Nuclear processes in ultrarelativistic, ultraperipheral Pb+Pb collisions

K. Mazurek, P. Jucha, M. Kłusek-Gawenda, A. Szczurek, M. Ciemała

The Niewodniczański Institute of Nuclear Physics - PAN, Kraków, Poland

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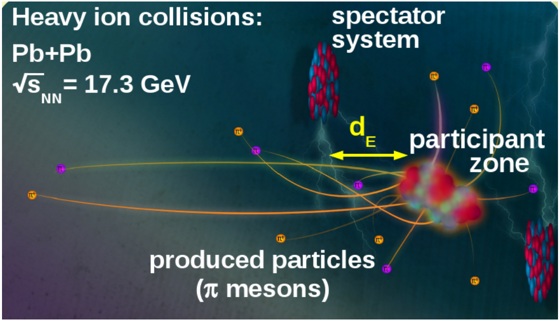
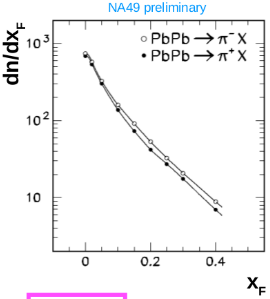
Modeling a Peripheral Heavy - Ion Collisions



- The collision takes place at a given impact parameter b.
- The two charged spectator systems follow their initial path.
- The participating system evolves until pions are produced.
- Charged pion trajectories are modified by EM interaction.
- **The spectator systems undergo a complicated nuclear deexcitation/fragmentation process.**
- The pion emission – single point in space. The emission time t_E is a free parameter.

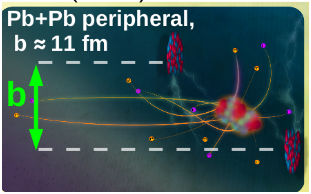
•**The fragmentation of the spectator systems was neglected**, the influence of participant charge, strong Final State Interaction were not considered.

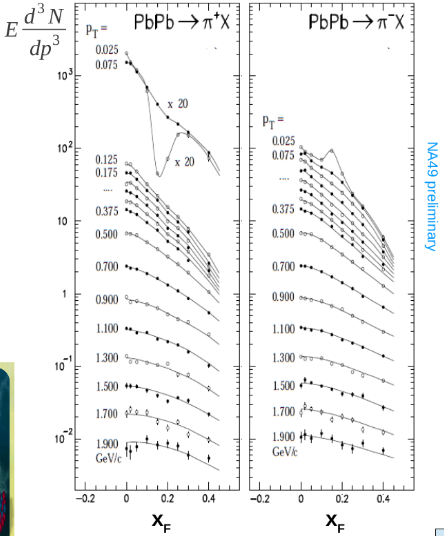
Modeling a Peripheral Heavy - Ion Collisions



$$x_F = \frac{p_L}{p_L^{beam}}$$

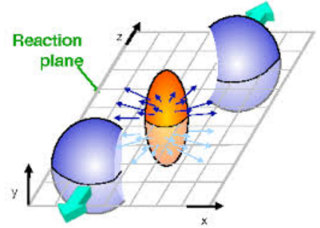
(c.m.s.)

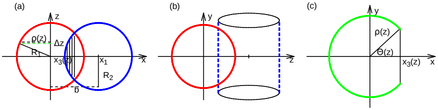


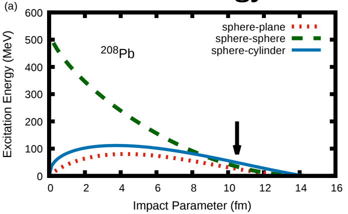


Pb + Pb Collision - Geometrical Scenarios

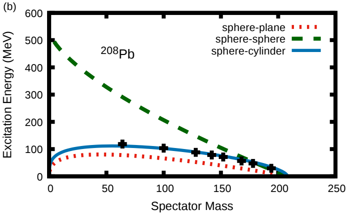
After collision - very deformed shapes of the spectator -
the deformation energy translated to excitation energy of the spectator







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

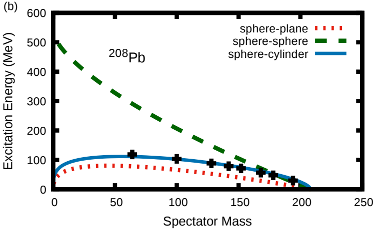


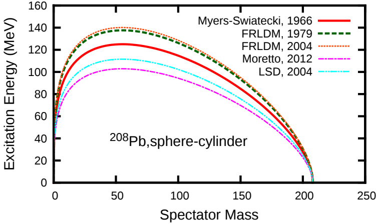
K. M., A. Szczurek, P.N. Nadtochy, APPB Proc. Suppl., 10 (2017) 113, arXiv:1708.03716

