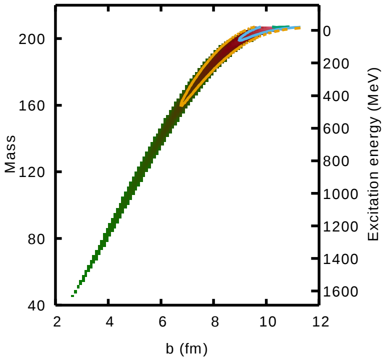
Pb + Pb Collision – Alternative estimations

The spectator mass and excitation energy could be calculated by:

ABRABLA code



Glauber formula



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

Spectator de-excitation as a Stochastic Process

Stochastic (random) process

– is a collection of random variables representing the evolution of some system of random values over time. Instead of describing a process which can only evolve in one way, in a stochastic, or random process, there is some indeterminacy: even if the initial condition (or starting point) is known, there are several (often infinitely many) directions in which the process may evolve.(http://pl.wikipedia.org)

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.

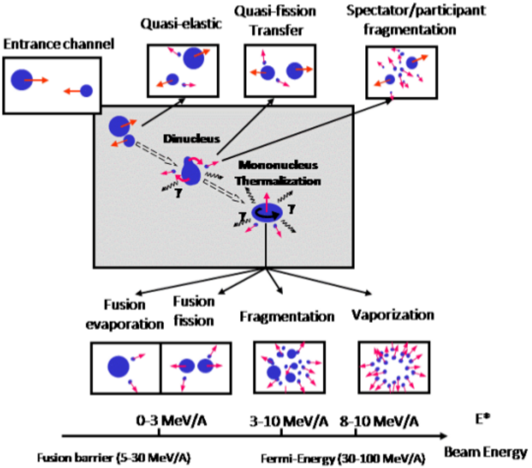


FIG. 33: *Illustration of the diversity of reaction mechanisms. Top: competing phenomena where fossil quasi-target and quasi-projectile survive. Middle: competing phenomena where a compound nucleus is eventually formed at the intermediate reaction stage. The excitation energy and/or beam energy for which these mechanisms appear are given in the bottom part (Adapted from (Lacroix, 2002b)).*

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".
- Monte Carlo method for choosing the shape, initial angular momentum, type and energy of emitted particles....

Coupling to the evaporation

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

Ingredients

Inertia ($[M^{-1}(\vec{q})]_{ij}$); Friction ($\gamma_i(t)$) and fluctuation (g_{ik})

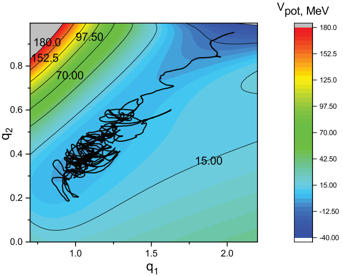
Macroscopic potential

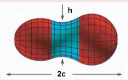
$(V(\vec{q}, K) \rightarrow F(\vec{q}, K) = V(\vec{q}, K) - a(\vec{q})T^2)$

Langevin equations

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

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



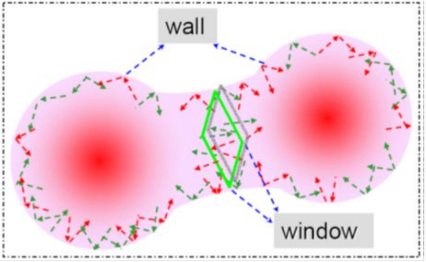


- c - the elongation of the nucleus
- h - constriction coordinate
- α - mass-asymmetry parameter related to the ratio of the masses of nascent fragments

Model Ingredients - Transport Tensors

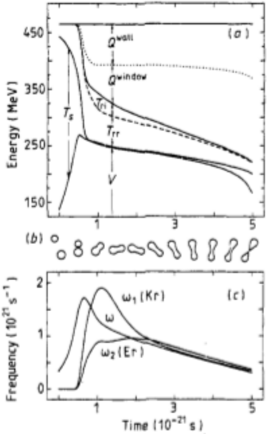
The hydrodynamic approximation for incompressible irrotational flow

- The Navier-Stokes equation solved in Werner-Wheeler method gives the two-body inertia tensor.
- The friction is calculated within one-body mechanism taking into account the Pauli blocking.
- Nuclear shapes without neck - 'wall' formula; other - 'wall-and-window' formula



Dissipation - irreversible transformation of the available energy into other form.

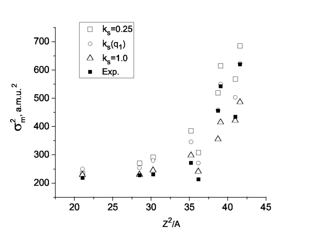
H. Feldmaier Rep.Prog.Phys.,50,915



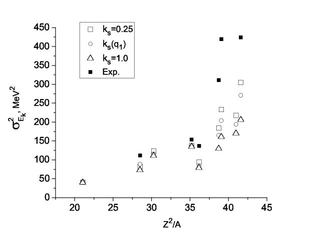
J. Blocki, et al., Ann. Phys. 113, 330 (1978); H. Feldmeier, Rep. Prog. Phys. 50, 915 (1987).

