WHAT SHALL WE DO WITH THE SPECTATOR SYSTEM IN ULTRARELATIVISTIC HEAVY-ION COLLISIONS?*

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This paper briefly reviews the first results of a coordinated study aimed at the clarification of the interplay between spectator fragmentation and electromagnetic phenomena in ultrarelativistic heavy-ion collisions at CERN SPS energies. The available experimental and phenomenological results are put in the context of recent theoretical calculations.

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1. Introduction

The IFJ PAN group in the NA61/SHINE experiment at the CERN SPS studies the electromagnetic (EM) effects in ultrarelativistic nucleus–nucleus collisions. These effects are induced by the nuclear "spectator" remnant on the spectra of charged particles produced in the course of the collision [1, 2]. The charged particles originate from the system of hot and dense matter (possibly the quark–gluon plasma) created in the "participant" zone. Selected results of such studies were presented at this conference in recent years [3]. One of them was the demonstration that EM effects can be sensitive to the space-time evolution of the spectator system [4].

In this paper, we present the first results of our coordinated effort aimed at studying the interplay between the latter EM effects on charged pions and the processes characteristic to the fragmentation of the spectator system. We note that the former are characteristic to the ultrarelativistic collision at the c.m.s. energy scale of about 10 GeV/nucleon, while the latter are governed

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by spectator excitation energies of the order of 0.1–1 GeV for the entire spectator system. This interplay is studied "from both sides", that is, by a direct experimental and phenomenological analysis of spectator-induced EM effects, put in contrast to dedicated model calculations based on state-of-the-art nuclear theory.

2. Electromagnetic effects in ultrarelativistic nuclear collisions

A simplified sketch of the high-energy nucleus–nucleus collision, based on the model proposed in Ref. [5], is shown in Fig. 1 (a). The system of hot and dense matter created from the participant nucleons (dark grey/red) is characterized by local collective velocities resulting from energy-momentum conservation (see Ref. [6] for comparison). This system is the dominant, if not unique, very abundant source of newly produced particles (mostly π mesons). The two spectator systems (light grey/yellow) fly away from the collision with essentially unchanged velocities. The trajectories of π^+ (π^-) mesons will be modified by the electromagnetic repulsion (attraction) induced by the spectator systems. This effect will depend on the longitudinal distance d_{E} between the emission zone of the pion and the spectator.

Very recently, this effect has been observed in non-central Ar+Sc collisions at $150\,A\,\mathrm{GeV}/c$ beam momentum [7], which corresponds to $\sqrt{s_{NN}} =$ 16.8 GeV in the nucleon+nucleon c.m.s. This is shown in Figs. 1 (b)–(d). The figures show the ratio of produced charged pions drawn as a function of $x_{\mathrm{F}} = p_{\mathrm{L}}^{\mathrm{pion}}/p_{\mathrm{L}}^{\mathrm{beam\ nucleon}}$, where p_{L} is the particle longitudinal momentum in the $N{+}N$ c.m.s. A sizeable depletion of the π^+/π^- ratio is evident from the experimental data, the largest effect being apparent for pions moving along the spectator system at the same velocity (or, equivalently, the same rapidity, $y \approx y_{\mathrm{beam}}$). This corresponds to $x_{\mathrm{F}} \approx 0.15 \approx m_\pi/m_N$ at low values of transverse momentum p_{T} considered here. We note that the latter depletion is the first observation of the spectator-induced EM effect in such a small colliding system[1] at the CERN SPS. For comparison, analogical experimental data obtained by the NA49 experiment [8] on peripheral Pb+Pb collisions at $158\,A\,\mathrm{GeV}$ beam energy ($\sqrt{s_{NN}} = 17.3$ GeV) are shown in Figs. 1 (e)–(f). Here, the effect is much larger thanks to the larger spectator charge.

The experimental data shown in Fig. 1 are compared to the results of our phenomenological Monte Carlo studies of the EM effect. The model which we applied is partially similar to that used in Refs. [3, 4]. Pions are emitted from a single formation point and the assumed distance d_{E} between the pion and the spherical, homogeneously charged spectator is

[1] The above Ar+Sc system consists of typically about 50 participant nucleons and the argon spectator charge is only about 8 elementary units [7]. The peripheral Pb+Pb system corresponds to an average of 54 ± 11 participating nucleons with a spectator charge of about 70 e.u. and an average impact parameter of 10.9 ± 0.5 fm [9].

