Enhancement of low-m_t kaons in AGS heavy-ion collisions

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Abstract

In the relativistic transport model, we show that the recently observed enhancement of low-m_t kaons (K^+ and K^-) in Si+Pb collisions at AGS can be explained if a density isomer is introduced in the nuclear equation-of-state.

I. INTRODUCTION

An interesting experimental observation in relativistic heavy-ion collisions at AGS energies is the enhancement of low-m_t kaons (both K^+ and K^-) in Si+Pb collisions at 14.6 (GeV/c)/nucleon [1]. The spectra of these extremely 'cold' (in terms of their transverse mass m_t) kaons can be characterized by an inverse slope parameter (temperature) as low as 15 MeV, which is about one order-of-magnitude smaller than the temperature of 'normal' kaons measured in earlier AGS experiments [2]. These low m_t kaons cannot be obtained in conventional calculations such as the relativistic quantum molecular dynamics [3]. At lower incident energies, a similar enhancement of low-p_t pions has already been observed at Bevalac [4] and SIS energies [5], and one of the plausible explanations for this enhancement, as put forward by Xiong *et al.* [6], is based on the attractive pion potential due to the Δ-hole polarization.

Very recently, Koch [7] has tried to explain the enhancement of low-m_t kaons at AGS energies by a similar mechanism as in Ref. [6], i.e., the attractive kaon potential. When a kaon 'climbs' out of a potential well, it has to lose its kinetic energy and thus gets cooled down. It was found in Ref. [7], however, that in order for the attractive potential to be effective in cooling down the kaons, the baryon fireball, which is the source for the kaon potential, has to expand slower than kaons, so that the latter will have the chance to climb out the potential well before it disappears.

In a relativistic transport model [8,9] based on the σ-ω model [10] for the nucleon-nucleon interaction, as the one used in this work and in Ref. [7], the expansion of the fireball is controlled by the delicate balance (or rather unbalance) between the scalar (σ) attraction and vector (ω) and thermal repulsion. In usual relativistic transport model, the scalar and vector coupling constants, which are determined by fitting the properties (saturation density, binding energy, effective mass and incompressibility) of normal nuclear matter, are assumed to be density and temperature independent. For a fireball at about six times normal nuclear matter density and a temperature of about 170 MeV, as expected for the AGS energies

[3,11], the scalar attraction is overwhelmed by the vector and thermal repulsion, as the former tends to saturate at high density due to relativistic effects. The fireball would thus expand rather fast and kaons cannot be cooled down effectively.

To slow down the expansion of the fireball, Koch [7] has suggested that the system initially goes through the chiral restoration transition, which leads to a softening of the equation-of-state and thus slows down the expansion of the fireball. This has been achieved in Ref. [7] by reducing the vector coupling constant to about half of the value used in the original Walecka model [10]. Using the coupling constants given in Ref. [7], however, the nuclear matter would have saturated around 0.6 fm^{-3} with a binding energy of about 250 MeV, which is clearly unrealistic.

In this paper, we propose that the slowing down of the fireball expansion is also possible if there is a density isomer at high densities and if the fireball is initially at this abnormal state. Lee and Wick [12] observed that the chiral sigma model can lead to an abnormal state at high densities. The binding energy of this state can be very large, leading to a secondary minimum in the nuclear matter equation-of-state. The chiral sigma model, however, cannot describe correctly the saturation properties of the nuclear matter. In a relativistic mean-field theory that includes the Δ degree of freedom, Boguta [13] has shown that it is possible to *simultaneously* describe the nuclear matter properties at saturation density and predict the existence of a density isomer at high density. This has been realised in Ref. [13] by assuming that the scalar interaction of the Δ is stronger than that of the nucleon. In the present exploratory study, we will simulate the effect of the density isomer by introducing a density-dependent vector coupling constant in the non-linear σ-ω model, which gives correct saturation properties of the nuclear matter at $\rho_0 = 0.16$ fm^{-3} and leads to a secondary minimum around (5-6)ρ_0. More consistently, one would like to combine the chiral sigma model with the Walecka model, so that both the nuclear matter saturation and the density isomer come out naturally from the underlying Lagrangian.

