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ROLE OF THE SPECTATOR SYSTEM IN ELECTROMAGNETIC EFFECTS*

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The electromagnetic effects on charged pion (π^+, π^-) spectra provide new, independent information on the space-time evolution of the ultrarelativistic heavy-ion collision. The spectator lifetime and its excitation energy may also be of importance for the understanding of the space-time evolution of the participant zone. This paper gives an overview of our coordinated effort to understand the interplay between electromagnetic phenomena and processes related to the fragmentation of the spectator system at forward rapidity in peripheral Pb+Pb collisions at top CERN SPS energies. Our study includes, on the one hand, the experimental analysis of electromagnetic effects and corresponding phenomenological Monte Carlo simulations and, on the other hand, dedicated theoretical calculations based on the abrasion–ablation model ABRABLA and the 4DLangevin approach.

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1. Introduction

The two preceding contributions to this Workshop reported studies of spectator-induced electromagnetic (EM) effects in different nuclear collision systems measured at the CERN SPS and RHIC [1, 2]. It is commonly accepted that the quark–gluon plasma is created in the participant zone and subsequently evolves to the hadronic phase, and that the two nuclear remnants, spectators, fly away from the collision. While the name "spectators" suggests that they do not take part in the reaction, experimental evidence has been recalled in Ref. [1] that they induce an electromagnetic distortion on charged pion (π^+, π^-) spectra (see also [3–5]). While at high-collision energies the π^+ and π^- total multiplicities should be comparable, it appears

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that depending on the pion transverse momentum, their distributions differ significantly, as it is presented in Fig. 1. This phenomenon is caused by electromagnetic interactions between charged pions and spectators. In non-central collisions, the electromagnetic fields modify trajectories of final-state charged particles. Positively charged spectators repulse the π^+ mesons and attract the π^- mesons. This behavior has been observed in the NA49 experiment in Pb+Pb collisions at 158 GeV/nucleon [1]. At this Workshop, it was for the first time confirmed for the Ar+Sc reaction at 150 A GeV/c by the NA61/SHINE Collaboration [2]. The aim of this paper is to complete the picture presented in [1, 2] by considering the fate of the spectator system. This work will concentrate on peripheral Pb+Pb collisions at the top SPS energy of 158 GeV/nucleon ($\sqrt{s_{NN}} = 17.3$ GeV).

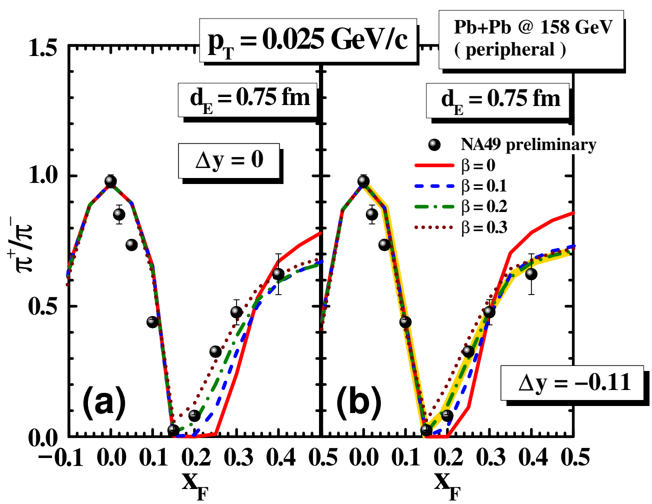

Fig. 1. (Color online) The charged pion ratio π^+/π^- measured at transverse momentum $p_{\mathrm{T}} = 0.025$ GeV/c in peripheral Pb+Pb collisions at 150 A GeV. The experimental data from the NA49 experiment [3] are compared to model simulations obtained for different combinations of the parameters d_{E}, β, and Δy described in the text. The optimal description of experimental data is indicated by the thick solid gray/yellow line.

2. EM effects in peripheral Pb+Pb collisions

The information on the distance d_{E} between the pion emission zone and the spectator was obtained with the help of Monte Carlo simulations by a direct comparison to experimental data for π^+ and π^- production. The best reproduction of experimental data for Pb+Pb collisions at 158 GeV/nucleon was obtained for $d_{\mathrm{E}} = 0.75$ fm [1]. The new calculations, presented in Fig. 1, take into account also the possibility of a radial expansion of the spectator with surface velocity β treated here as a free parameter, and the possible change of spectator rapidity Δy. The result of the new calculation is consistent with the earlier value of $d_{\mathrm{E}} = 0.75$ fm, but we obtain a better quantitative description of the NA49 data. As apparent from Fig. 1 (a), a stable spectator ($\beta = 0$) moving at the original beam velocity does not provide the optimal description of the data points, and the agreement is improved by assuming a considerable expansion velocity. We note that the optimal description is achieved once a shift $\Delta y = -0.11$ from the original beam rapidity is assumed in the model for the spherically expanding charged cloud, see Fig. 1 (b). We presently interpret this as an indication for the presence of not only the spectator charge, but also the faster part of participant charge in the total charged cloud responsible for the EM effect. Qualitatively, the presence of participant charge at high rapidity in peripheral Pb+Pb collisions would be naturally expected from the energy-conservation-based model discussed at this Workshop [6]. However, it is clear that the EM effect will be also sensitive to the expansion/fragmentation of the spectator system. For this reason, our studies of the latter will be summarized below.