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

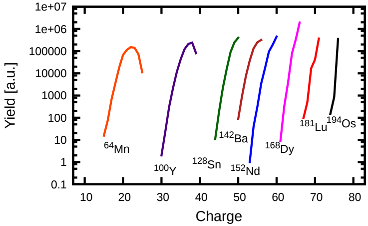
Pb + Pb Collision - Dynamic Evolution of Spectator

The excited Compound Nuclei (eight) have been evaluated in 4D Langevin code to estimate the evaporation and fission channels. We assume $\frac{Z_S}{A_S} = \frac{Z_{Pb}}{A_{Pb}}$

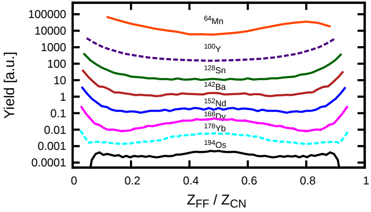




Evaporation Residue charge distribution



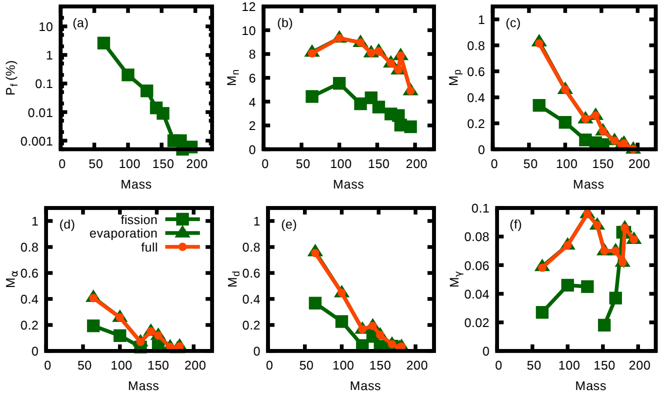
Fission Fragment charge distribution



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

Pb + Pb Collision - Particle Multiplicities

At high energies the Zero Degree Calorimeters (ZDC) measure neutral particles (RHIC, LHC).



The fission probability and the multiplicities of emitted n, p, α, d and γ in fission and evaporation channels.

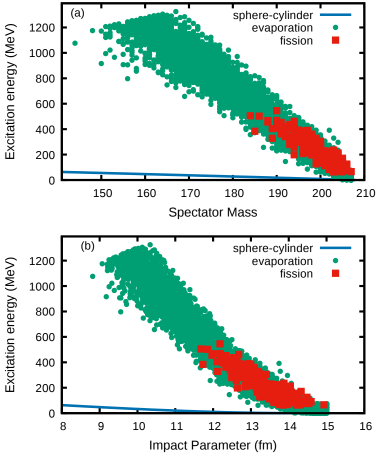
Larger impact parameter (more peripheral collision)

– lower fission probability.

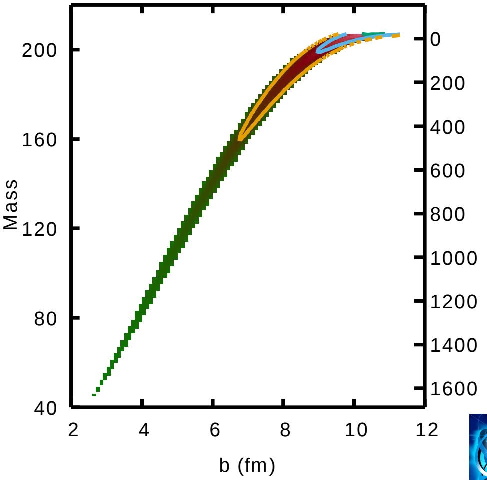
Pb + Pb Collision – Alternative estimations

The spectator mass and excitation energy could be calculated by:

ABRABLA code



Glauber formula



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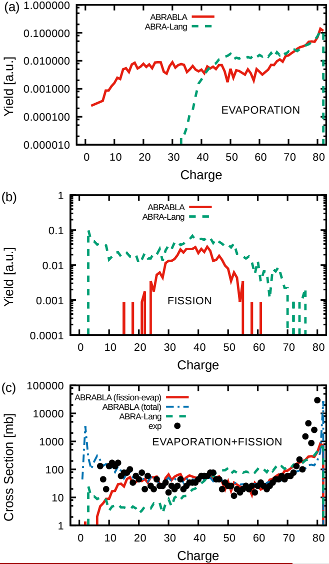
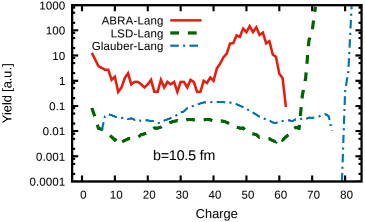
Pb + Pb Collision - Dynamic Evolution of Spectator

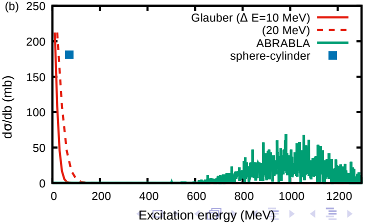
ABRA+Langevin



Impact parameter b=10.5 fm

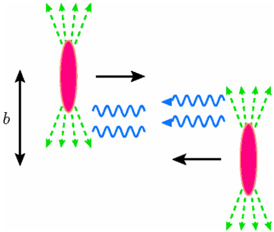
following predictions of A. Rybicki and A. Szczurek, PR**C75** (2007) 054903;PR**C87** (2013) 054909.

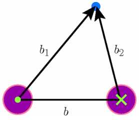




Equivalent Photon Approximation - EPA model

The equivalent photon approximation (EPA) is standard semiclassical alternative to the Feynman rules for calculating the cross section of EM interaction. Due to coherent action of all the protons in the nucleus, the EM field surrounding the ions is very strong. Produce the 'equivalent' or 'quassireal' photons.





M. Kłusek-Gawenda, PRC82,014904

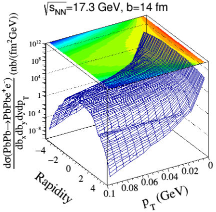
Double scattering production of l^+l^- pairs using the b-space equivalent photon approximation (EPA) model (G. Baur, L. Filho, NPA 518(4), 786 (1990);

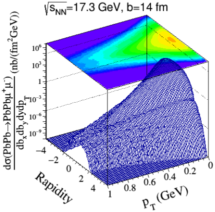
$$\sigma_{A_1A_2\to A_1A_2 l^+l^-}(\sqrt{s_{A_1A_2}}) =$$

$$= \int \frac{d\sigma_{\gamma\gamma\to l^+l^-}(W_{\gamma\gamma})}{d\cos\theta} N(\omega_1, b_1) N(\omega_2, b_2) S^2_{abs}(b)$$

$$\times \quad 2\pi b db d\overline{b_x} d\overline{b_y} \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma} dY_{l^+l^-} \; d\cos\theta,$$

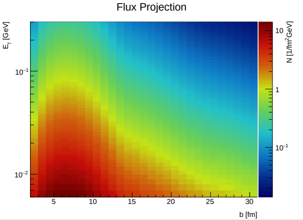
where $N(\omega_i, b_i)$ -photon fluxes; $W_{\gamma\gamma} = M_{l^+l^-}$ - invariant mass; $Y_{l^+l^-} = (y_{l^+} + y_{l^-})/2$ - system rapidity; θ - the scattering angle in the $\gamma\gamma \to l^+l^-$ center-of mass system. The gap survival factor S^2_{abs} assures that only ultra-peripheral reactions are considered. (K.M. EPJA, 58 (2022) 245)



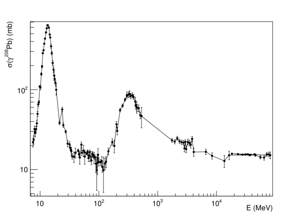


Ultraperipheral Pb+Pb collision

Photon production/absorption

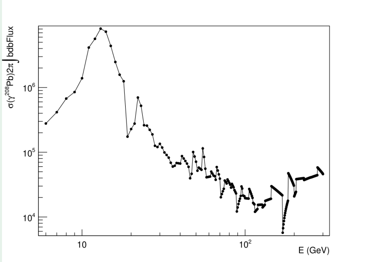


Photons flux.



Experimental photoabsorption cross-section as a function of photon energy with error bars. (J. Ahrens, Nucl. Phys. A 446, 229 (1985)).

