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SPECTATOR-INDUCED EM EFFECTS ON CHARGED MESON RATIOS IN HEAVY-ION COLLISIONS*

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This paper gives an overview of studies of *spectator-induced electromagnetic (EM) effects* on charged pion emission in ultrarelativistic heavy-ion collisions. These effects, caused directly by the electromagnetic field generated by positively charged spectators, are found to induce large distortions in spectra and ratios of produced charged π^+, π^- mesons as well as induce a *charge splitting* of measured pion directed flow. Recent studies demonstrate that the analysis of spectator-induced EM effects shows sensitivity to the actual distance $d_{\rm E}$ between the pion formation zone at freeze-out and the spectator matter. This gives a new possibility of studying the space-time evolution of dense and hot matter created in the course of the collision. The analysis of the dependence of the distance $d_{\rm E}$ as a function of pion rapidity gives a first estimate of the pion decoupling time from EM effects which can be directly compared to existing HBT data. Consequently, spectator-induced EM interactions appear as an alternative tool for studying the space-time characteristics and longitudinal evolution of the system.

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1. Introduction

In the simplified picture of the non-central heavy-ion collision, it is common to distinguish two regions of the reaction: the participant zone responsible for the production of new particles and the spectator systems, namely, two highly charged nuclear remnants that do not participate in the collision. Positively charged spectators moving in opposite directions at relativistic speeds generate electromagnetic (EM) fields which influence the trajectories of charged particles produced in the collision and, therefore, modify the spectra of measured charged particles. Recent studies provide the evidence that

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the above *spectator-induced electromagnetic effect* is sensitive to the space-time evolution of the system and can become a new source of information in this matter.

This paper presents a general overview of the above spectator-induced EM phenomena and highlights the role of the studies of these effects as a potential alternative method to obtain new knowledge on the space-time evolution of the system created in non-central nucleus–nucleus collisions.

2. EM effects in peripheral Pb+Pb and in Pb+gas collisions

A comparative study of spectator-induced EM phenomena observed in π-meson spectra is presented in panels (a) and (b) of Fig. 1. Both panels show the π^+ over π^- ratio, plotted as a function of the Feynman variable x_{F}[1] for selected values of transverse momentum p_{T}; both variables x_{F} and p_{T} were considered in the collision c.m.s. These results were obtained for two

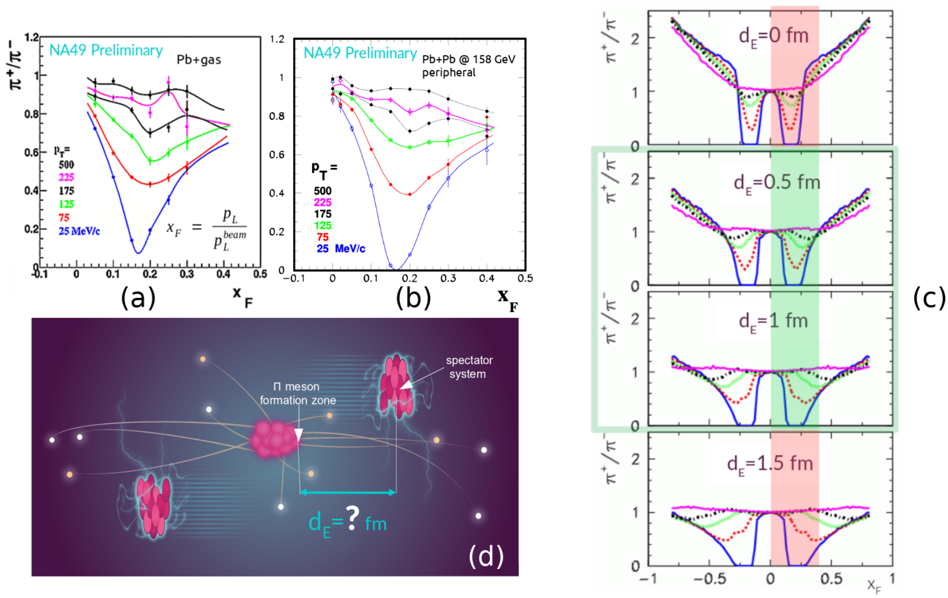

Fig. 1. (Color online) Panels (a)–(b) show the ratios of charged π mesons (π^+/π^-), drawn as a function of x_{F} in nucleon–nucleon c.m.s. at several values of p_{T}, for experimental data (a) on Pb+gas collisions [2] and (b) on peripheral Pb+Pb reactions [3] at $\sqrt{s_{NN}} = 17.3$ GeV. Panel (c) shows Monte Carlo simulations on the π^+/π^- ratio in peripheral Pb+Pb collisions for selected values of d_{E} [1]. The values of d_{E} which match the experimental data are marked by a gray/green frame. Panel (d) illustrates the non-central nucleus–nucleus collision.

