Systematic behavior of K/π ratio in relativistic nucleus-nucleus collisions

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A simple hadronic transport model is proposed for studying the rescattering effect of the pion on the K/π ratio in relativistic nucleus-nucleus collisions. The experimental evidences of evolutionary increase of the K/π ratio from $p+p$ to $p+$Au and to Si+Au at similar incident energy per nucleon are reproduced reasonably. Experimental results of the K/π ratio at CERN energy (200 GeV/nucleon $p+W$ and $S+W$) comparable with corresponding results at the Brookhaven Alternating Gradient Synchrotron energy (14.6 GeV/nucleon $p+$Au and Si+Au) are reproduced as well.

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I. INTRODUCTION

The main purpose of experimental and theoretical efforts in the field of ultrarelativistic nucleus-nucleus collisions is to explore the possibility of the formation of a new phase of matter, quark-gluon plasma (QGP), in reaction processes. Among the predicted signatures [1] of QGP formation, the enhancement of the K^+/π^+ ratio in $A+B$ collisions comparing to $p+A$ and/or $p+p$ collisions at similar incident energy per nucleon is one of the most widely investigated [2–12] issues.

The question of whether the above enhancement of the K^+/π^+ ratio can also be worked out on the hadronic scenario arises naturally. Several purely hadronic models [2–12] have already been developed. Those models can be roughly cataloged into two kinds, the thermal models [6–9] and the transport models [10–12]. Though most of the thermal models gave positive answers, the answers of two transport models [10–11] were completely different.

In order to make things clear, we propose a simple hadronic transport model for studying the rescattering effect of the pion on the K^+/π^+ ratio in relativistic nucleus-nucleus collisions. In this model the primary produced particles (pions and kaons here) and the participant nucleons are supplied with the FRITIOF event generator and distributed randomly in the cylinder formed when projectile passes through the target nucleus. Spectator nucleons are arranged randomly outside the cylinder and inside the target sphere, and given thermal momenta sampled from a Boltzmann distribution. Rescattering transport processes are then started; pion reinteractions with each other and with nucleons are taken into account hereafter. It has turned out that, with the thermal motion of nucleons and the full rescattering (both were neglected in Ref. [11]), the enhancement of the K^+/π^+ ratio in Si(14.6 GeV/nucleon)+Au reactions can be explained. That is in agreement with Ref. [10].

Further, the model is compared with the experimental evidences of the evolutionary increase of the K^+/π^+ ratio from $p+p$ to $p+A$ and to $A+B$ [2–5] reactions, and to the remarkable similarity of the K^+/π^+ ratios in nucleus-nucleus collisions at CERN energy (200 GeV/nucleon) and at the Brookhaven Alternating Gradient Synchrotron (AGS) energy (14.6 GeV/nucleon) [5]. It is very encouraging that those experimental systematic behaviors are also reproduced reasonably.

II. MODEL AND CORRESPONDING SIMULATION

As is well known in the Lund model, the independent-fragmentation scheme FRITIOF [13] assumes that projectile nucleons move on straight lines through the target nucleus. They are excited continuously via collisions with target nucleons which are within a tube (around corresponding trajectory of projectile nucleon) with a cross section given by the inelastic nucleon-

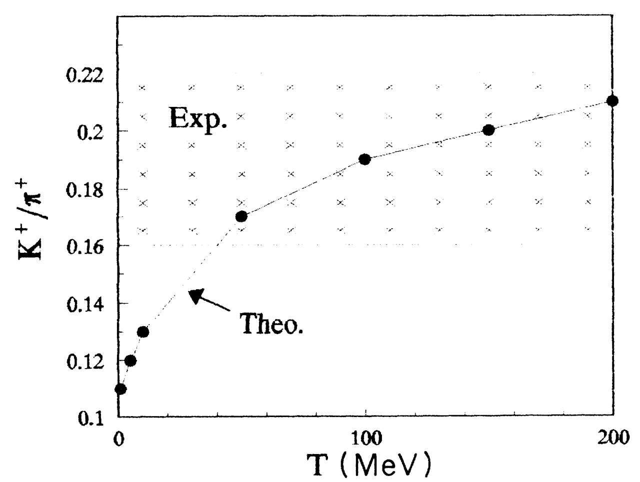

FIG. 1. The curve of the K^+/π^+ ratio versus temperature of spectator nucleons (with full rescattering and $\sigma_{\pi\pi\to KK}=2.0$ mb).

