ELECTROMAGNETIC EFFECTS IN Pb+Pb COLLISIONS AT THE SPS; FROM NUCLEAR PHYSICS OF THE SPECTATOR SYSTEM TO THE SPACE-TIME EVOLUTION OF THE QGP*

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We review our studies of spectator-induced electromagnetic (EM) effects on charged pion emission in heavy-ion collisions at CERN SPS and RHIC BES energies. These effects are found to consist in the electromagnetic charge splitting of pion directed flow as well as very large distortions in spectra and ratios of produced charged particles. As it emerges from our analysis, they offer sensitivity to the actual distance d_E between the pion formation zone at freeze-out and the spectator matter. As a result, this gives a new possibility of studying the space-time evolution of the dense and hot matter created in the course of the collision. A specific picture emerges, where the centrality dependence of pion rapidity spectra at CERN SPS energies may be interpreted as a pure consequence of local energy-momentum conservation. Furthermore, as follows from our analysis, EM effects also show sensitivity to the space-time scale of spectator breakup. We comment on a recent study of the dynamical evolution of the spectator system, which gives very different predictions for spectator excitation energy depending on the dynamical scenario assumed. In this context, we argue that EM effects in ultrarelativistic heavy-ion collisions can provide a unique, independent experimental input to test nuclear models in extreme conditions.

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1. Introduction

In non-central ultrarelativistic heavy-ion collisions, one can identify two different regions of the reaction: the *participant zone*, created by the nucleons directly participating in the collision, which emits final-state particles,

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and the two *spectator systems*, the two nuclear remnants which do not participate directly in the reaction. Historically, the main attention in studies of ultrarelativistic heavy-ion collisions was given to the phenomena associated with the participant zone, like the creation of quark–gluon plasma (QGP), most of the time ignoring the presence of spectators. However, as was shown in our earlier works [1–3], taking into account the electromagnetic field generated by charged spectators can provide additional, independent information on space-time evolution of the dense and hot matter of the participant zone. What is more, it turns out that the same effect can also shed light on space-time properties of the evolution of the spectator system itself.

This work summarizes what we already learned, or can learn in future studies of spectator-induced electromagnetic (EM) effects in charged particle emission — on both regions of the reaction. These effects are the following: charged spectators generate electromagnetic fields, which modify trajectories of final-state charged particles (most of them being pions); oppositely charged particles are affected oppositely, what leads to charge asymmetries in distributions of produced particles. Two observables are considered in this context — the directed flow v_1 of positive and negative pions as a function of rapidity y (Fig. 1 (a)), and the π^+/π^- ratio as a function of Feynman-x x_{F} and transverse momentum p_{T} (Fig. 3 (a)).

2. Fire streaks in the participant zone

In Fig. 1 (a), one can see the directed flow v_1 as a function of pion rapidity normalized to beam rapidity, for positive and negative pions in intermediate centrality Au+Au collisions. The measurements come from the STAR experiment [4]. The overall trend for both charges is similar, but a systematic splitting is apparent. This charge splitting was explained by the above-mentioned EM effects [5]. In order to obtain a satisfactory agreement with the experimental data, it had to be assumed that the distance d_E between the pion formation zone and the spectator is of the order of 3 fm.

Taking together results of three such analyses of EM effects in three different data sets on Au+Au and Pb+Pb collisions [4, 6, 7], we obtained the dependence of d_E on pion rapidity [3], which is depicted in Fig. 1 (b). The figure shows that faster pions are produced closer to the spectator system.

The latter observation was explained in Ref. [8] in a new, independent realization of the fire streak model [9]. The overall idea is presented in Figs. 1 (c) and (d). In the collision centre-of-mass frame, the two incoming nuclei are represented as two continuous, Lorentz-contracted 3D mass distributions defined by the known nuclear density profiles [10, 11]. They are then divided into “bricks” in the transverse plane of the collision, with transverse sizes of 1×1 fm^2. Each brick collides independently with the one from the opposite nucleus, forming a “fire streak”. For each pair, local