Partial cross-section



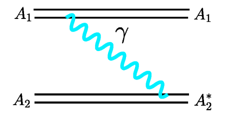
The cross section contains photon flux ($N(E_\gamma, b)$), photoabsorbtion cross section ($\sigma_{abs}(E_\gamma)$) and the neutron emission probability density ($P_k(E_\gamma)$)

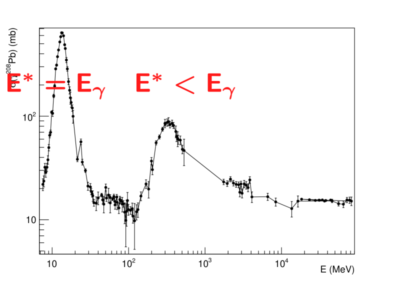
$$\sigma_{\gamma,kn} = \int \int P_k(E_\gamma)\sigma_{abs}(E_\gamma)N(E_\gamma, b)2\pi bdbdE_\gamma.$$

The hot nucleus deexcites by emission of particles and photons, but also fission.

Method

Photon absorption by Pb nucleus

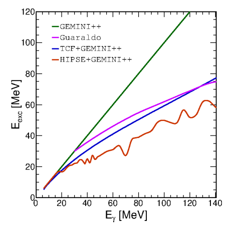




Experimental photoabsorption cross-section as a function of photon energy with error bars.
(J. Ahrens, Nucl. Phys. A 446, 229 (1985)).

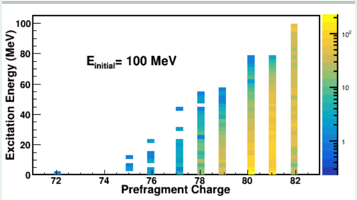
Models of nuclear deexcitation

- **GEMINI++** - statistical model of nucleus deexcitation (PRC 82, 014610)
- **TCF** - Two-component formula where the probability density from GEMINI++ is corrected by $\mathbf{P(E^*; E_\gamma) = c_1(E_\gamma)\delta\left(E^* - E_\gamma\right) + c_2(E_\gamma)/E_\gamma}$.
- **HIPSE** - Heavy-ion particle emission generator, pre-equilibrium physics is included (PRC 69, 054604).
- **EMPIRE** - a modular system of nuclear reaction codes for advanced modeling of nuclear reactions using various theoretical models. PCROSS or HMS for photon induced reactions (Nucl. Data Sheets 108, 2655).



Results - HIPSE simulation (n+Pb) E_n = 6-140 MeV

Nuclear deexcitation

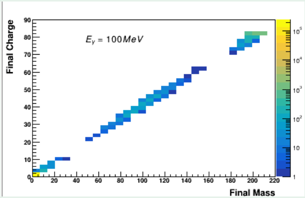


⇐

initial;

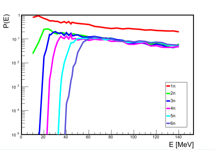
final

⇒



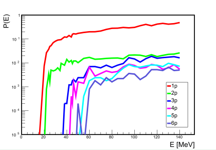
Evaporated Particle Multiplicity

Probabilities of emission 1,2,3,4 particles provided by HIPSE approach.

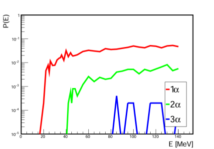


Neutron

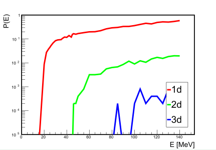
(Thanks to S. Słotwiński)



Proton

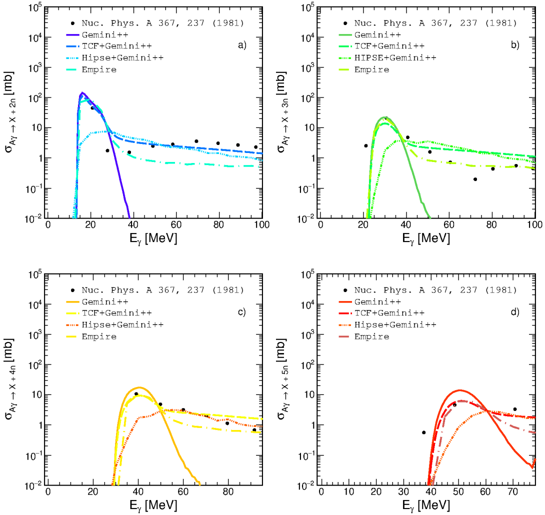


Alpha



Deutron

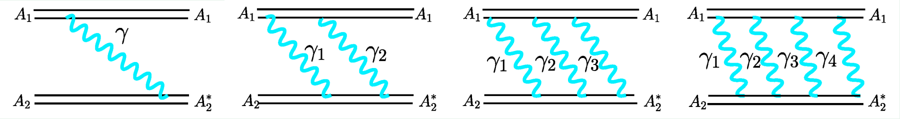
Results - Comparison with experiment (1)