3. Simulation of the spectator system

Basic kinematical considerations suggest that fast pions at $p_{\mathrm{T}} = 0$ at top SPS energy can spend a time of the order of 400–2000 fm/c in the collision c.m.s. in the close vicinity of the spectator system. This implies that we are mostly interested in the fate of the spectator remnant for the first few hundreds of fm/c in its own c.m.s. Thus, a discussion of the spectator excitation energy and its de-excitation processes is necessary. This is studied within the abrasion–ablation statistical model (ABRABLA) [7, 8]. This approach was employed previously with success in the description of relativistic collisions. Its application to ultrarelativistic energies, that is, to Pb+Pb reactions at 158 GeV/nucleon considered here, was presented in Ref. [9].

Information on the spectator evolution in time is extracted from models used in low-energy physics, based on solving transport equations of the Langevin type. The dynamics of the spectator de-excitation is treated as fission or particle and γ-evaporation processes. The ensemble of spectators created with the abrasion process by ABRABLA is evolved in space and time, by changing spectator shape, excitation energy, emitting particles and γ rays. In the final stage, information on mass, charge of the fission fragments and evaporation residua, as well as multiplicity and energy spectra of emitted particles and further observables is available. The details of the model and references can be found in Ref. [10]. The hybrid method of combining the abrasion part from the ABRABLA code with the dynamically solved set of Langevin equations brings the information on the space-time evolution of the spectator system.

4. Results

In Ref. [9], the predictions for excitation energies were presented within different theoretical approaches. For instance, the geometrical (macroscopic) approach was based on the assumption that the remnant of the collision of two nuclei at ultrarelativistic energies had a shape of a sphere cut by a cylinder. The deformation energy of such a shape was translated directly into the excitation energy of the spectator within the Lublin–Strasbourg Drop approach, based on the liquid drop model. This brought the deformation (excitation) energy of the order of 100 MeV, indicated by the straight line in Fig. 2.

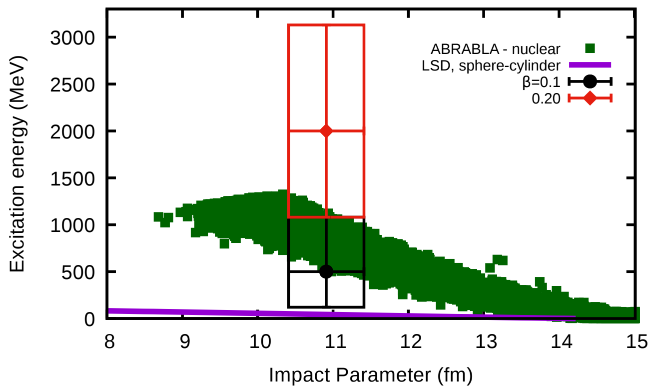

Fig. 2. (Color online) The distribution of the excitation energy of the spectator in ^{208}Pb+^{208}Pb collisions at 158 GeV/nucleon beam energy, predicted by the abrasion–ablation model ABRABLA (dark gray/green squares), and assuming the geometrical model of sphere-cylinder collision (stright/purple line) [9]. The medium gray/red rectangle gives the estimated kinetic energy range for the expanding charged sphere corresponding to the optimal description of EM effects ($\beta = 0.2 \pm 0.05$, thick solid gray/yellow line in Fig. 1 (b)). For comparison, the same estimate for $\beta = 0.1 \pm 0.05$ is also presented.

On the other hand, the ABRABLA code estimates the excitation energy from a microscopic picture. Its estimation for the spectator excitation energy is displayed in Fig. 2 (dark gray/green squares). For comparison, the figure also includes the estimation of kinetic energy of an expanding charged sphere which gives the best description of NA49 data on electromagnetic effects ($\beta = 0.2 \pm 0.05$). This is shown as the medium gray/red box in Fig. 2, placed at the average impact parameter estimated for this data sample [11]. It is clear from Sec. 2 that it is premature to make strong conclusions from this comparison: the presence of participant in addition to spectator charge will contribute to the expansion of the total charge cloud "seen" by pions at high rapidity. This will come on top of the evolution of the spectator *per se*. It is nevertheless evident that the order of magnitude of kinetic energy corresponding to the charge cloud apparent from EM effects is quite comparable to that of excitation energy obtained from ABRABLA.

The subsequent fate of the spectator system can be illustrated by probability of its various decay channels. These are extracted from ABRABLA calculations incorporating statistical de-excitation. The result is presented in Fig. 3. The hot spectator can de-excite via nuclear processes such as: evaporation, fission, cluster emission or multifragmentation. The vaporization and break-up reactions are omitted in this discussion; they lead to almost immediate disintegration of the nucleus. Fission is possible only for peripheral collisions and multifragmentation dominates for smaller impact parameters. The evaporation of neutrons, protons and other light particles is almost constant for $b = 9$–15 fm.