[1] The Feynman variable: $x_{\mathrm{F}} = \frac{p_{\mathrm{L}}}{\sqrt{s_{NN}}}$.

colliding systems, asymmetric Pb+gas and symmetric, peripheral Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV by the fixed target NA49 experiment at the CERN SPS. The Pb+gas reactions should be understood as collisions of the large Pb projectile with smaller nuclei of gas (Pb+N, Pb+O) in the vicinity of the NA49 target. The measurement was made in the projectile hemisphere ($x_{\rm F} > 0$). Experimental data were compared with the π^+/π^- ratio computed in a Monte Carlo model of the peripheral Pb+Pb reaction which included simulations of the electromagnetic interaction. Results of simulations are also presented in Fig. 1 (c).

For the experimental data, there is a visible qualitative and quantitative similarity between results obtained for Pb+gas, Fig. 1 (a), and peripheral Pb+Pb collisions, Fig. 1 (b). In both figures, a surplus of negative over positive π mesons is present for all the considered kinematic range. A moderate excess of negative over positive pions, visible in the figures for higher transverse momentum, can be explained by the isospin effect arising from the nucleonic composition of Pb projectile (surplus of neutrons over protons in the nucleus). However, for low values of $p_{\rm T}$, a characteristic structure as a function of $x_{\rm F}$ and $p_{\rm T}$, with a sharp decrease of the π^+/π^- ratio around $x_{\rm F} = 0.15$ is observed which breaks isospin symmetry. The position of the minimum corresponds to pions moving longitudinally with the same velocity as the spectator system ($x_{\rm F} = m_\pi/m_p = 0.15$). The largest distortion of the π^+/π^- ratio occurs for the lowest values of transverse momentum. This minimum in the π^+/π^- meson ratio observed in Pb+gas and peripheral Pb+Pb collisions is a direct result of the electromagnetic interaction between charged pions and the spectator system, namely of the repulsion of π^+ and attraction of π^- by the fragment of the positively charged nucleus surviving the collision.

A more detailed description of the model used in Monte Carlo simulations of peripheral Pb+Pb collisions can be found in [1]. This simplified model assumed a single pion emission point, with the produced charged π mesons interacting with the spectator systems modeled as a two uniform charged spheres in their respective rest frames. The propagation of charged pions through the spectator EM field was described by classical relativistic equations of motion. The free parameter of the model was the distance $d_{\rm E}$ between the π meson freeze-out point and the spectator system (Fig. 1 (d)). As shown in Fig. 1 (c), the Monte Carlo studies were carried for different values of the distance $d_{\rm E}$, namely 0 fm, 0.5 fm, 1.0 fm, and 1.5 fm.

From Fig. 1 (c), it is immediately apparent that spectator-induced electromagnetic effects are highly sensitive to the distance $d_{\rm E}$ between the pion emission zone and the spectator system. Moreover, a direct comparison between results measured for the experimental data and obtained from Monte Carlo simulations show clearly which π meson emission scenario is possible and which should be indisputably excluded from the analysis. This gives the evidence that spectator-induced EM phenomena can provide independent information on the space-time evolution of particle production process. More detailed studies of EM effects on π^+/π^- ratios in peripheral Pb+Pb collisions (see Fig. 1 (c) and Ref. [4]) indicate that charged pions are formed in the longitudinal distance $d_{\mathrm{E}} = 0.75$ fm behind the spectator system.

It should be noted that the apparent similarity in the behavior of the data points in Fig. 1, panels (a) and (b) implies that the spectator-induced EM effect in the projectile hemisphere is largely dominated by a single (projectile) spectator (see [5] for comparison). This somewhat generalizes the widespread notion that particle production in the region of a large positive x_{F} depends only on the projectile, and not on the target (see also Ref. [6]). This also suggests that not only the particle distributions in the final state, but also the space-time evolution of fast particle production in Pb+gas and peripheral Pb+Pb collisions are similar.

3. Spectator-induced EM effects and the space-time evolution of pion production

As the spectator-induced electromagnetic effects can be recognized as an alternative way to study the longitudinal space-time evolution of the system created in heavy-ion collisions, the question arises whether it is possible to obtain from them any information comparable to results of HBT analyses.

