TIME EVOLUTION OF PION EMISSION IN HEAVY ION COLLISIONS AT SIS ENERGIES*

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Using a magnetic spectrometer pions, kaons and protons were detected in mass-symmetric heavy ion reactions from C+C to Au+Au and at incident energies between 0.6 and 2.0 A·GeV. The center-of-mass pion spectra deviate from a Boltzmann distribution for all collision systems. Results are presented indicating that high-energy pions are emitted at an early stage of the collision. This is based on *(i)* a comparison of π^+ and π^- spectra and *(ii)* the shielding of pions by spectator matter in peripheral collisions.

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1. Introduction

Central heavy ion collisions at relativistic energies represent an ideal tool to study nuclear matter at high densities and at high temperatures. However, these collisions are rather complex. An understanding of their time evolution is needed before detailed informations can be extracted. Pions are the most abundantly produced particles at relativistic energies. Due to their high interaction cross section with nuclear matter they are continuously "absorbed" by forming baryonic resonances (*e.g.* $\pi N \to \Delta$) which then decay

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again into pions. Therefore, pions can be emitted from the first interactions until a very late stage of the collision.

In this paper an overview of the measured pion spectra is given in the first part. The second part addresses the question of the origin of high-energy pions.

The experiments were performed using the Kaon Spectrometer [1] at the heavy-ion synchrotron SIS at GSI (Darmstadt). For details see Ref. [2].

2. Pion spectra

Data on pion spectra up to laboratory momenta of 1400 MeV/c have been measured in mass symmetric systems from A = 12 to A = 197 and at incident energies from 0.6 to 2.0 A·GeV. As a representative selection, Fig. 1 shows double differential cross sections of positively charged pions in the Boltzmann representation $1/(pE)\, d^2\sigma/(dEd\Omega)$ for various mass systems and at different incident energies. The spectra are measured at laboratory angles corresponding to a center-of-mass angular range within 90±30 degrees.

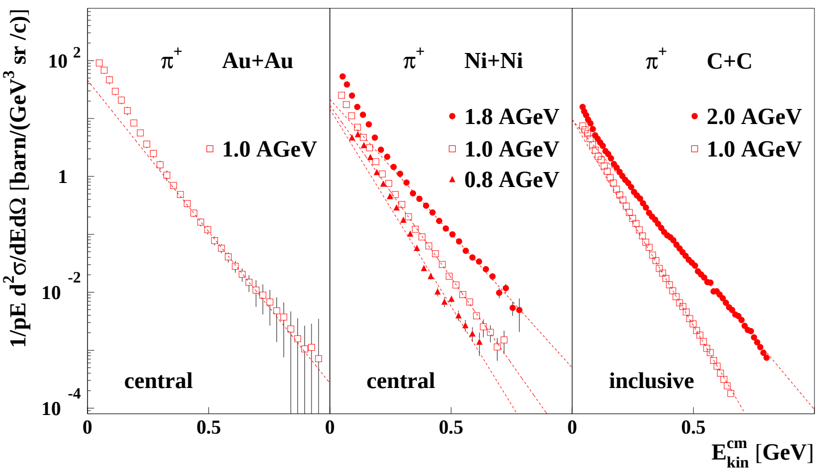

Fig. 1. Spectra of positively charged pions in the center-of-mass frame in a "Boltzmann" representation for various reactions (preliminary data).

All spectra exhibit concave shapes in this representation. Straight lines (Boltzmann distributions) fitted to the high-energy tail, *i.e.* to kinetic energies above the corresponding free NN kinematical limit, are shown. The inverse slope parameters increase with incident energy and with increasing mass of the collision system. The inverse slope parameters of positively charged kaons are about the same, those of protons are always higher as shown in Ref. [2].