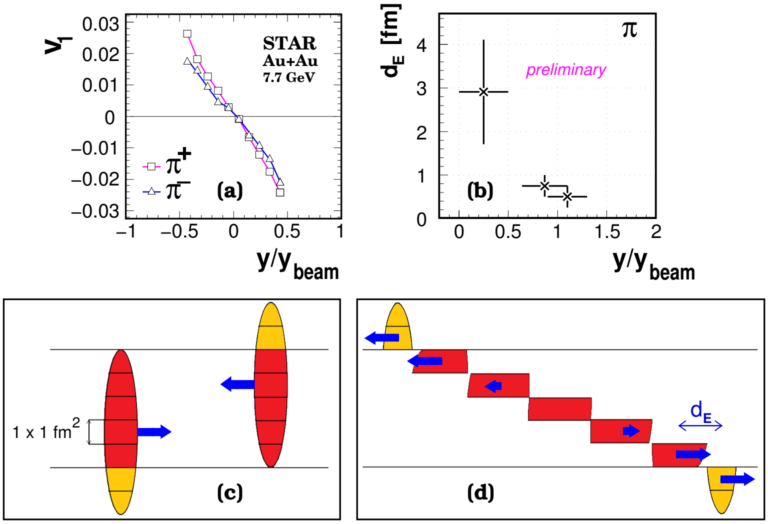

Fig. 1. (a) Directed flow for π^+ and π^- in Au+Au collisions [5]; original data from Ref. [4]. (b) Dependence of d_E on pion rapidity for Au+Au and Pb+Pb collisions at RHIC BES/CERN SPS energies [3]. (c) "Bricks" of matter considered in the fire streak model of Ref. [8] before the collision. (d) Fire streaks formed after the collision, also redrawn from Ref. [8]. Thick arrows indicate velocity vectors.

energy-momentum conservation is assumed (the different pairs do not "feel" each other). From this assumption, the excitation energy E_s^* and rapidity y_s follow directly for each fire streak[1]. The final ingredient of the model is that each fire streak fragments independently into n pions, according to the function [8]

$$\frac{\mathrm{d}n}{\mathrm{d}y} \sim A\,(E_s^* - m_s)\,\exp\left(-\frac{\left[(y-y_s)^2+\epsilon^2\right]^{\frac{r}{2}}}{r\sigma_y^r}\right) \qquad (1)$$

of pion rapidity y with free parameters A, r, σ_y independent of the fire streak *and collision centrality*, $\epsilon = 0.01$, m_s being the sum of "cold" masses of the two "bricks" before the collision, and the other parameters (E_s^*, y_s) being given strictly by the conservation rule. Please note that the number of produced pions $\mathrm{d}n/\mathrm{d}y$ is proportional to the energy available for particle production $(E_s^* - m_s)$, in agreement with energy conservation. From the distribution of fire streak velocities, depicted as thick arrows in Fig. 1 (d), and formula (1), it is visible that on average, pions produced closer to the spectator system are moving faster.

[1] For the actual non-trivial distribution of E_s^* and y_s in the transverse space as a function of collision centrality, and for the detailed discussion of normalisation issues in comparison of the model to the experimental data discussed later in the text, the reader is referred to Ref. [8].

Summing formula (1) over all fire streaks, one obtains the full rapidity spectrum of pions. The fit of the model to data from the NA49 experiment [12], for different centrality classes, is shown in Fig. 2. It is visible that the model describes well both the yields of pions and shapes of pion rapidity spectra. This means that the centrality dependence of pion rapidity distributions at CERN SPS energies can be interpreted as a *pure consequence of local energy-momentum conservation.*

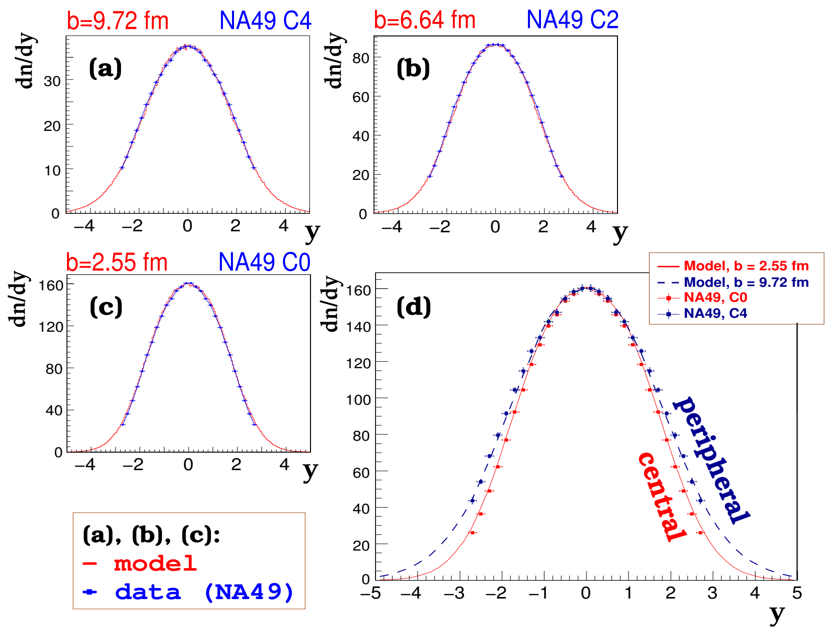

Fig. 2. (a)–(c) Rapidity distributions of negative pions measured by the NA49 experiment in three centrality classes, from the most peripheral to the most central Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV, compared to the fire streak model [8]; experimental data from Ref. [12]. (d) Shape comparison of rapidity spectra for two extreme centrality classes together with the fire streak model. The spectrum for peripheral collisions is renormalized at its peak to central collisions.

