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New results on Coulomb interaction effects in relativistic heavy ion collisions

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Summary. — The effects of the Coulomb interaction on charged pion production in Au+Au collisions at RHIC-BES energies are studied. From p_T spectra of charged pions measured with STAR experiment, the negative-to-positive pion ratios as a function of transverse momentum are obtained. Based of these pion ratio the final-state Coulomb interaction can be investigated. The "Coulomb kick" (a momentum change due to Coulomb interaction) and initial pion ratio for RHIC-BES energies (7.7 GeV, 11.5 GeV, 19.6 GeV, 27 GeV and 39 GeV) and various centrality classes are obtained. The energy and centrality dependence of the Coulomb kick is presented. These results are connected with the kinetic freeze-out dynamics.

1. – Introduction

In heavy-ion collisions, the difference in shape between the positive and negative pion transverse momentum spectra at low p_T can be used to study the Coulomb final-state interaction [1-4]. The produced charged particles are moving in a Coulomb field generated by the net positive charge of the stopped participant protons. Due to their small mass and large multiplicities, the charged pions are the particles strongest affected by this Coulomb field and their final momentum is changed. The strength of the Coulomb field depends on the degree of the baryon stopping produced in the collision.

The Coulomb effects on charged pion production in Au+Au collisions at RHIC-BES energies were studied using an analytic model developed in [5, 6]. The model assumes that, due to Coulomb interaction, on average, a charged pion will receive a momentum change or "Coulomb kick", $\pm p_c$ for $\pi^\pm$ respectively:

$$p_c \equiv |p_T - p_{T,0}| \cong 2e^2 \frac{dN^{ch}}{dy} \frac{1}{R_f} \tag{1}$$

where p_T is the final transverse momentum, $p_{T,0}$ is the transverse momentum at thermal freeze-out, dN^{ch}/dy is the net positive charge distribution and R_f is the thermal freeze-out radius. The π^-/π^+ ratio is described by the following equation:

$$\frac{\pi^-}{\pi^+} = \left\langle \frac{\pi^-}{\pi^+} \right\rangle \frac{p_T + p_c}{p_T - p_c} \exp\left(\frac{m_T^- - m_T^+}{T}\right) \tag{2}$$

where $\langle \pi^-/\pi^+ \rangle$ is the initial pion ratio, $m_T^{\pm} = \sqrt{m^2 + (p_T \pm p_c)^2}$ and T is the thermal freeze-out temperature.

2. – Results

The pion ratios were obtained from the p_T spectra produced in Au+Au collisions at RHIC-BES energies ($\sqrt{s_{NN}}$ = 7.7 GeV, 11.5 GeV, 19.6 GeV, 27 GeV and 39 GeV) at midrapidity and measured by STAR experiment [7]. The uncertainties on pion ratios were obtained using the experimental point-to-point uncertainties on the STAR p_T spectra. Figure 1 shows the π^-/π^+ ratios as a function of transverse momentum for the most central Au+Au collisions (0-5% centrality). For all energies, at low p_T values, an increase of the pion ratio above unity is observed, however, as the beam energy increases, the asymmetry between π^- and π^+ production is much less significant. These ratios were fitted with Eq. 2, where the Coulomb kick, p_c and initial pion ratio, $\langle \pi^-/\pi^+ \rangle$, are the free fit parameters. The thermal freeze-out temperature is fixed parameter and is taken from [7]. The fit range was chosen in the low p_T range because in this region the Coulomb interaction is stronger. By increasing the fit range, the fit quality decreases (χ^2/dof increases).

The Coulomb momentum as a function of the center of mass energy is presented in the left panel of Fig. 2. Black points are obtained from STAR-BES data and colored points are AGS and SPS results from [5]. The errors on p_c are obtained from the fits and are statistical. The p_c decreases with the increase of the energy showing that the Coulomb interaction is stronger at lower energies. If the two colliding nuclei are fully stopped, the net positive charge in the fireball is large, generating a strong electric field

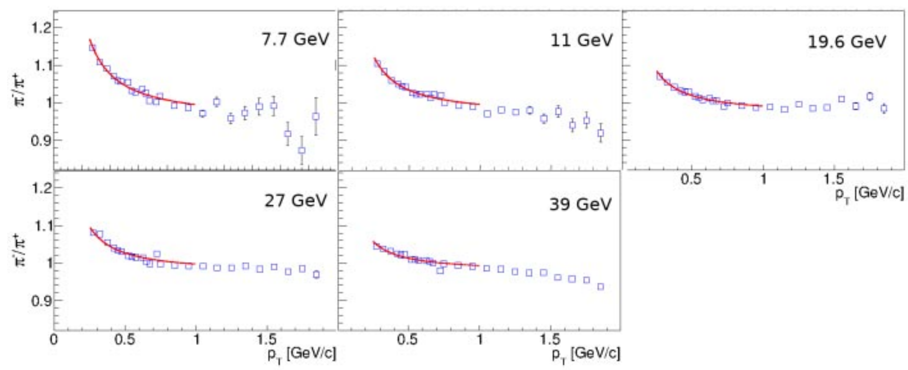

Fig. 1. – The π^-/π^+ ratios produced in most central Au+Au collisions (0-5% centrality) at $\sqrt{s_{NN}}$ = 7.7 GeV, 11.5 GeV, 19.6 GeV, 27 GeV and 39 GeV, as a function of p_T. Data are from [7]. The red lines are the fits with Eq. 2.