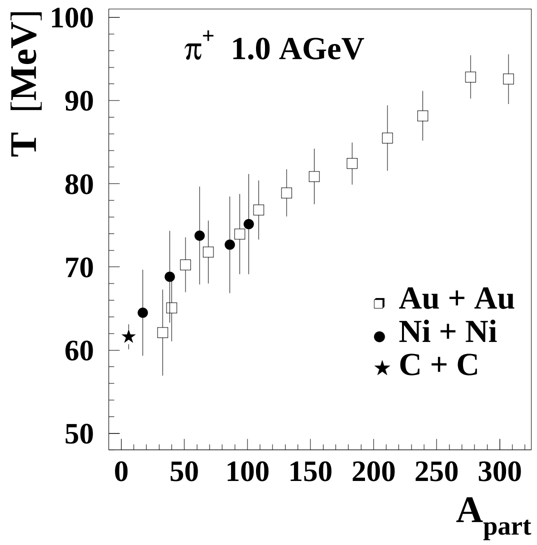

Fig. 2. The inverse slope parameters of the high-energy part of the spectra of positively charged pions for different collision systems reveal a very similar behaviour if plotted as a function of A_{part}.

It is of interest to study the variation of the slopes of the high-energy part of the pion spectra with centrality, *i.e.* as a function of A_{part}. Fig. 2 shows that the inverse slope parameters increase with A_{part}. It is interesting to remark that all collision systems fall on a common line. Furthermore, the inverse slope parameters obtained for positively charged kaons agree with this systematics [3]. These findings together with the obtained slope parameters from participating protons fit into a picture of a thermal, radially expanding source. Since the influence of flow increases with the mass of the emitted particle, protons show higher "apparent temperatures". At incident energies around $1A \cdot \mathrm{GeV}$ pions are either "free" or "bound"in baryonic resonances. At freeze out the pion spectra are then composed of a "thermal" component and another one governed by the decay kinematics of the excited baryonic resonances. Indeed, the measured shapes (Fig. 1) can be qualitatively understood by such a scenario. Recent quantitative examples of such a decomposition are found *e.g.* in Ref. [4, 5].

The arguments presented so far are pointing towards the interpretation within a thermal concept. A recent attempt to understand the particle ratios and spectra is given in Ref. [6]. Next, arguments are given that the assumption of a unique freeze-out time for all particles and even for particles of different kinetic energy, here pions, is highly questionable.

3. On the origin of high-energy pions

A detailed interpretation of the pion spectra is still under debate. Many models, either thermal concepts or microscopic descriptions, have difficulties to describe the entire pion spectra properly. While there is little discussion on the rise of the low-energy part of the spectra (decaying baryonic resonances), the origin of the high-energy part of the pion spectra remains open. Here, independent observations are given which can be summarized as follows: High-energy pions are emitted at an early stage of the collision. This is based on:

(i) Spectra of oppositely charged pions emitted in central Au+Au collisions at 1.0 A·GeV are compared. The π^--π^+ difference is attributed to the influence of isospin and Coulomb field. This allows to extract the effective Coulomb field at the instant of the pion emission. It turns out that a constant Coulomb potential V_{Coul} is unable to describe the entire difference between the spectra. A rather weak V_{Coul} is needed to describe the low-energy part of the spectra; in contrast to the much stronger V_{Coul} needed for the high-energy part. This reduction of V_{Coul} indicates a more dilute charge distribution at freeze out for low-energy pions. This part is published in [7].

(ii) Studying the yield of high-energy pions and K^+ as a function of centrality, a similar behaviour is found when comparing at the same total energy needed for their production. This indicates the dominant role of multiple collisions in the production of both particel species [2, 8].

(iii) Direct experimental evidence for the time evolution of pion emission is presented based on the shadowing of spectator matter in certain space-time regions. For this purpose we have chosen peripheral collisions of Au+Au at 1.0 A·GeV incident energy. The moving spectator matter acts like a shutter of a camera shielding the pion, *i.e.* modifying the pion emission pattern according to the spatial distribution of the spectator matter at the time of the pion freeze out. The motion of the spectator serves as a calibrated clock. A preferential emission perpendicular to the reaction plane has already been observed for this collision system [9, 10]. Recently, an enhanced in-plane emission of pions was observed [11]. This "antiflow" behaviour is found to be pronounced only in peripheral collisions. In this work we reveal the effects of "flow" and "antiflow" as resulting from the interplay of the time evolution of the pion emission with the shadowing of the surrounding matter.