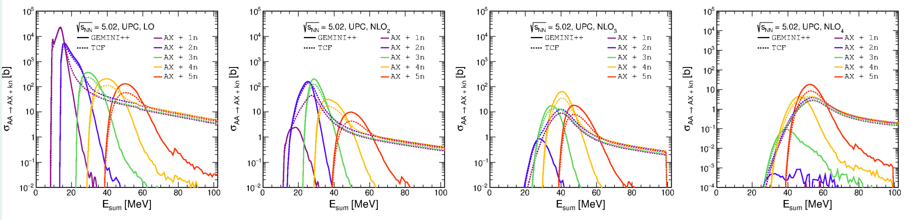
Different neutron multiplicity. Experimental data and estimates from the EMPIRE and HIPSE models.
Reference: Nuc. Phys. A 367, 237 (1981)

Single nucleus excitation

Multiple photons hit single nucleus



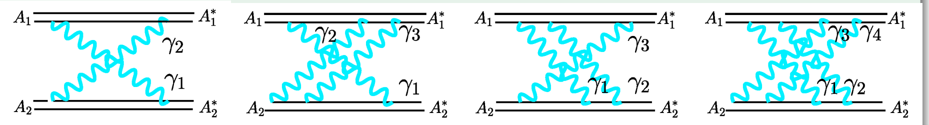
Neutron emission



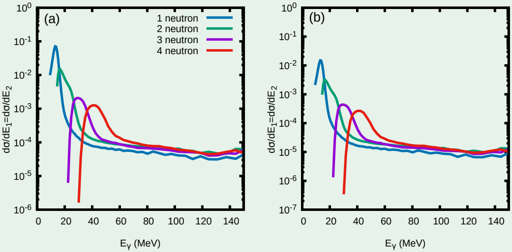
Distribution in excitation energy for a given number of exchanged photons and a given number of emitted neutrons.

Mutual nuclei excitations

Multiple photons hit single nucleus



Mutual excitation inset



The differential cross section for emission of a given number of neutrons from one nucleus and 1 neutron (a) and 2 neutrons (b) from one of the nucleus mutually excited by the other nucleus in mutual excitation.

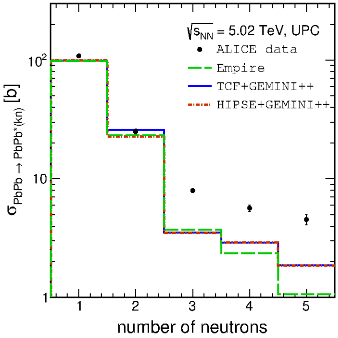
Results

Multiplicity of emitted particle

Results of our calculations using photon flux, photoabsorption cross section, and de-excitation models (EMPIRE and HIPSE) compared to values obtained from ALICE.

σ [b]	EMPIRE	HIPSE	ALICE
$1n$	111.12	136.1	108.4 $\pm$3.9
$2n$	32.75	19.63	25.0$\pm$1.3
$3n$	4.75	7.73	7.95 $\pm$0.25
$4n$	2.40	6.04	5.65 $\pm$0.33
$5n$	1.19	5.29	4.54 $\pm$0.44
n_{tot}	152.21	174.79	151.5 $\pm$4.7
1p	**0.78**	**7.73**	-
2p	-	**2.78**	-
3p	-	**1.66**	-
1α	**0.05**	**0.96**	-
2α	-	**0.57**	-
1d	**0.89**	**5.24**	-

ALICE data



Summary

- The moddeling of the heavy-ion collisions suffered of the lack of knowledge about time evolution of the spectators and deexcitation channels.
- Our 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.
- Spectator-induced EM effects in charged pion production give insight to space-time properties of the system of hot and dense matter created in heavy ion collisions.
- They suggest a picture of the longitudinal evolution of the system at the initial stage at CERN SPS energies largely governed by the energy-momentum conservation.
- The impact parameter equivalent photon approximation is well suitable for investigating the electromagnetic effects.
- Single and multiple photon production was estimated.
- Single and mutual nuclei excitation by photons absorption were investigated.
- The neutron and charged particle emission has been studied by TCF, HIPSE and EMPIRE approaches and compared to ALICE data.