Results: Fission of heavy nuclei at different viscosity

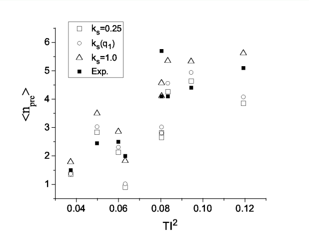
FF mass distribution variance



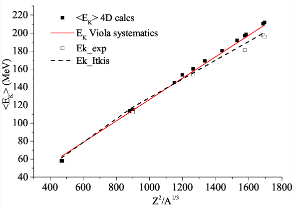
FF kinetic energy distribution variance



Prescission neutron multiplicity



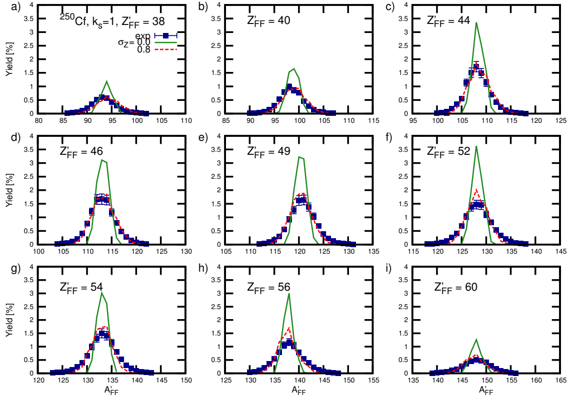
FF mean kinetic energy $\langle E_K \rangle$ as the function of fissility $Z^2/A^{1/3}$

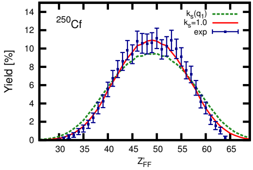


The closed squares are the results of the 4D calculation obtained with k_s=0.25 and γ_K=0.077 $(\mathrm{MeV\ zs})^{-1/2}$.

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

The charge variance is nescessary to reproduce the isotopic distribution.





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

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

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

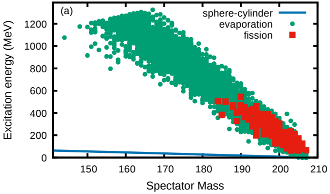
K.M., C. Schmitt, P. Nadtochy PRC 91, 041603(R) (2015),

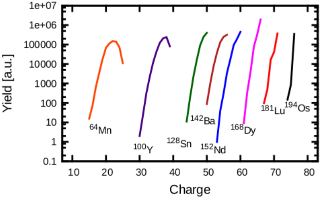
M. Caamano et al. PRC **88**, 024605 (2014)

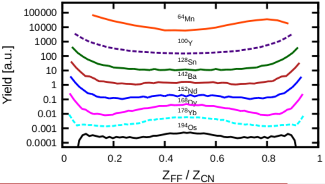
A.V. Karpov, G.D. Adeev
Phys.At.Nucl. 65,1596 (2002);

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

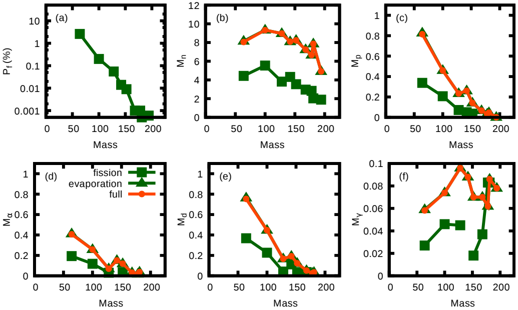
Pb + Pb Collision - Dynamic Evolution of Spectator







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.

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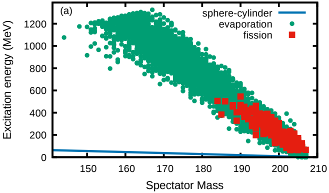
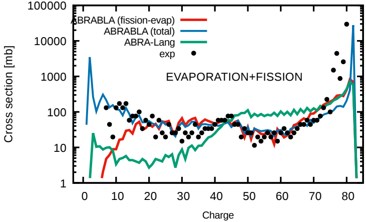
Pb + Pb Collision - Dynamic Evolution of Spectator

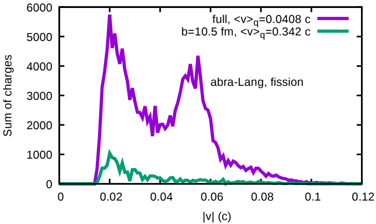




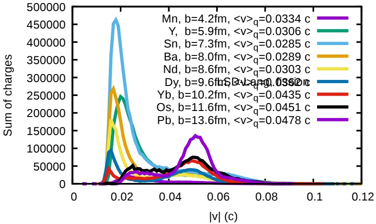
The final distribution of the fission fragments and evaporation residues produced by de-excitation of the spectator, compared to the experimental results of ALADIN
(S. Cecchini, et al., Nucl. Phys. A 707(3), 513 (2002); H. Dekhissi, et al., Nucl. Phys. A 662, 207 (2000)).

The velocity of the final fission fragments in the CM of the spectator.