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TABLE I. K/π ratio in Si(14.6A GeV/c)+Au. $\sigma_{\pi\pi\to KK}=2.0$ mb.

Rescattering	no	first	full	full	first	full	Exp.[a]
T (MeV)	static	static	static	1	200	200	
K^+/π^+	0.073	0.093	0.10	0.11	0.09	0.21	0.19±0.03
K^-/π^-	0.031	0.037	0.039	0.039	0.03	0.044	0.036±0.008

[a]cf. Ref. [4].

nucleon cross section. The excited projectile and target nucleons decay independently after the actual collision process ceased. Pions, kaons, etc. are created just at the decay of the excited nucleons, but the reinteractions of produced particles with each other and with nucleons is not included in FRITIOF.

From the transport processes the relativistic quantum molecular dynamic (RQMD) [10] is self-consistent but relies strongly on the Lund model (its subroutine JETSET, especially) in the treatment of hadronization (i.e., particle production). Thus, for investigating the rescattering effects of the pions on the K^+/π^+ ratio it is reasonable to start the simulation from the outputs of the FRITIOF event generator [13] for simplicity.

The primary pions and participant nucleons from FRITIOF are then distributed randomly in the cylinder formed when the projectile passes through the target nucleus. Spectator nucleons, which are assumed (in the case of a center collision) to be the projectile and target nucleons minus the nucleons from FRITIOF, are arranged randomly in the region outside the cylinder and inside the target nucleus. The initial momentum of spectator nucleon is sampled from the Boltzmann distribution

$$f(p)=C\frac{p^2}{T^{1.5}}\exp\left[-\frac{p^2}{2m_nT}\right], \quad (1)$$

$$\langle p\rangle=(2m_nT)^{1/2}, \quad (2)$$

where C is the normalization constant, T (in GeV) stands for the temperature of spectator nucleons, m_n refers to the mass of nucleon, and $\langle p\rangle$ (in GeV/c) is the average momentum of spectator nucleon. The momenta of pions, kaons, and participant nucleons are given by FRITIOF.

As the yield and the reinteraction cross section of the kaon is quite small compared with the pion, the kaon rescattering is neglected. The kaons from the FRITIOF event generator are then counted directly. Thus the collision list of rescattering is concerned with pions and nucleons only. The collision list is then constructed due to two requirements: the minimum approaching distance between colliding particles (i and j, for instance, which represent the pion and/or nucleon) should satisfy

$$d_{\min}^{i,j}\le\left[\frac{\sigma_{\rm tot}}{\pi}\right]^{1/2} \quad (3)$$

(where $\sigma_{\rm tot}$ refers to the total cross section of πn or $\pi\pi$ interaction), and the collision should happen in the future. Here the assumption of constant total cross section ($\sigma_{\rm tot}^{\pi n}=25$ mb and $\sigma_{\rm tot}^{\pi\pi}=10$ mb) has been taken for simplicity.

After selecting the smallest collision time and performing the corresponding collision (between i and j, for instance), the collision list has to be updated. First, all collisions involving colliding particles (i or j) should be removed. Second, the new collisions, composed of one colliding particle, from i and j, and another from particles in the current particle list (except i and j), that satisfy the above requirements should be added to the collision list. The particle list is also then updated. The above steps are repeated until the collision list is empty.

Since the kaon production rate is quite low whether in πn or $\pi\pi$ collision, the weight recording method is adopted to count the produced kaons in reactions. For $\pi\pi$ rescattering, for instance, the following inelastic processes

$$\pi^+\pi^-\to K^+K^-, \quad \pi^+\pi^0\to K^+\bar{K}^0, \quad \pi^0\pi^0\to K^+K^-, \quad (4)$$

TABLE II. Systematic behavior of K/π ratio.

		AGS energy (14.6 GeV/nucleon)			CERN energy (200 GeV/nucleon)		
		$p+p$[a]	$p+$Au[b]	Si+Au[c]	$p+p$[d]	$p+W$[e]	$S+W$[f]
K^+/π^+	Exp.	0.04–0.1	0.125	0.19±0.03	0.108±0.09	0.141±0.008	0.197±0.009
	Theo.	0.073	0.100	0.210	0.098	0.158	0.180
K^-/π^-	Exp.	0.03–0.06	0.028	0.036±0.008	0.086±0.008	0.037±0.004	0.053±0.004
	Theo.	0.031	0.026	0.044	0.082	0.064	0.095