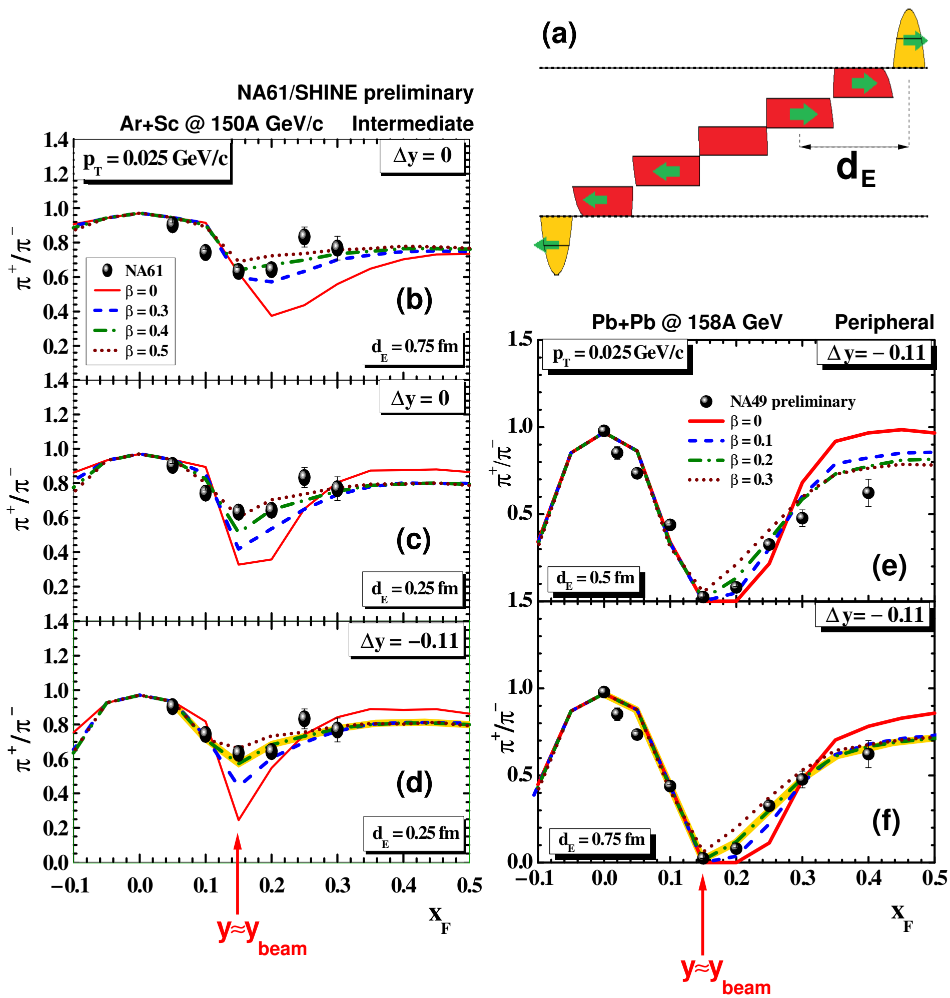

Fig. 1. (Colour on-line) (a) Schematic sketch of the ultrarelativistic nucleus–nucleus collision made according to the model [5]. (b), (c), (d) Ratio of the number of emitted π^+ over π^- measured in Ar+Sc collisions at intermediate centrality by the NA61/SHINE Collaboration [7]. The experimental data points are compared to model simulations described in the text. The different combinations of d_{E}, β and Δy are indicated in the plots. The combination which we judge to give the optimal description of the data is indicated by the thick light grey/yellow line. (e), (f) Similar comparison as for the three previous panels, made for peripheral Pb+Pb collisions measured by the NA49 experiment [8]. The optimal description of experimental data is indicated by the thick light grey/yellow line. The plots are redrawn from Refs. (a) [5], (b)–(d) [7], (f) [10].