The orientation of the reaction plane is determined using the recipe given by Danielewicz [12]. In previous works [9, 10] the observation of preferential emission of pions perpendicular to the reaction plane has been reported.

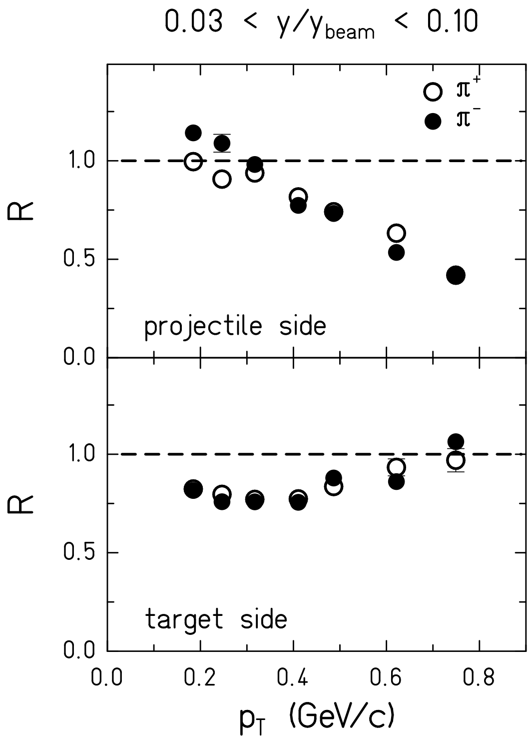

Fig. 3. Ratio of the pion spectra for in-plane emission to the one out of plane in peripheral Au+Au collisions at 1 A·GeV. The upper part refers to the emission to the "projectile side", the lower one to the "target side". Full (open) symbols refer to π^- (π^+) emission.

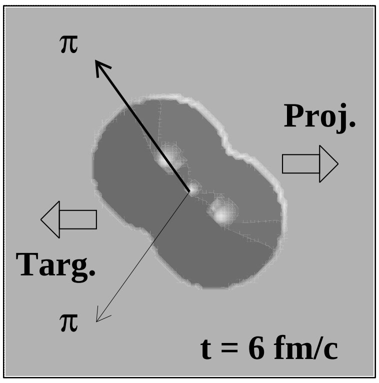

Fig. 4. Sketch of the geometrical situation of the spectators at 6 fm/c after the instant when the nuclei touch for Au+Au collisions at 1 A·GeV.

Here, we subdivide the in-plane emission comparing the number of pions emitted to the same side as the projectile remnants (projectile side) with the one on the opposite side (target side). Assuming that the out-of-plane emission reflects the least disturbed pion spectra, the in-plane spectra are divided by the out-of-plane ones. As an example Fig. 3 shows these ratios obtained at a laboratory angle of 84 degrees ($0.01 \leq y/y_{\rm beam} \leq 0.10$). The most interesting observation is the drastic drop for high-energy pions on the "projectile side", while on the "target side" the ratio is about one. For low-energy pions one observes a slight reduction only on the "target side". The observations for π^- and π^+ are nearly identical, demonstrating that the effect is not caused by the opposite Coulomb force. To illustrate the reduction of high-energy pions on the "projectile side", Fig. 4 exhibits the geometrical situation just at the beginning of the collision. The projectile spectator is just inbetween the fireball and the detector on the projectile side, thus shielding pions emitted at this instant. However, at this "early" stage the target spectator is not shielding the emission to the "target side"as can be observed in Fig. 3. Hence, high-energy pions are emitted at this early stage ($\approx$ 6fm/c) of the collision. The emission time interval is estimated to be $\approx$ 10 fm/c from the time of fly-by of the projectile residue. Low-energy pions seem to be emitted during the whole collision as no pronounced suppression is seen. The slight reduction on the target side indicates a preferred emission at later times.

4. Summary

A global survey of the spectral shapes of the emitted pions, K^+ and protons points towards an interpretation within a thermal concept. However, a detailed inspection of the pion emission (comparison of π^+, π^- emission and shadowing of pions by spectator matter in peripheral collisons) reveals that high-energy pions freeze out at an early stage of the collision, while the low-energy ones are emitted during the whole collision process.

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