[a]$\sigma_{\pi\pi\to KK}=2.0$ mb, $\langle p\rangle=600$ MeV, data taken from Ref. [1].
[b]$\sigma_{\pi\pi\to KK}=2.0$ mb, $T=20$ MeV, data taken from Ref. [9].
[c]$\sigma_{\pi\pi\to KK}=2.0$ mb, $T=200$ MeV, data taken from Ref. [3].
[d]$\sigma_{\pi\pi\to KK}=3.5$ mb, $\langle p\rangle=600$ MeV, data taken from Ref. [5].
[e]$\sigma_{\pi\pi\to KK}=2.0$ mb, $T=20$ MeV, data taken from Ref. [5].
[f]$\sigma_{\pi\pi\to KK}=3.5$ mb, $T=200$ MeV, data taken from Ref. [5].

TABLE III. Systematic rescattering effect on K/π ratio at AGS energy.

	no rescattering			full rescattering		
	$p+p$	$p+$Au	Si+Au	$p+p$	$p+$Au	Si+Au
K^+/π^+	0.071	0.036	0.049	0.073	0.100	0.210
K^-/π^-	0.029	0.017	0.014	0.031	0.026	0.044

TABLE IV. Spectator nucleon effect on K/π ratio in Si(14.6A GeV)+Au. $\sigma_{\pi\pi\to KK}=1.5$ mb, $T=200$ MeV, full rescattering.

Spectator nucleon	without	with
K^+/π^+	0.084	0.193
K^-/π^-	0.033	0.038

have their own occurring probability (equal to the ratio of the cross section of the corresponding process and the $\sigma_{\rm tot}^{\pi\pi}$), by which the corresponding kaon production rate is then counted. For the πn collision, the following inelastic processes

$$\pi^+p\to K^+\Sigma^+ \,,\quad \pi^+n\to K^+\Sigma^0 \,,\quad \pi^+n\to K^+\Lambda \,, \tag{5}$$

$$\pi^-p\to K^+\Sigma^- \,, \tag{6}$$

$$\pi^0p\to K^+\Lambda \,,\quad \pi^0p\to K^+\Sigma^0 \,,\quad \pi^0n\to K^+\Sigma^- \,, \tag{7}$$

also have their own probability by which the kaon production is recorded as well.

On the other hand, the transport process proceeds by comparing the probability above with a random number to decide whether the corresponding inelastic process really does happen. If so, the simulation is ended. If not, the simulation continues. One first calculates the final states of colliding particles (due to elastic scattering law here, for simplicity), then all particles move along their own trajectory within a time interval (equal to the smallest collision time selected above), and update collision list, update particle list, and so on.

Due to the fact of a lack of experimental information, $\sigma_{\pi\pi\to KK}$ is assumed to be constant [6, 10, 11] and the values of 0.5, 1.0, 2.0, and 3.5 mb are tried. The isospin averaged parametrization formulas of Ref. [14] are adopted for the cross-section of $\pi n\to K^+Y$ (Y is here denoted for Λ or Σ).

III. RESULTS AND DISCUSSIONS

Figure 1 shows the theoretical curve of the K^+/π^+ ratio ($\sigma_{\pi\pi\to KK}=2.0$ mb, full rescattering) versus the temperature of spectator nucleons in the reaction of Si(14.6 GeV/nucleon)+Au and the experimental data (the area with crosses in figure). One sees from this figure that, relying on the thermal motion of spectator nucleons and the full rescattering (both were not included in Ref. [11]), the experimental data are well reproduced under reasonable parameters. It should be mentioned again that the thermal motion of the participant nucleons (which was also not included in Ref. [11]) provided by FRITIOF has already been considered in the theoretical results.

As shown in Table I in the situation of static nucleons (without thermal motion of spectator nucleons, here) the best theoretical results (with full rescattering) of the K^+/π^+ ratio reach half of the experimental data only. By comparing columns 4 (or 5), 6, and 7 with each other and with experimental data, one knows that neither the results of column 4 or 5 (the case of considering full rescattering only) nor the results of column 6 (the case of considering thermal motion of spectator nucleons and first rescattering only) can compare with the experimental data. It is also shown by columns 5 and 6 that the multiple rescattering effect is somewhat more important than the thermal motion of spectator nucleons.

