The effect of the spectator charge on the charged pion spectra in peripheral ultrarelativistic heavy-ion collisions.

A Szczurek\textsuperscript{1,2}, A Rybicki\textsuperscript{1}, A Z Górski\textsuperscript{1}
\textsuperscript{1} Institute of Nuclear Physics ul. Radzikowskiego 152, 31-342 Kraków, Poland
\textsuperscript{2} University of Rzeszów, ul. Rejtana 16, 35-959 Rzeszów, Poland
E-mail: antoni.szczurek@ifj.edu.pl

Abstract. We estimate the electromagnetic effect of the spectator charge on the momentum spectra of charged pions produced in peripheral Pb+Pb collisions at SPS energies. We find a large effect which results in strongly varying structures in the $x_F$ dependence of the $\pi^+/\pi^-$ ratio, especially at low transverse momenta where a deep valley in the above ratio is predicted at $x_F \sim 0.15 – 0.20$. The effect depends on initial conditions. Thus, it provides new information on the space and time evolution of the non-perturbative pion creation process.

1. Introduction

The nuclear collisions at SPS energies, when combined with the NA49 apparatus, open a possibility to study several subtle effects \cite{1} which are difficult to study at larger energies, like e.g. at RHIC. On the other hand, a few new typically nuclear effects have been predicted recently for SPS energies \cite{2,3}.

Recently the NA49 experiment made a preliminary observation \cite{4} of a new interesting phenomenon in peripheral collisions, which after a more refined experimental analysis was advocated \cite{5} to be a Coulomb effect due to spectator charge. Here we discuss the origin of this effect. In particular, we discuss electromagnetic (EM) interaction between the remnants of the two colliding nuclei and $\pi^+$ and $\pi^-$ produced in the collision. The two highly charged spectator systems generate a rapidly changing EM field which modifies the pion trajectories. This causes a distortion of observed kinematical pion spectra. We show that this distortion is interrelated to the dynamics of the collision, and in particular to the time evolution and initial conditions of the participant and spectator zones.

We study this EM effect for the specific case of peripheral Pb+Pb collisions at SPS energies (158 GeV/nucleon beam energy, $\sqrt{s_{_{NN}}}=17$ GeV). This short presentation is based on our recent detailed studies \cite{6}.
2. Propagation of pions in the EM field

Our approach is based on a Monte Carlo simulation of initial conditions and subsequent propagation of charged pions in the EM field of moving spectator charge. In Ref. [6] we have devoted a separate section where we discuss the choice of the initial conditions. These roughly correspond to experimental samples available at the SPS. Here we concentrate only on propagation of pions in the EM field.

We define \( \vec{E}'_L \) as the constant electrostatic field generated by the spectator \( L \) in its rest frame, and \( \vec{E}'_R \) as the field generated by the spectator \( R \) in its rest frame. We assume both spectator systems to be uniform spheres with a normal nuclear density \( \rho = 0.17/fm^3 \) and with a total charge \( Q = 70 \) elementary units. Then the static electric fields is given by a simple nuclear-physics text-book formula [6].

We transform the fields \( \vec{E}'_L, \vec{E}'_R \) to the overall center of mass system. Here

\[
\vec{E}_L(\vec{r}, t) = \gamma_s \vec{E}'_L(\vec{r}_c^L) - \frac{\gamma_s^2}{\gamma_s + 1} \frac{\vec{v}_L}{c} \left( \vec{v}_L \cdot \vec{E}'_L(\vec{r}_c^L) \right), \quad \vec{B}_L(\vec{r}, t) = \gamma_s \left( \frac{\vec{v}_L}{c} \times \vec{E}'_L(\vec{r}_c^L) \right)
\]

(1)

for the left spectator and

\[
\vec{E}_R(\vec{r}, t) = \gamma_s \vec{E}'_R(\vec{r}_c^R) - \frac{\gamma_s^2}{\gamma_s + 1} \frac{\vec{v}_R}{c} \left( \vec{v}_R \cdot \vec{E}'_R(\vec{r}_c^R) \right), \quad \vec{B}_R(\vec{r}, t) = \gamma_s \left( \frac{\vec{v}_R}{c} \times \vec{E}'_R(\vec{r}_c^R) \right)
\]

(2)

for the right spectator.

In the equations above, the \( \gamma_s \) factor is defined as \( \gamma_s = (1 - v_s^2/c^2)^{-1/2} \). The vectors \( \vec{E}_L (\vec{E}_R) \) and \( \vec{B}_L (\vec{B}_R) \) are respectively the electric and magnetic fields generated by the left (right) spectator at the space-time position \( (\vec{r}, t) \).

The resulting pion trajectory \( \vec{r}_\pi(t) \) is defined by its time-dependent velocity \( \vec{v}_\pi(\vec{r}, t) \):

\[
\frac{d\vec{r}_\pi}{dt} = \vec{v}_\pi(\vec{r}, t) = \frac{\vec{p}_\pi}{\sqrt{p_\pi^2 + m_\pi^2}},
\]

(3)

where \( m_\pi \) is the pion mass.