3. Evolution of the spectator system

In Fig. 3 (a), one can see the π^+/π^- ratio measured by the NA49 experiment in peripheral Pb+Pb collisions at the top CERN SPS energy of $\sqrt{s_{NN}} = 17.3$ GeV. It is drawn as a function of $x_{\rm F}$ at fixed values of $p_{\rm T}$. A very peculiar structure is visible, with a pronounced minimum at low transverse momenta. This structure is again attributed to spectator-induced EM effects and appears sensitive to the spatial distribution of spectator charge [13].

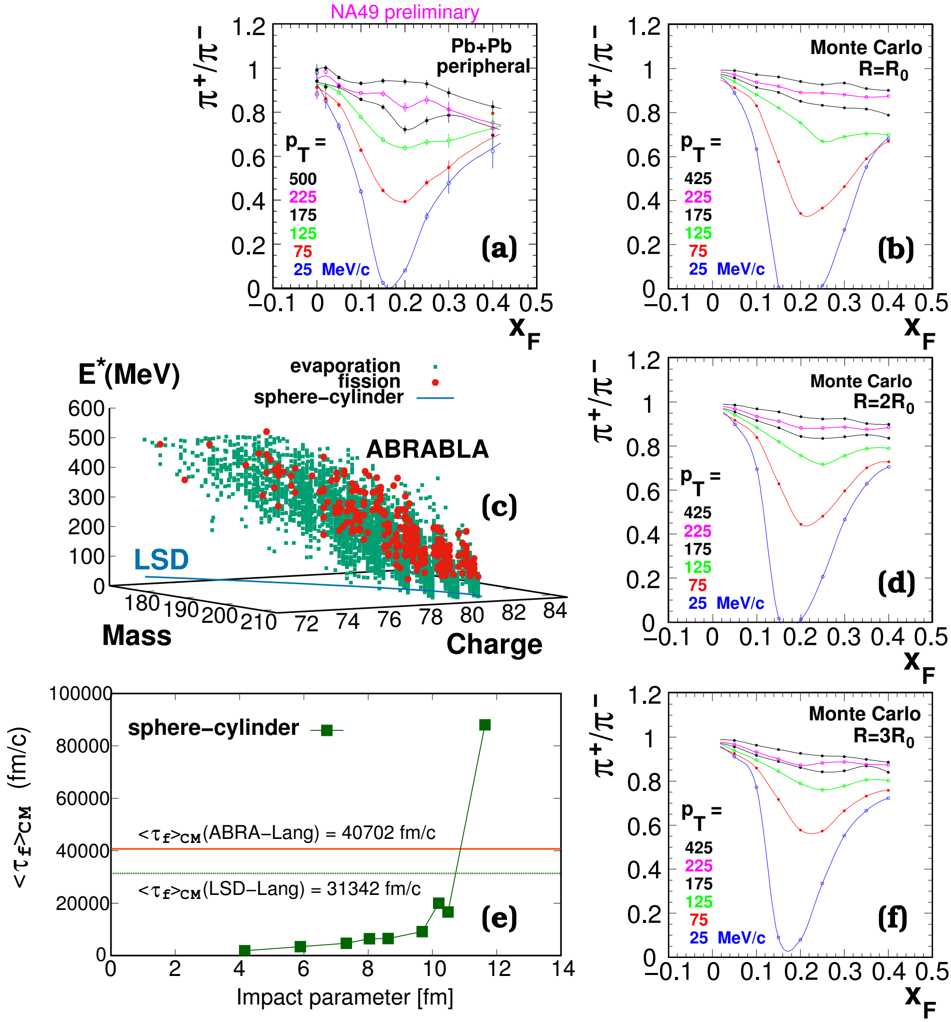

Fig. 3. (a) π^+/π^- ratio measured in peripheral Pb+Pb collisions, drawn as a function of x_{F} at fixed values of p_{T} [13]. (b), (d), (f) Results of the Monte Carlo simulation for three different spectator charge spatial distributions (see the text) [13]. (c) Correlation between spectator mass, charge and excitation energy in two abrasion models (see the text), for two deexcitation channels [15]. (e) Mean fission time in collision centre-of-mass frame as a function of the collision impact parameter, in the LSD–Lang model, as well as mean fission times averaged over all considered impact parameter values for the LSD–Lang and ABRA–Lang models [15]. Plots in panels (c) and (d) courtesy of Katarzyna Mazurek, 2017.

