Revisit of Coulomb effects on π^-/π^+ ratio in heavy ion collisions

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We show that the large π^-/π^+ ratio at low pion energies recently observed in the reaction of Au+Au at $E_{beam}/A = 1.0$ GeV at SIS/GSI is due to the strong Coulomb field of the reaction system.

It was found recently by the KaoS and FOPI collaborations at SIS/GSI that the π^-/π^+ ratio increases as the pion kinetic energy or transverse mass decreases [1–4]. The ratio is found to depend strongly on the mass of the reaction system. For example, in the reaction of Au+Au at $E_{beam}/A = 1.0$ GeV the ratio increases continuously from about 1 at $E^{\pi}_{kin} \approx 400$ MeV to about 2 at $E^{\pi}_{kin} \approx 100$ MeV. While in the reaction of Ni+Ni at $E_{beam}/A = 1.8$ GeV the ratio goes upto only about 1.15 [5]. More recently, the E866 collaboration also studied the π^-/π^+ ratio as a function of the pion transverse energy E_t for Au+Au, Si+Au, Si+Cu and Si+Al reactions at AGS/Brookhaven [6]. For the first two reactions the π^-/π^+ ratio rises to about 2 at low E_t, while for the last two systems the ratio is only about 1 in the whole energy range.

The phenomenon has renewed some interests on the study of π^-/π^+ ratio in relativistic heavy ion collisions. The main question of interest is whether it is a manifestation of the well known Coulomb effect or an indication of some new physics. Moreover, it seems also necessary to well understand the isospin and Coulomb effects in order to study the more interesting phenomena found in the pion spectra of these experiments, such as, the enhancement of low/high energy pions. For this purpose we perform a quantitative study on the π^-/π^+ ratio in heavy ion collisions at SIS/GSI energies using a hadronic transport model [7,8]. We show that the large π^-/π^+ ratio found at SIS/GSI is indeed a manifestation of the Coulomb effect. Although we consider here reactions at SIS/GSI energies only, results of this study may also shed some light on understanding the similar effect found at AGS energies.

For completeness we first mention some of the early studies on the π^-/π^+ ratio in nuclear reactions. A large π^-/π^+ ratio at very low laboratory energies was observed a long time ago in experiments using protons, alphas and cosmic rays, and was explained as due to the Coulomb interactions. These studies were summarized and discussed in great detail in ref. [9]. Later on, much interest was generated by the discovery of structures in charged pion spectra at the Bevalac. A very distinctive feature observed in collisions of nearly equal mass projectile and target nuclei is an enhancement of the π^+ yield in the mid-rapidity region, which appears as a peak in the π^+ spectra at $\theta_{cm} = 90^0$. Such a peak was first observed at transverse momentum $p_t \approx 0.4 m_\pi c$ in the reaction of Ar+Ca at $E_{beam}/A = 1.05$ GeV by Wolf et al. [10], and at a slightly higher p_t by Chiba et al. [11] in the reaction of Ne+NaF at $E_{beam}/A = 0.8$ GeV. Additional structure in the low energy region at $\theta = 0^0$ in the projectile frame was found first by Benenson et al. [12] in the reaction of Ne+NaF at $E_{beam}/A \leq 400$ MeV. Corresponding to the strong π^- peak at $p_t = 0$ a dip was seen in the π^+ spectrum in the same experiments. Some systematic studies on the π^-/π^+ ratio were also performed at the Bevalac [13–16]

On the theoretical side, all studies seem to indicate the Coulomb nature of the phenomenon. By comparing the π^+, π^- wave functions in the electromagnetic field generated by the moving projectile fragment, Bertsch was able to explain the peak in the π^-/π^+ ratio found by Benenson et al. and its beam energy dependence [12,17]. Libbrecht and Koonin showed that the π^+ peak at $\theta_{cm} = 90^0$ and $p_t = 0.4 m_\pi c$ could be a result of the Coulomb focusing due to the relatively moving charged fragments [18]. In their analysis the charge distribution was approximated by spreading part of the protons along a line between the nuclear centers with the remainder continuing with the unaltered velocities. The classical equations of motion for pions were then sloved in the Coulomb field. Gyulassy and Kauffmann derived various approximate expressions for π^-/π^+ ratio in the Coulomb field of projectile and target remanants as well as the thermally expanding fireball [19]. Later, the π^-/π^+ ratio was also studied in ref. [20] using a statistical model for pion production at subthreshold energies [21].

In the present study we use the hadronic transport model [7,8] for relativistic heavy ion collisions. The model uses explicit isospin degrees of freedom for all hadrons involved in the reaction. In particular, isospin-dependent hadron-hadron collision cross sections and branching ratios for the decay of baryon resonances are fully incorporated in the model. The time dependent, selfconsist mean field for baryons including the Coulomb field and an isosymmetry term is a basic ingredient of the model. It has been rather successful in studying many aspects of relativistic heavy ion collisions. We refer the reader to our previous publications for more details of the model [22]. In view of the fact that in most of the previous theoretical studies on the subject one had to assume an idealized, simple and often static charge distribution during the reaction, the present study has the advantange of incorporating dynamically effects of the varying charge distribution.