taken as a free parameter. Additionally, the simulation allows for a radial expansion of the spectator with a given assumed surface velocity β, and for a change of spectator rapidity Δy with respect to the beam rapidity. This comparison demonstrates that a stable spectator ($\beta = 0$) cannot describe the EM effect measured in Ar+Sc collisions. The size and shape of the depletion of the π^+/π^- ratio induced by repulsion of π^+ and attraction of π^- appears to depend on the three parameters enumerated above, and a reasonable description is achieved by assuming a sizeable surface expansion velocity ($\beta \approx 0.4$), combined with the distance $d_{\mathrm{E}} = 0.25$ fm, and with a decrease in rapidity $\Delta y = -0.11$. The situation is altogether similar for peripheral Pb+Pb collisions where the best description is presently obtained for $d_{\mathrm{E}} = 0.75$ fm, $\beta \approx 0.2$, and again a backward shift in rapidity by $\Delta y = -0.11$. We interpret this shift in rapidity as the indication for the presence of not only the spectator charge, but also a part of the participant charge in the effective charged cloud seen by the pion on its trajectory. The presence of net positive participant charge at high rapidity (below that of the beam) and close behind the spectator system is natural to expect from the model of the high-energy collision discussed above; this is apparent in Fig. 1 (a). The same is valid for fast pions being produced at a small distance behind the spectator system, which supports the values of $d_{\mathrm{E}} \approx 0.25$–$0.75$ fm which emerge from our Monte Carlo analysis. What remains to be clarified is to what extent the expansion of the charge cloud should be attributed to the participant charge, and to what extent it reflects the fragmentation of the spectator system. For that reason, our studies of the space-time evolution of the spectator system will be reported below.

3. Evolution of the spectator system

Our analysis of the spectator system is focused on non-central Pb+Pb collisions at 158 A GeV beam energy. At this energy, basic kinematical considerations can give us an initial estimate of the time spent by a fast pion at $p_{\mathrm{T}} = 0$ in close spectator vicinity. This is of the order of 400–2000 fm/c in collision c.m.s. Therefore, we are mostly interested in the first few hundreds of fm/c of spectator evolution in its own c.m.s.

This evolution is studied within a hybrid approach. First, the spectator excitation energy and the probabilities of its de-excitation processes are computed within the abrasion–ablation statistical model (ABRABLA) [11, 12]. The latter model was applied with success to nuclear collisions at lower energies, and its application to ultrarelativistic Pb+Pb reactions is described in Ref. [13]. Subsequently, for the ensemble of spectators obtained by the abrasion part of the ABRABLA code, their evolution in time is computed by solving transport equations of Langevin type. The details of the model can be found in Ref. [14]. At the end of the computation process, we obtain information on masses and charges of fission fragments and evaporation residua. Information on energy and multiplicity of emitted particles as well as their emission times is also available. Until the present moment, our study focused on the fission and evaporation channels of spectator de-excitation.

In Fig. 2 (a), we present the distribution of spectator excitation energies obtained in our ABRABLA sample of non-central Pb+Pb collisions. As apparent from the plot, the range of impact parameters available in this sample is representative for the experimental sample of Pb+Pb reactions from Fig. 1 (around 11 fm on the average [9]). The ABRABLA calculation is compared to a geometrical estimate obtained by assuming a sphere-cylinder collision, with the resulting deformation of spectator shape translated into excitation energy using the Lublin–Strasbourg approach based on the Liquid Drop model [13]. The excitation energies obtained in the two approaches differ very significantly. For comparison, the figure includes also the estimate for the kinetic energy of a radially expanding charged sphere with the surface velocity $\beta = 0.2 \pm 0.05$ which gives the optimal description of the EM effect on the π^+/π^- ratio (thick light grey/yellow line in Fig. 1 (f)). It is evident from the discussion made in Section 2 that one should restrain from formulating too strong conclusions from this comparison: once we recognize the presence of net participant charge on top of spectator charge to be responsible for the EM effect, the former will contribute to the effective expansion of this charge cloud “seen” by the emitted pion. This will add up

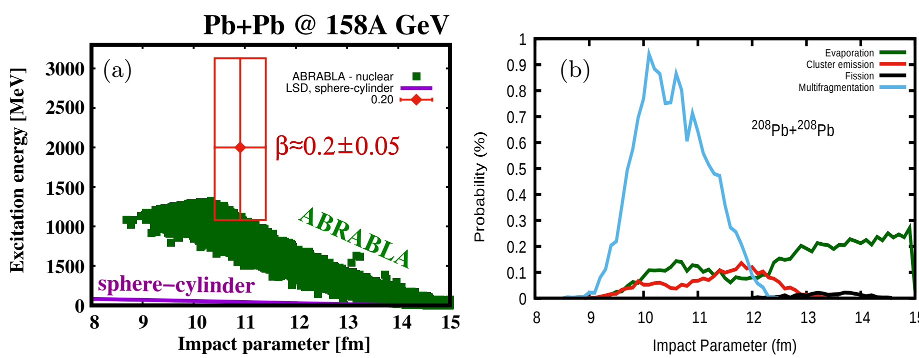

Fig. 2. (Colour on-line) (a) Excitation energy of the spectator in non-central ^{208}Pb+^{208}Pb collisions at 158 A GeV beam energy, computed in the abrasion-ablation model ABRABLA (green squares). The latter is compared to the excitation energy predicted by the geometrical model of sphere-cylinder collision (thick solid/purple line). The red rectangle gives the estimated kinetic energy range for the expanding charged sphere described in the text. The plot is redrawn from [13]. (b) Probability distribution in bins of impact parameter of the non-central ^{208}Pb+^{208}Pb reaction, obtained for our ABRABLA event sample and broken into different spectator de-excitation channels.