In Figs. 3 (b), (d), (f), results of our EM Monte Carlo simulations are shown for the spectator system assumed of the same total charge, but of three different volumes. In Fig. 3 (b), the spectator is, in its own reference frame, a sphere with radius R_0 given by the standard nuclear density and by the number of nucleons defined by collision centrality [13] (a non-decayed spectator). In Figs. 3 (d) and (f), the sphere radius R is respectively doubled and tripled to simulate different stages of the spectator breakup. Comparing to Fig. 3 (a), it is visible that the detailed shape of the π^+/π^- structure simulated close to spectator velocity ($x_F \approx 0.15$, low p_T) changes as a function of the assumed spatial distribution of spectator charge. *Thus, EM effects are sensitive to the space-time scale of spectator fragmentation.*

We note that if the spectator was actually decaying in a time scale relevant for EM effects, the final picture of the EM distortion of the π^+/π^- ratio would be an average of pictures (b), (d), (f) and possibly further ones with even larger radii. Thus, an obvious question arises: what is known about spectator deexcitation at CERN SPS energies? Here, we address a very recent theoretical development [14, 15] which to the best of our knowledge, sheds new light on this question. It is based on a two-step approach. First, the initial spectator shape and excitation energy are computed within three different abrasion[2] models. Then a dynamical calculation is performed by means of the multidimensional stochastic Langevin equation in order to obtain deexcitation time scales and the resulting final state of the spectator. Only two deexcitation channels are considered, evaporation and fission.

In Fig. 3 (c), the correlation between initial spectator mass, charge and excitation energy is shown for two abrasion models [15]. It is visible that the LSD (Lublin–Strasbourg liquid Drop [16, 17]) model predicts significantly smaller excitation energies than the abrasion–ablation statistical model ABRABLA [18, 19]. The two models converge only for very peripheral collisions. In the former model, the excitation energy is the difference between liquid drop model energy of the deformed initial shape of the spectator (obtained by a geometrical cut of a sphere by a cylinder) and the corresponding energy for a sphere of the same volume. The ABRABLA model takes into account the energy of vacancies created in single-particle levels, when nucleons are removed randomly. For this model, events leading to evaporation and fission are shown separately in Fig. 3 (c).

As discussed in Ref. [15], evaporation will lead to an approximately spherical spectator which can have, at large impact parameters of the collision, an electrical charge almost unchanged w.r.t. that of the initial state after abrasion. In the case of fission, typical time scales are still large if compared to these characteristic to EM effects. This is apparent in Fig. 3 (e)

[2] Abrasion is the process in which the spectator is torn off from the colliding nucleus.

which shows the mean fission time in the collision c.m.s. drawn as a function of the impact parameter, in the LSD–Lang (LSD abrasion + Langevin deexcitation) model, and mean fission times averaged over all considered impact parameters for the LSD–Lang and ABRA–Lang (abrasion from ABRA model + Langevin deexcitation) models [15]. Fission occurs faster — and its probability increases — in more central collisions where larger excitation energies are predicted. We note that for even larger excitation energies, other deexcitation channels open. These are not considered in the cited reference but will probably lead to a faster "explosion" of the spectator.

From the above, we draw several conclusions:

(a) depending on the assumed abrasion scenario, state-of-the-art model calculations give very different predictions for the excitation energy of the spectator system in ultrarelativistic heavy-ion collisions,

(b) theoretical tools exist to compute the spectator space-time evolution as a function of the predicted excitation energy,

(c) the resulting discrepancies between the different assumed scenarios will, as a rule, rapidly increase with decreasing impact parameter of the collision, and

(d) studies of EM effects at the CERN SPS, sensitive to spectator fragmentation space-time scales, can therefore give us a unique opportunity to test the different models in extreme conditions — that is, away from their standard application range.

In this context, we presently perform further feasibility studies in view of possible new, high statistics measurements of spectator space-time evolution in Pb+Pb collisions by the NA61/SHINE experiment after 2020.

4. Summary

Spectator-induced electromagnetic effects on charged pion emission in heavy-ion collisions at CERN SPS and RHIC BES energies bring new information on the space-time position of the pion formation zone. This zone turns out to be much closer to the spectator system for faster pions than for slower ones. This, in turn, leads to the "fire streak" picture of the collision at CERN SPS energies. The fire streak model is found to describe very well the dependence on centrality of both the yields of pions and shapes of pion rapidity spectra measured by the NA49 experiment. Thus, the centrality dependence of pion rapidity spectra at CERN SPS energies may be interpreted as a pure consequence of local energy-momentum conservation.

Electromagnetic distortions are also shown to be sensitive to the space-time scale of spectator breakup. New theoretical calculations of spectator evolution, based on the multidimensional stochastic Langevin equation, suggest that different possible abrasion scenarios result in largely different predictions for the latter. The corresponding discrepancies between model predictions will increase with decreasing impact parameter. Thus, new measurements of EM effects in ultrarelativistic heavy-ion collisions as a function of centrality can provide a unique, independent experimental input to test nuclear models in extreme conditions.

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