3. Results

In this Section we present some results of our Monte-Carlo studies described in detail in [6].

Our main results are illustrated in Fig. 1. Panel (a) shows the initial spectra of emitted pions. As explained in Ref. [6], in our simple model these spectra are identical for \( \pi^+ \) and \( \pi^- \). The presented \( \frac{d^2N}{d\phi d\phi_T} \) density distributions are scaled down by the number of participant pairs.

In panel (b), the corresponding distributions of \( \pi^+ \) in the final state of the Pb+Pb reaction are shown. These are obtained by our Monte-Carlo simulation. It is clearly apparent that the distributions are distorted by the Coulomb repulsion between the pion and spectator charges. The effect is largest for pions moving close to spectator velocities \( (x_F \approx \pm 0.15) \) and at low transverse momenta \( (p_T = 25 \text{ MeV/c}) \). Here,
Figure 1. Double-differential density of $\pi^+$ and $\pi^-$ produced per participant pair in peripheral Pb+Pb reactions. a) Initial density of emitted $\pi^+$ and $\pi^-$. b) Density of $\pi^+$ in the final state. c) Density of $\pi^-$ in the final state. The pion density is drawn as a function of $x_F$ at $p_T = 25$ MeV/c (thin solid), 75 MeV/c (dash), 125 MeV/c (dot), 175 MeV/c (dash-dot), and 325 MeV/c (thick solid); $p_T$ values corresponds to a bin of ±25 MeV/c. This simulation was made for $t_E=0$.

two deep valleys in the $\pi^+$ density are visible. A similar but smaller distortion is also apparent at $p_T = 75$ MeV/c.

An opposite distortion is present for $\pi^-$ densities shown in panel (c). Negative pions are attracted by the positive spectator charge and gather at low transverse momenta close to spectator velocities. This results in the presence of two large peaks at $x_F \approx \pm 0.15$. Remnants of these peaks are apparent at $p_T = 75$ MeV/c.

Fig. 2 shows the $x_F$-dependence of the $\pi^+ / \pi^-$ for different pion emission time $t_E$ (the time is measured since the time of the closest approach of two colliding nuclei). For $t_E = 0$ the spectator Coulomb field appears to produce a characteristic, complex pattern of deviations from unity. The first element of this pattern is a double, two-dimensional valley which covers the low-$p_T$ region in the vicinity of $x_F \approx \pm 0.15$; the valley remains still visible at $p_T = 175$ MeV/c. The second element is a smooth rise of the $\pi^+ / \pi^-$ ratio at higher $|x_F|$. This rise is present for all the considered $p_T$ values; at fixed $x_F$, the ratio slowly decreases with increasing $p_T$.

The central result of our analysis is the sensitivity of spectator-induced Coulomb effects to initial conditions. Indeed, clear differences appear for different $t_E$ values (Figs.2a,b,c,d). With increasing $t_E$, a broadening of the double valley at $x_F \approx \pm 0.15$, and a decrease of the $\pi^+ / \pi^-$ ratio at higher absolute $x_F$, are visible.

4. Conclusions

The electromagnetic interaction between highly charged spectators and charged pions produced in the peripheral Pb+Pb reaction has been studied by means of a simplified but realistic model. This interaction leads to significant distortions on the final state densities of $\pi^+$ and $\pi^-$. The main feature of this “Coulomb” effect is a big dip in the $\pi^+$ density distribution at low transverse momenta in the vicinity of $x_F \approx \pm 0.15$, accompanied by an increase
Figure 2. Ratio of cross sections for $\pi^+$ and $\pi^-$ for a peripheral Pb+Pb reaction, for five values of $t_E$. The $\pi^+ / \pi^-$ ratio is drawn as a function of $x_F$ at $p_T = 25$ MeV/c (thin solid), 75 MeV/c (dash), 125 MeV/c (dot), 175 MeV/c (dash-dot), and 325 MeV/c (thick solid).

of $\pi^-$ density in the corresponding region of phase space. This results in the presence of a two-dimensional valley in $(x_F, p_T)$ for the $\pi^+ / \pi^-$ cross section ratio. In addition, at higher absolute $x_F$, a smooth increase of $\pi^+ / \pi^-$ with $x_F$ may appear.

The sensitivity of this EM effect to initial conditions has been estimated. The effect is clearly sensitive to initial conditions. Changes of the pion emission time by 0.5 fm/c (in c.m.s. time) are sufficient to modify the observed distortion pattern. In our model, such changes are equivalent to changes of position of the formation zone by 0.5 fm relative to the two spectator systems. Thus, the EM effect appears to depend on the evolution of the pion production process in space and in time. Therefore, it constitutes a new source of information on the non-perturbative process of light–meson production.

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