II. NUCLEAR EQUATION-OF-STATE

Our study is based on the relativistic transport model for the expansional stage of the fireball formed in a Si+Pb collision at 14.6 (GeV/c)/nucleon [14,15]. In Ref. [16], we have proposed two sets of parameters for the non-linear σ-ω model. In this work, we use slightly different parameters which are determined by requiring a saturation density of 0.16 fm^{-3}, a binding energy of 15.96 MeV, a nucleon effective mass m^*/m=0.77, and an incompressibility of 380 MeV. Using the notation of Ref. [16], these parameters have the following values

$$C_V = 10.5, \quad C_S = 13.61, \quad B = -0.003131, \quad C = 0.02908.$$

The nuclear equation-of-state corresponding to this parameter set is shown in Fig. 1 by the dashed curve. To simulate the density isomer at high densities, we assume that the vector coupling constant is density-dependent and is determined by nuclear matter properties at saturation density and the assumption that around $5.5\rho_0$ a secondary minimum appears. Explicitly, we have

$$\begin{aligned} C_V &= 10.5, \quad \rho \le \rho_0, \\ &= 10.59 - 0.0923\Big(\frac{\rho}{\rho_0}\Big)^2, \;\; \rho_0 < \rho \le 5.5\rho_0, \\ &= 7.8, \quad \rho > 5.5\rho_0. \end{aligned} \tag{1}$$

The nuclear equation-of-state with this density-dependent vector coupling constant is plotted in Fig. 1 by the solid curve. A secondary minimum is seen around $5.5\rho_0$ with a binding energy of about 2 MeV.

We note that the density dependence of the vector coupling constant leads to a so-called rearrangement potential for the nucleon. In the present case, this potential is attractive, so it tends to further slow down the expansion of the fireball.

The fireball, which contains nucleons (N), deltas (Δ), hyperons (Y), pions (π), rhos (ρ), as well as kaons (K^+) and antikaons (K^-), is assumed to have an initial density of $6\rho_0$ and temperature of 170 MeV. The initial density is higher than that used in the fireball model of

Ref. [17] but is consistent with that predicted by the cascade model [11] and the relativistic quantum molecular dynamics [3]. The motions of these particles are then described by the relativistic transport model. The treatment of two-body scattering is the same as in Refs. [15,16]. For kaon-baryon and antikaon-baryon elastic scattering we use the empirical cross sections [18]. The kaon-pion and anitkaon-pion scattering are dominated by K^* resonances, and we use the Breit-Wigner cross section of Ref. [19]. For an antikaon, it can also be annihilated by a nucleon into a hyperon and a pion ($K^-N \to Y\pi$). The annihilation cross section is appreciable and is expected to be modified strongly in a medium due to changing in-medium hadron masses. The in-medium cross section for antikaon annihilation will be discussed later.

III. KAON AND ANTIKAON POTENTIALS

In a nuclear medium, a kaon feels an attractive scalar potential due to explicit chiral symmetry breaking and a repulsive vector potential due to ω-exchange. The vector potential for an antikaon is attractive under the G-parity transformation. In mean-field approximation, the kaon and antikaon dispersion relations can be written as

$$\begin{aligned}\omega^{*2} &= m_K^2 + \mathbf{k}_K^2 - \frac{\Sigma_{KN}}{f_K^2}\rho_S \pm \frac{3}{4}\frac{\omega_K^*}{f_K^2}\rho_B \\ &= m_K^2 + \mathbf{k}_K^2 - \frac{\Sigma_{KN}}{f_K^2}\rho_S \pm \frac{2}{3}\omega_K^*\Big(\frac{g_\omega}{m_\omega}\Big)^2\rho_B,\end{aligned} \tag{2}$$

where ρ_B and ρ_S are the baryon and scalar densities, respectively. The second line follows from the SU(3) relation $g_\omega = 3g_\rho$ and the KFSR relation $m_\rho = 2\sqrt{2}fg_\rho$ (assumption of $f_K = f_\pi = f$ is implied) [20].

In Eq. (2) the plus and minus signs are for kaon and antikaon, respectively, Σ_{KN} is the KN sigma term, and f_K is the kaon decay constant. In this work, we use $\Sigma_{KN} = 350$ MeV and f_K= 93 MeV, as used in our study of kaon and antikaon production in heavy-ion collisions at SIS energies [21,22]. Following Ref. [23], we define the kaon (antikaon) potential as

$$U_{K,\bar{K}}(\rho,\mathbf{k})=\omega^*(\rho,\mathbf{k})-\omega_0(\mathbf{k}). \tag{3}$$

The results for the kaon (antikaon) potential with zero momentum in a nuclear medium is shown in Fig. 1. One sees that the kaon potential is weakly repulsive at low densities, qualitatively consistent with that from the impulse approximation based on the kaon-nucleon (KN) scattering length. At high densities (above about $3\rho_0$) the kaon potential becomes attractive as a result of the reduced repulsive vector interaction. The antikaon potential is attractive at all densities.