Figure 2 (a) shows the compilation of our studies of EM effects focused on the space-time evolution of pion formation in heavy-ion collisions [7]. These were carried on the basis of three available experimental data sets: the charged pion ratio in peripheral Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV from Fig. 1 (b), the positive pion directed flow measured by the WA98 experiment in Pb+Pb reactions at $\sqrt{s_{NN}} = 17.3$ GeV [8], and the charge-dependent pion directed flow in Au + Au collisions at $\sqrt{s_{NN}} = 7.7$ GeV, obtained by the STAR experiment [9]. The experimental data were interpreted in terms of the Monte Carlo model discussed in Sec. 2. This provided the information on the π-meson distance d_{E} from the spectator system at the moment of pion emission.

In Fig. 2 (a), the values of d_{E} are plotted as a function of scaled pion rapidity y/y_{beam}. The presented results show an evident decrease of the distance d_{E} between the pion emission zone and the spectator system with increasing y/y_{beam}. In other words, the faster is the pion, the closer to the spectator system it is formed.

This dependence of d_{E} on pion rapidity was further studied by means of another set of Monte Carlo model simulations. The proposed model was based on resonance dominance in particle production: it assumed the majority of π mesons being produced from resonances (like $\Delta(1232)$ or $\rho(770)$), or other hadronic states characterized by similar features [7]. The results of the corresponding Monte Carlo study are also presented in Fig. 2 (a). In the simulations, two scenarios of particle production were considered:

(1) In the first scenario, depicted in Fig. 2 (b), π mesons were produced from resonances forming instantly after the collision, without any intermediate state. Results for this prediction are shown in Fig. 2 (a) as the dashed blue line.

(2) In the second scenario, illustrated in Fig. 2 (c), the existence of an intermediate system characterized by a given proper lifetime of the order of $\tau \approx 2.4$ fm/c and preceding the resonance formation was postulated. Results for this case are shown in Fig. 2 (a) as dotted red line.

From the comparison of the black data points with the results of our simulations, Fig. 2 (a), it is clearly visible that both model scenarios (1) and (2) qualitatively predict the observed trend of decrease of the π-meson emission distance $d_{\rm E}$ with increasing pion rapidity. However, a quantitative agreement is apparent only when the second scenario (2) is assumed in our

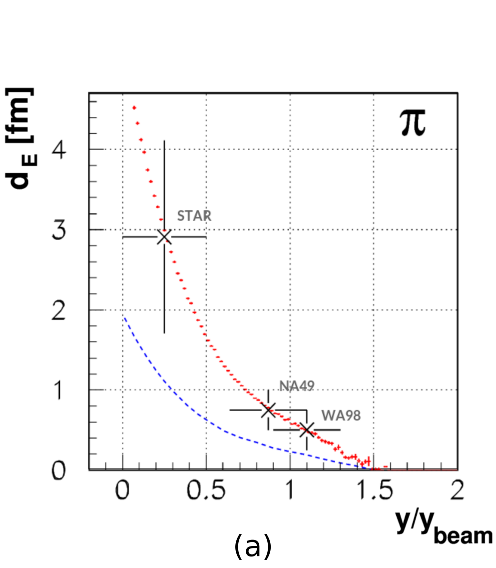

Fig. 2. (Color online) Panel (a) shows the dependence of the pion emission distance $d_{\rm E}$ on scaled pion rapidity (black data points), compared to the results of the Monte Carlo model simulation discussed in the text (dashed blue, dotted red). The panels (b)–(c) illustrate the two resonance production models considered in the text: one in which resonances are produced instantly at the moment of the collision ($\tau = 0$), and one in which they are produced from an intermediate system with a given proper lifetime ($\tau > 0$). Redrawn from [7].

model. Thus, the analysis of spectator-induced EM effects evidently points at the presence of the intermediate system of hot and dense matter, prior to resonance formation in heavy-ion collisions. We note that the same analysis allowed us to evaluate the preliminary value of the final time of pion emission in scenario (2) to be of 5.3 ± 2.2 fm$/c$ at central pion rapidity. This result, obtained directly from EM phenomena, appears to be in reasonable agreement with compilation of pion decoupling times published by the ALICE Collaboration (about $\tau_f \approx 6$ fm$/c$ at this collision energy [10]).

4. Summary

From this short review of the spectator-induced electromagnetic phenomena, several findings emerge. It is evident that the presence of EM fields in the heavy-ion collision results in charge-dependent effects on various observables. These effects are sensitive to the distance d_{E} between the pion emission zone and the spectator(s). Therefore, these phenomena can provide new information on the space-time evolution of the system created in nucleus–nucleus collisions, independent and partially complementary to the HBT method. However, the question of whether the analysis of spectator-induced EM effects can indeed provide a "new femtoscopy" remains still open. Specifically, there is abundant room for more progress in determining the sensitivity of the EM effects to the space-time evolution of the spectator system itself. This issue will be further addressed in the two subsequent contributions to this Workshop [11, 12].

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