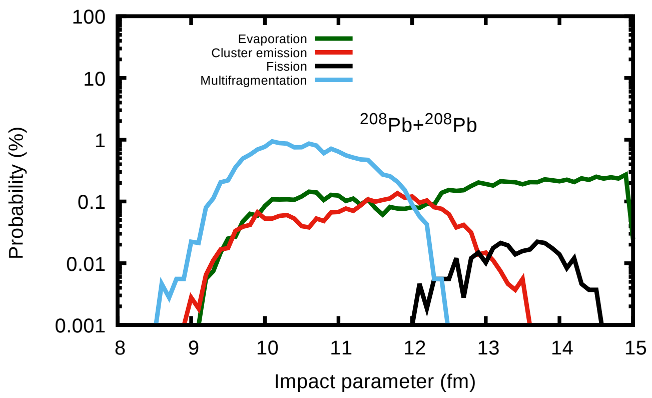

Fig. 3. The ABRABLA estimate of the probability of various nuclear processes (evaporation, fission, cluster emission and multifragmentation) as de-excitation channels for the hot spectator in Pb+Pb collisions at 158 GeV/nucleon.

In Ref. [9], we discussed the fission lifetime, but the latter fission constitutes only a small part of the hot spectator de-excitation in Fig. 3. Therefore, the evaporation of particles: neutrons, protons and γ-rays may possibly give a better estimation for typical lifetimes of the spectator system. During the cooling down of the spectator, the Langevin code provides information on the evaporation time of each particle. As it appears from the calculations, neutron emission is much more probable than other emissions. For example, for the impact parameter $b = 10.5$ fm, the mean multiplicity of emitted neutrons is 26, while that of protons is 6.

Figure 4 shows the distribution of emission time of evaporated neutrons, protons, and γ. The corresponding calculation was performed with the 4DLangevin code, where the initial conditions were taken from ABRABLA,

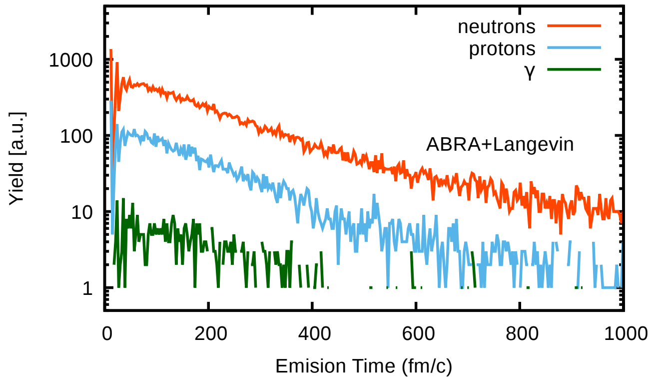

Fig. 4. The time distribution (in spectator c.m.s.) of neutron, proton and γ emission in the evaporation process. The initial ensemble of spectators has been generated by the ABRABLA code and de-excited via the 4DLangevin code.

similarly as in Ref. [9]. Our 4DLangevin prediction shows that nucleons are mostly evaporated in a time below 600 fm$/c$ in the spectator c.m.s. Account taken of the Lorentz boost ($\gamma \approx 9.2$ at this collision energy), this appears quite comparable to our estimated time of 400–2000 fm$/c$ for the charged pion to remain in close spectator vicinity. This implies that evaporation and the EM effect will interplay in the course of the Pb+Pb collision.

5. Summary

Spectator-induced EM effects on charged particle distributions provide new information on the space-time evolution of the system created in nucleus–nucleus collisions. Up to now, modeling of these effects in heavy-ion collisions suffered from lack of knowledge on the time evolution of the spectator system. On the other hand, it was known that this evolution was an important issue in the corresponding phenomenological studies. A first coordinated effort has been undertaken to investigate this problem from both sides (experimental data on EM effects and phenomenological simulations, *versus* dedicated nuclear theory). First results are encouraging: for peripheral Pb+Pb collisions considered here, multifragmentation is the dominant spectator de-excitation channel. It seems indicated to obtain more information on this latter channel in our future studies. Fission plays an increasingly significant role only for much more peripheral Pb+Pb collisions, but neutron, proton and γ evaporation has non-negligible probability for a wide range of impact parameters. The spectator excitation energy obtained from theoretical calculations, and our first phenomenological estimates of kinetic energy of expansion of the effective charged cloud, have begun to converge.

Nonetheless, first indication for the presence of participant on top of spectator charge in this latter cloud is apparent from EM effects, which could provide another verification of the collective model based on energy-momentum conservation [6]. It is our hope that these inter-disciplinary studies can help us to improve our understanding of both the longitudinal evolution of the QGP and the excitation and decay of the spectator system.

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