The theoretical results of the evolutionary increase of the K/π ratio from $p+p$ to $p+A$ and to $A+B$ at both AGS and CERN energies and their comparison with the experimental data are given in Table II. It is really encouraging, not only that the experimental fact of systematic increase of K/π ratio from $p+p$ to $p+A$ and to $A+B$ at similar bombarding energy per nucleon [3,4] is reproduced reasonably, but also the fact that K/π ratio of $p+p$, $p+A$, and $A+B$ collisions at CERN energy are comparable with corresponding ones at AGS energy [5] is reproduced as well. It should be mentioned that the result of $p+$Au at AGS energy is calculated with the value of $\sigma_{\pi\pi\to KK}=2.0$ mb in order to keep consistency with those used in $p+p$ and $A+B$ reactions. If 3.5 mb is used, one gets a better K^+/π^+ ratio of 0.112. The best theoretical result of K^+/π^+ ratio in $p+W$ reaction at CERN energy is 0.148 by using $\sigma_{\pi\pi\to KK}=1.0$ mb, and the worst is 0.17 using $\sigma_{\pi\pi\to KK}=3.5$ mb.

Table III seems to indicate that the rescattering effect plays an important role consistently in all of $p+p$, $p+$Au, and Si+Au reactions at AGS energy, and nearly the same conclusion holds for CERN energy. The important role played by spectator nucleons is shown completely in Table IV for Si(14.6 GeV/nucleon)+Au reaction;

TABLE V. Increasing of K^+ production in Si(14.6A GeV/c)+Au. $\sigma_{\pi\pi\to KK}=2.0$ mb, $T=200$ MeV.

Reaction	$p+$Au				Si+Au			
meson	K^+		π^+		K^+		π^+	
rescattering	no	full	no	full	no	full	no	full
yield	8.0	16.3	221	172	217	621	4427	2948
increasing (decreasing) factor	2.03		(1.28)		2.85		(1.50)	

TABLE VI. Density effect on K/π ratio in Si(14.6A GeV/c)+Au. $\sigma_{\pi\pi\to KK}=2.0$ mb, $T=200$ MeV, full scattering.

ρ_n (fm^{-3})	0.16	0.32	0.64
K^+/π^+	0.21	0.23	0.25
K^-/π^-	0.044	0.050	0.055

TABLE VII. Formation time effect on K/π ratio in Si(14.6A GeV/c)+Au. $\sigma_{\pi\pi\to KK}=1.5$ mb, $T=150$ MeV, full rescattering.

Formation time (fm/c)	0	0.5	1.0
K^+/π^+	0.20	0.074	0.055
K^-/π^-	0.036	0.016	0.015

that is, in agreement with the experimental analysis of Ref. [5].

In an experimental paper, Ref. [4], it has been pointed out that the evolutionary increase of the K^+/π^+ ratio from $p+p$ to $p+A$ and to $A+B$ can be largely attributed to the increased production of K^+ and not to the suppression of π^+. This observation is also seen nicely in theoretical calculations as shown in Table V.

Table VI investigates the nucleon density effect on the K^+/π^+ ratio in the reaction of Si(14.6 GeV/nucleon) +Au. Although the K^+/π^+ ratio does systematically increase with increasing the nucleon density, the density effect is not significant anyway. The reason for this might be that the nucleon density is taken into account via the radius of the nuclear system (the radius of the target nucleus) only. If the effect of restoration of broken chiral symmetry (i.e., decreasing the particle mass with increasing temperature and/or density) is taken into account, the influence might be much larger.

It is commonly believed that the formation time of pion plays an important role in the rescattering. In order to look for that, pions from FRITIOF are given a formation time of 0, 0.5, and 1.0 fm/c and the calculations are repeated. The results are given in Table VII. One sees from this table that the formation time effect is quite strong. Of course, in our model it is more reasonable to assume that the formation time of pions is equal to zero. Results in other tables are all due to zero formation time.

In summary, the proposed hadronic transport model for pion rescattering in relativistic nucleus-nucleus collisions can reproduce the enhancement of the K^+/π^+ ratio, the evolutionary increase of the K^+/π^+ ratio from $p+p$ to $p+A$ and to $A+B$, and the systematic remarkable similarity of those ratios at CERN energy to the ones at AGS energy, respectively. Therefore, regarding the enhancement of the K^+/π^+ ratio as a possible signature of QGP formation in ultrarelativistic nucleus-nucleus collisions might be questionable.

In addition, it should be mentioned that during the calculation of this paper, Aichelin and Werner proposed a novel approach to rescattering in ultrarelativistic nucleus-nucleus collisions [15]. They treat the rescattering in a consistent way in string model. It is hopeful that by using their model the experimental evidences investigated here may be reproduced as well.

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