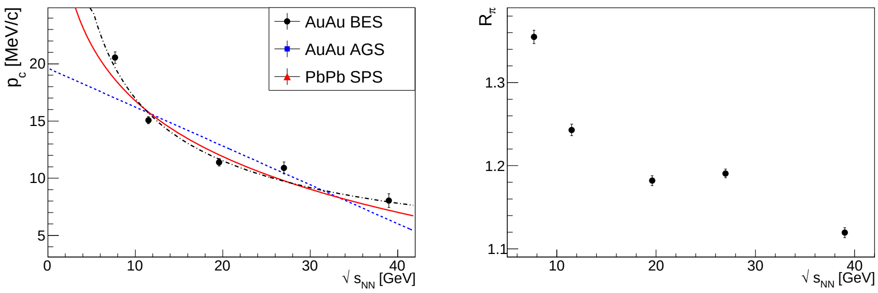

Fig. 2. – Left: The Coulomb kick as a function of beam energy. The lines are the fits with three functions described in the text. Right: Initial pion ratio as a function of energy.

that will influence the charged pions produced in collision. As the energy increases, ie the nuclei become more transparent and the net-positive charge in central interaction region decreases, as fewer of the original nucleons are stopped at midrapidity. Therefore the Coulomb effects are less significant.

We used three functions to describe this energy dependence. Fit functions, parameters and χ^2/dof are given in Table I. The power-law function seems to describe better the energy dependence of the Coulomb kick (red - f_1, black - f_2 and blue - f_3).

At thermal freeze-out, the ratio of the yields of π^- and π^+ is considered as *initial* pion ratio. After thermal freeze-out, the final-state Coulomb interaction modifies the p_T spectra, the positive pions being accelerated and negative pions being deccelerated by the net positive charge, resulting the detected (final) spectra.

The energy dependence of the initial pion ratio is shown in Fig. 2 (right). The errors on the initial pion ratio are obtained from the fits and are statistical. The $\langle\pi^-/\pi^+\rangle$ values decrease with the increase of the energy. At low energies, due to contributions from Δ resonances and isospin conservation, $\langle\pi^-/\pi^+\rangle$ values are larger than unity. With increasing energy the ratios decrease towards unity, indicating that the pion production mechanisms are changing and pion pair production dominates.

Figure 3 (left panel) shows the Coulomb kick as a function of collision centrality expressed as N_{part} (the number of participating nucleons) in Au+Au at 7.7 GeV, 11.5 GeV and 19.6 GeV. The errors on p_c are obtained from the fits and are statistical. The N_{part} values and associated errors were taken from [7]. The p_c values increase in more central collisions for all energies because the overlap volume is larger and therefore a more intense positive charge generates a stronger Coulomb field in the interaction region. For all centrality classes the largest values of p_c are at 7.7 GeV, due to large baryon stopping at midrapidity at this energy. As the energy increases, the degree of baryon stopping

Table I. – *The fit functions used to describe the energy dependence of the Coulomb kick.*

Function	a	b	χ^2/dof
$f_1 = a + b\ln\sqrt{s_{NN}}$	32.98±1.08	-7.04±0.38	10.11
$f_2 = a\,(\sqrt{s_{NN}})^b$	61.66 ± 5.01	-0.56±0.03	4.25
$f_3 = a + b\sqrt{s_{NN}}$	19.62 ± 0.41	-0.34±0.02	28.23

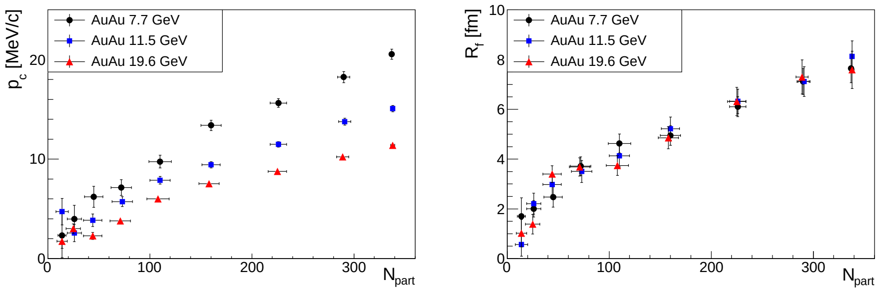

Fig. 3. – Left: The centrality and energy dependence of the Coulomb kick. Right: The thermal freeze-out radius as a function of collision centrality.

reduces and consequently the Coulomb interaction. For semi-central and peripheral Au+Au collisions at $\sqrt{s_{NN}}$ = 27 GeV and 39 GeV the pion ratios show no significant enhancement at low p_T and the information related to the Coulomb interaction from these data could not be obtained.

From Eq. 1, using the p_c values, the thermal freeze-out radius was obtained. The $dN^{ch}/dy = dN^{p}/dy - dN^{\bar{p}}/dy$ values were taken from [7], where dN^{p}/dy and $dN^{\bar{p}}/dy$ are the rapidity densities for protons and antiprotons, respectively. The R_f uncertainties were obtained using the experimental uncertainties of STAR dN^{p}/dy and $dN^{\bar{p}}/dy$ data and p_c uncertainties from the fits with Eq. 2. The energy and centrality dependence of the freeze-out radius is shown in right panel of Fig. 3. From 7.7 GeV to 19.6 GeV the freeze-out radius shows no energy dependence. R_f increases in more central Au+Au collisions indicating the formation of a larger system.

3. – Conclusions

The π^-/π^+ ratios produced in Au+Au collisions at RHIC-BES energies were used to study the Coulomb interaction between the charged pions and the net-positive charge in the fireball at midrapidiy. The Coulomb interaction effects are stronger in central collisions and at lower beam energies. The initial pion ratio decreases with energy suggesting a change in the pion production mechanisms and the increased role of pair production mechanism at higher energies. The size of the system at freeze-out R_f increases in more central collisions and is not changing with energy for the energy range considered here.

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