Fig. 1 shows the calculated π^-/π^+ ratio as a function of pion kinetic energy with and without Coulomb interactions for the reaction of Au+Au at $E_{beam}/A = 1.0$ GeV. In the case without Coulomb interaction the ratio is a constant of about 1.9 for $E_{kin} \leq 500$ MeV, beyond 500 MeV the ratio has large statistical error bars. The constant π^-/π^+ ratio is very close to the estimate using the isospin argument [23]

$$R_I \equiv \frac{I^-}{I^+} = \frac{5N^2 + NZ}{5Z^2 + NZ}, \tag{1}$$

which gives 1.95 for the Au+Au reaction. While in the case with Coulomb interactions the ratio is larger than the isospin average for $E_{kin} \leq 150$ MeV and decreases as the pion energy increases. The cross over of the two calculations at $E_{kin} \approx 150$ MeV is a direct result of the competition between the Coulomb momentum impulse and the phase space distortion. This can be understood qualitatively using classical considerations similar to that of refs. [18,19]. In terms of the inclusive cross section $\sigma_0^\pm \equiv d^3\sigma_0^\pm/dp^3$ in the absence of the Coulomb field and the change of the phase space density $\partial^3 p_0/\partial^3 p$, the cross section in the presence of the Coulomb field $\sigma^\pm \equiv d^3\sigma^\pm/dp^3$ can be written as

$$\sigma^\pm(\vec{p}) = \sigma_0^\pm(\vec{p}_0(\vec{p}))|\frac{\partial^3 p_0}{\partial^3 p}| \approx I^\pm \cdot \sigma_0(\vec{p}_0(\vec{p}))|\frac{\partial^3 p_0}{\partial^3 p}|, \tag{2}$$

where $\vec{p}$ is the momentum of pions after moving through the Coulomb filed starting with an initial momentum $\vec{p}_0$. In the last approximation we factorized out the isospin factor $I^\pm$ since the π^-/π^+ ratio is almost a constant in the absence of the Coulomb interactions. The Coulomb impulse is

$$\delta\vec{p} = \pm(\vec{p} - \vec{p}_0(\vec{p})) \tag{3}$$

for π^+ and π^-, respectively. Thus, the impulse results in an increase (decrease) for π^+ (π^-) in the σ_0 term of eq. (2) which has approximately an exponential form $exp(-p_0^2/2m_\pi T)$, where T is the slope parameter of the pion spectra. The phase space distortion $|\partial^3 p_0/\partial^3 p|$ generally results in a decrease (increase) for π^+ (π^-), its exact form depends on the dynamics of the nuclear charge distribution and the trajectory of individual pions. An example of pion emission from the origin of a sphere with the total charge Ze and a radius r is instructive, though not very realistic. The potential energy of $\pm$ charged pions at the origin is $V_0 = \pm\frac{3}{2}Z\alpha/r$, energy conservation leads to

$$\vec{p}_0(\vec{p}) = \vec{p}(1 \mp p_c^2/p^2)^{1/2}, \tag{4}$$

where $p_c = \sqrt{2m|V_0|}$. One therefore obtains that

$$|\frac{\partial^3 p_0}{\partial^3 p}| = (1 \mp p_c^2/p^2)^{1/2}, \tag{5}$$

and

$$\sigma^{\pm}(p) = I^{\pm} \cdot \sigma_0(p) \cdot exp(\pm|V_0|/T)(1 \mp p_c^2/p^2)^{1/2}. \tag{6}$$

Keeping the first order in $Z\alpha$, the π^-/π^+ ratio is approximately

$$R = \frac{\sigma(\pi^-)}{\sigma(\pi^+)} \approx R_I \cdot [1 + 2|V_0|(\frac{m}{p^2} - \frac{1}{T})]. \tag{7}$$

The competition of the two factors m/p^2 and $1/T$ causes the π^-/π^+ ratio to change from $R \geq R_I$ to $R \leq R_I$ as the energy increases to above $E_{kin} = T/2$. The variation of the π^-/π^+ ratio in the transport model calculations is therefore understandable.

We now perform a comparison with the experimental data. Before comparing the ratio we first compare in Fig. 2 and Fig. 3 the π^+ and π^- spectrum, respectively. The data were taken for the Au+Au reaction at $\theta_{lab} = 44^0$ by the KaoS collaboration at SIS/GSI [2]. It is seen that the model can very well reproduce the available experimental spectra. Fig. 4 shows a comparison of the π^-/π^+ ratio. The model calculation is in good agreement with the available data at low energies, more complete data will be available from both the KaoS and FOPI collaborations at SIS/GSI. It is interesting to mention that a model calculation for the reaction of Ni+Ni at $E/A = 1.8$ GeV, which is almost isosymmetric, shows that the

π^-/π^+ ratio is about constantly 1 within statistical error bars. Comparing to the Au+Au reaction, it further indicates the strong Coulomb effect on the π^-/π^+ ratio in heavy systems.

In summary, using a hadronic transport model we have shown that the recently observed large π^-/π^+ ratio at low energies in relativistic heavy ion collisions is a manifestation of the strong Coulomb field of the reaction system.

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FIGURE CAPTIONS

Fig. 1 The calculated π^-/π^+ ratio with and without Coulomb interactions for the reaction of Au+Au at $E_{beam}/A = 1.0$ GeV.

Fig. 2 Comparison to the π^+ spectrum measured at $\theta_{lab} = 44^0 \pm 4^0$ in the reaction of Au+Au at $E_{beam}/A = 1.0$ GeV

Fig. 3 Same as in Fig. 2 but for the preliminary π^- spectrum.

Fig. 4 The π^-/π^+ ratio for the reaction of Au+Au at $E_{beam}/A = 1.0$ GeV. The preliminary data was measured at $\theta_{lab} = 44^0 \pm 4^0$ and the calculation is done at $\theta_{lab} = 45^0 \pm 15^0$.

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