Role of the spectator system in electromagnetic effects

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Charged spectators in non-central collisions generate electromagnetic fields. These modify the trajectories of final state charged particles. Opposite charges affect oppositely → charge asymmetries in distributions of produced particles → information on distance $d_E$ and spectator breakup.
$$R_{\text{spect}} = R_0$$

$$R_{\text{spect}} = 2R_0$$

$$R_{\text{spect}} = 3R_0$$

**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
Electromagnetic effects in pion emission

\[ R_{\text{spect}} = R_0 \]

Spectator-pion distance

\[ p_T = \sqrt{p_x^2 + p_y^2} \]

\[ \chi_F = \frac{2p_z}{\sqrt{s_{NN}}} \]

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

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EM effects of the spectator

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Electromagnetic effects in pion emission

**Pb + Pb Collision - Geometrical Scenarios**

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

\[ E_{\text{def}} = E_{\text{surf}}(\text{def}) - E_{\text{surf}}(0) \]

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

208Pb + 208Pb at 158 GeV/A SPS CERN
Pb + Pb Collision – Alternative estimations

The spectator mass and excitation energy could be calculated by:

**ABRABLA code**

![Graph showing ABRABLA code](image1)

**Glauber formula**

![Graph showing Glauber formula](image2)

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, $\alpha$ and $\gamma$.

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

**Langevin equations**
$$\frac{dq_i}{dt} = \sum_j [M^{-1}(q)]_{ij}p_j$$
$$\frac{dp_i}{dt} = -\frac{1}{2} \sum_{j,k} \frac{d[M^{-1}(q)]_{jk}}{dq_i}p_jp_k - \frac{dF(q, K)}{dq_i}$$
$$- \sum_{j,k} \gamma_{ij}(q)[M^{-1}(q)]_{jk}p_k + \sum_j g_{ij}(q)\Gamma_j(t)$$
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. Feldmeier, 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 $\gamma_K=0.077'(\text{MeV} \text{ zs})^{-1/2}$.

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EM effects of the spectator

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Isotopic Distributions: $U + C \rightarrow \text{Cf} \ (E_{lab}=6.2 \ \text{AMeV})$

The charge variance is necessary to reproduce the isotopic distribution.

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

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

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

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

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

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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
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**

- Mn, $b=4.2$ fm, $\langle v \rangle_q = 0.0334$ c
- Y, $b=5.9$ fm, $\langle v \rangle_q = 0.0306$ c
- Sn, $b=7.3$ fm, $\langle v \rangle_q = 0.0285$ c
- Ba, $b=8.0$ fm, $\langle v \rangle_q = 0.0289$ c
- Nd, $b=8.6$ fm, $\langle v \rangle_q = 0.0303$ c
- Dy, $b=9.6$ fm, $\langle v \rangle_q = 0.0362$ c
- Yb, $b=10.2$ fm, $\langle v \rangle_q = 0.0435$ c
- Os, $b=11.6$ fm, $\langle v \rangle_q = 0.0451$ c
- Pb, $b=13.6$ fm, $\langle v \rangle_q = 0.0478$ c

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EM effects of the spectator

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Dynamical evolution of the spectator system

**Pb + Pb Collision - Impact parameter b=10.5 fm**

Mass spectator $A=178$ following predictions of A. Rybicki and A. Szczurek, PRC75 (2007) 054903; PRC87 (2013) 054909.

- **Graph 1:** Spectator mass 178. 
  - $^{208}\text{Pb}^{208}\text{Pb}$ (158 GeV/u)
  - Excitation energy (MeV) vs. Impact parameter (fm)
  - Graph shows different predictions (ABRABLA, LSD) with markers indicating data points.

- **Graph 2:** Sum of charges vs. $|v|$ (c). 
  - Different impact parameters (b=8.5-10.5 fm, b=10.5-12.5 fm, b=12.5-14.5 fm) with different colors.
  - Graph includes abra-Lang, fission prediction.

- **Graph 3:** Average velocity of charged cloud $<|v|>$ (c) vs. Impact Parameter (fm).
  - Comparison of LSD-Lang and ABRABLA with markers and lines.

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Dynamical evolution of the spectator system

**Pb + Pb Collision**

Energy from surface expansion velocity

Total kinetic energy of spectator corresponds to $\beta = 0.2 \pm 0.05$ (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

Time of passing the pion through spectator - 400–2000 fm/c
During the interaction time between pion and spectator only few nucleons could be evaporated: excitation energy of spectator changes slightly.
Summary

- The modeling 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