to the expansion of charge resulting from the fragmentation of the spectator system. On the other hand, it is apparent that the order of magnitude of this first estimate of kinetic energy of the charge cloud is rather comparable (within a factor of two with large uncertainties) to ABRABLA excitation energies at this impact parameter of the collision.

Figure 2 (b) presents the probability distributions of the four channels of spectator de-excitation considered in our study: multifragmentation, cluster emission, fission, and evaporation. Vaporization and break-up channels are for now excluded from the study. We expect them to dominate at lower impact parameters corresponding to more central collisions. From the figure, it is apparent that for Pb+Pb reactions undergoing the EM effect presented in Figs. 1 (e)–(f), multifragmentation remains dominant for spectator de-excitation, which calls for further studies of this channel. Fission, discussed in detail in Ref. [13], constitutes only a tiny fraction of all possible processes, of some relevance only for very peripheral collisions. On the other hand, evaporation remains non-negligible for a wide range of impact parameters, including that characteristic for our EM effect. For that reason, this channel will be discussed in more detail below.

In Ref. [10], we described our study of emission times of neutrons, protons and γ resulting from the evaporation process. Information on the evaporation time of each particle during the cooling down of the spectator system was provided by our dynamical 4DLangevin code. As it appeared, the density of emitted nucleons decreased by a factor of 10 within a time of the order of 400–600 fm$/c$ in spectator c.m.s. Put in comparison with our times of 400–2000 fm$/c$ estimated above and account taken of the Lorentz γ factor of about 9.2 at this collision energy, we learned that spectator evaporation and the EM effect indeed take place within comparable times. Therefore, they will interplay in the course of the Pb+Pb reaction.

In Table I, we present the average multiplicities of the particles emitted in the evaporation process, estimated by ABRABLA and by our 4DLangevin code. These are obtained for our full spectator ensemble generated by ABRABLA as shown in Fig. 2. Fission processes are included for comparison.

TABLE I

Average multiplicities of particles emitted in evaporation, fission and electromagnetic dissociation (EMD) processes, estimated by the statistical model ABRABLA and by its ABRA part combined with the dynamical 4DLangevin code.

	Evaporation		Fission		EMD	
	ABRABLA	ABRA-Lang	ABRABLA	ABRA-Lang	ABRABLA	ABRA-Lang
M_n	13.550	14.699	19.003	15.962	1.467	—
M_p	1.992	2.117	0.561	2.999		
M_α		0.613	0.048	0.730		

We note that the electromagnetic (EMD) excitation of the spectator in ultra-peripheral collisions provides an energy large enough to emit neutrons. The evaporation channel in spectator de-excitation in ultrarelativistic Pb+Pb reactions is clearly neutron-dominated and the difference between the pure ABRABLA and the ABRA-Lang approach is much smaller than for the case of fission.

In Fig. 3, we present the energy spectra of evaporated photons, neutrons, protons and α particles broken in different ranges of collision centrality, computed by the 4DLangevin code. In Fig. 3 (a) the photon spectra are supplemented by the average temperatures estimated for the spectator system. The centrality sample of Pb+Pb collisions used for our studies of the EM effect, Fig. 1, is marked by the second from the top (red) line and would correspond to $T \approx 3.7$ MeV.