ABRA+Langevin

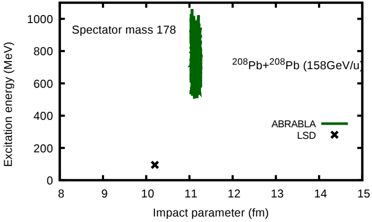


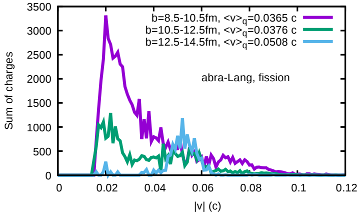
Geometrical model

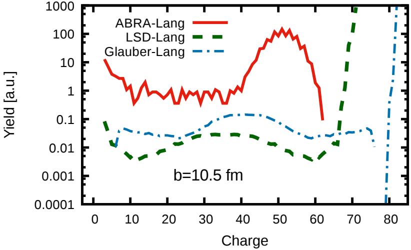


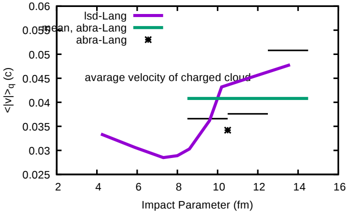
Pb + Pb Collision - Impact parameter b=10.5 fm

Mass spectator A=178 following predictions of A. Rybicki and A. Szczurek, PR**C75** (2007) 054903;PR**C87** (2013) 054909.



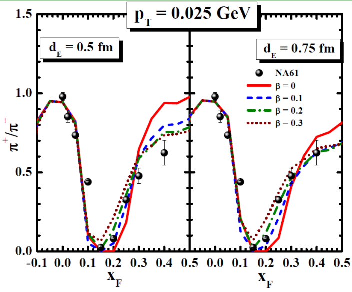






Pb + Pb Collision

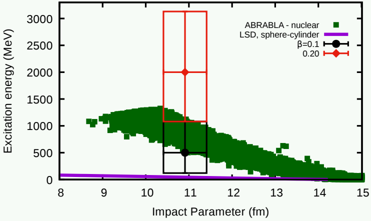
Energy from surface expansion velocity



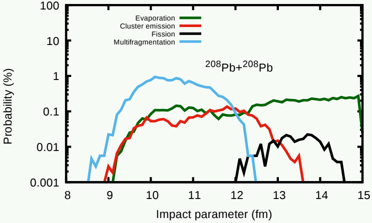
Total kinetic energy of spectator corresponds to β=0.2±0.05 (Calculation done by V. Ozvenchuk)

- 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

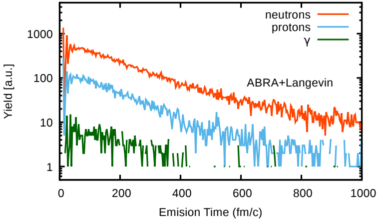


Spectator de-excitation processes

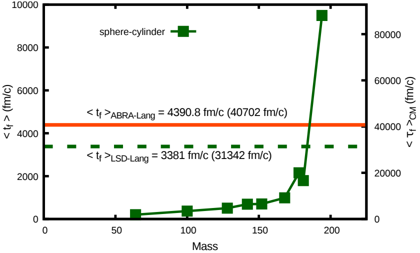


Pb + Pb Collision - Time

Minimal time for evaporation of particle - 200 fm/c

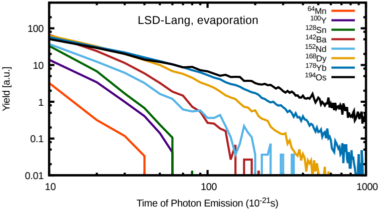


Fission emission time



Time of passing the pion through spectator - 400–2000 fm/c

During the interaction time between pion and spectator only few nukleons could be evaporated:
excitation energy of spectator changes slightly.



Summary

- The moddeling of the heavy-ion collisions suffered of the lack of knowledge about time evolution of the spectators and deexcitation channels.
- **Spectator-induced EM effects bring new information on the space-time evolution of the system created in the nucleus-nucleus collision.**
- **The space-time evolution (expansion) of the spectator system is an important "technical problem" in corresponding phenomenological studies.**
- **A first coordinated effort has been undertaken to investigate this problem from both sides (experimental data on EM effects + phenomenological simulations, versus dedicated nuclear theory).** First results are encouraging: fission seems to be dominant for very peripheral Pb+Pb collisions. Estimated excitation energies start to coincide.
- **These so-called "inter-disciplinary" studies would help us to improve both the longitudinal evolution of the QGP and the excitation and decay of the spectator system.**
- Studying the excitation energy and space-time evolution of the spectator system does not really belong to the classical ultrarelativistic heavy ion domain: it is interesting whether one can use the QGP as a "charged pion factory for spectator studies".

  First proposal in NA61/SHINE Collab., CERN-SPSC-2018-008: Addendum to the NA61/SHINE Proposal SPSC-P-330 of Hadron-Nucleus and Nucleus-Nucleus Study Collisions at the CERN SPS Early Post-LS2 Measurements and Future Plans