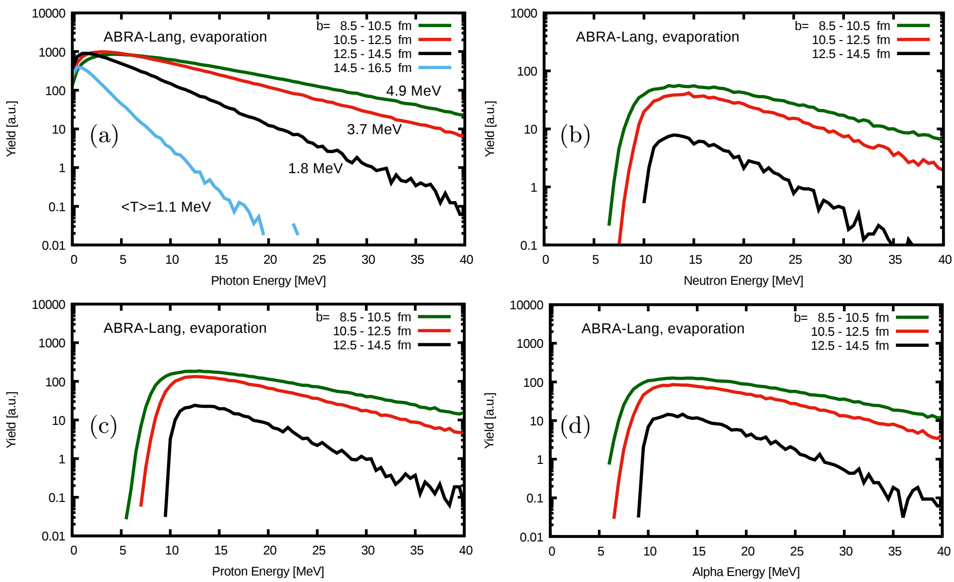

Fig. 3. (Colour on-line) Energy spectra of photons (a), neutrons (b), protons (c) and α (d) in different ranges of impact parameter of Pb+Pb collisions at 158 A GeV beam energy. All the particles are emitted by the excited spectator produced in the collision by the ABRA part of the ABRABLA model, with the de-excitation process computed in the 4DLangevin approach. Average spectator temperatures, estimated from the excitation energies E^* using the formula $T = (E^*/a)^{1/2}$, are indicated in panel (a).

4. Summary

The aim of the work described in this paper was to provide information on the interplay between the phenomena related to the fragmentation of the spectator system, and spectator-induced EM effects presently studied by the IFJ PAN group of the NA61/SHINE Collaboration. First results of this coordinated effort are encouraging. Phenomenological studies of EM effects, put together with model calculations based on state-of-the-art nuclear theory, suggest that the magnitude of kinetic energy of expansion of the charge cloud made by the spectator and fast participant charge can be comparable, within a factor of two and with large uncertainties, to the excitation energy of the spectator system. The evaporation channel of spectator de-excitation interplays with the EM effect due to comparable time scales. Ultrarelativistic peripheral Pb+Pb collisions available to experimental studies of EM effects [7, 8] are dominated by the multifragmentation channel. For that reason, further studies of the latter channel as well as vaporization and break-up channels for Pb+Pb, Ar+Sc and Xe+La collisions can be of great importance for future studies of the space-time evolution of the reaction by electromagnetic effects. They may also possibly allow us to test nuclear models away from their standard application range.

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REFERENCES

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

[2] A. Rybicki, A. Szczurek, *Phys. Rev. C* **87**, 054909 (2013).

[3] A. Rybicki *et al.*, *Acta Phys. Pol. B* **46**, 737 (2015).

[4] A. Rybicki, *Acta Phys. Pol. B* **42**, 867 (2011).

[5] A. Szczurek, M. Kiełbowicz, A. Rybicki, *Phys. Rev. C* **95**, 024908 (2017).

[6] R. Hagedorn, Thermodynamics of Strong Interactions, CERN 71-12, 1971.

[7] M. Kiełbowicz [NA61/SHINE Collaboration], talk at the XIII Workshop on Particle Correlations and Femtoscopy (WPCF2018), Kraków, Poland, to appear in *Acta Phys. Pol. B Proc. Supp.* (2019).

[8] A. Rybicki [NA49 Collaboration], *PoS* **EPS-HEP2009**, 031 (2009).

[9] M. Kłusek-Gawenda *et al.*, *Acta Phys. Pol. Proc. Supp.* **6**, 451 (2013) and references therein.

[10] K. Mazurek *et al.*, talk at the XIII Workshop on Particle Correlations and Femtoscopy (WPCF2018), Kraków, Poland, to appear in *Acta Phys. Pol. B Proc. Supp.* (2019).

[11] J.-J. Gaimard, K.-H. Schmidt, *Nucl. Phys. A* **531**, 709 (1991).

[12] A. Kelic, M.V. Ricciardi, K.-H. Schmidt, `arXiv:0906.4193 [nucl-th]`.

[13] K. Mazurek *et al.*, *Phys. Rev. C* **97**, 024604 (2018) and references therein.

[14] K. Mazurek *et al.*, *Eur. Phys. J. A* **53**, 79 (2017).