The propagation of kaons and antikaons in their mean-field potentials is given by the following equations of motion

$$\frac{d\mathbf{x}}{dt} = \frac{\mathbf{k}}{E^*}, \quad \frac{d\mathbf{k}}{dt} = -\nabla_x U_{K,\bar{K}}(\rho,\mathbf{k}), \tag{4}$$

where $E^*=\left[m_K^2+\mathbf{k}^2-(\Sigma_{KN}/f_K^2)\rho_S+(\frac{1}{3}\frac{g_\omega^2}{m_\omega^2}\rho_B)^2\right]^{1/2}$, and $U_{K,\bar{K}}$ is given by Eq. (3). When a kaon (antikaon) propagates from the high density to the low density (especially when it crosses the surface of the fireball), its momentum is reduced by the attractive potential. This is the mechanism by which the attractive potential cools down particles.

IV. ANTIKAON ANNIHILATION IN MEDIUM

A main difference between a kaon and an antikaon in a dense matter is that the latter can be annihilated by a nucleon into a hyperon and a pion, i.e., $K^-N\to Y\pi$. This cross section at low energies has been analysed by the K-matrix method of Martin *et al.* [24], and the results can be fitted by the following parameterization

$$\sigma_{ann.}(\sqrt{s}) = \frac{134.8}{1.0+76.7(\sqrt{s}-\sqrt{s_0})+161.1(\sqrt{s}-\sqrt{s_0})^2}, \tag{5}$$

where $\sqrt{s}$ is the invariant energy of the K^-N system and $\sqrt{s_0}=m_N+m_K$. In nuclear medium, we assume that the form of the annihilation cross section does not change, but replace $\sqrt{s}$ and $\sqrt{s_0}$ by $\sqrt{s^*}$ and $\sqrt{s_0^*}=m_K^*+m_N^*$, respectively. Another important medium effect is that the reaction $K^-N\to Y\pi$ may be forbidden in the medium. To see this, we take the scalar potential of an antikaon to be approximately 1/3 of the nucleon scalar potential U_S and that of hyperon to be $(2/3)U_S$. In the reaction $K^-N \to Y\pi$, the total scalar potential is then $(4/3)U_S$ in the initial state and is more negative than that in the final state, which is $(2/3)U_S$. For antikaons with low momenta, which we are interested in, there is thus a possibility that the invariant energy $\sqrt{s^*}$ of the antikaon and nucleon is below $m_Y^* + m_\pi$, so the antikaon cannot be annihilated.

V. RESULTS

Because of the density isomer around $5.5\rho_0$, the fireball expands rather slowly. In Fig. 3, we show the baryon density profile of the fireball at different times. In the first 4 fm/c, the central density decreases by only about 10%. From t=4 fm/c to 8 fm/c, the central density decreases from $5.5\rho_0$ to about $2.0\rho_0$. Up to 10 fm/c, a well-defined surface is seen, and when kaons move across this surface their momenta are changed.

To obtain good statistics, we use the perturbative test particle method of Ref. [25] for kaons and antikaons. Furthermore, we average the transverse mass spectra of kaons and antikaons over the entire rapidity range as in Ref. [7]. Using a bin size of 5 MeV, we have more than one thousand events within each transverse mass bin. In Fig. 4, we show the transverse mass spectra of kaons at different times. The upper-left panel gives the initial kaon spectrum which are in an equilibrium fireball at temperature $T = 170$ MeV. The spectrum can be fitted by $\exp(-m_t/T')$ with an apparent temperature $T' \sim 145$MeV, which is smaller than the source temperature T. This difference is mainly due to the rapidity effect, as the apparent temperature T' is related to the source temperature T by $T = T'\cosh\,(y)$, where y is the kaon rapidity in the center-of-mass frame of the fireball.

The upper-right panel gives the kaon spectrum after 4 fm/c. During this time interval, kaons with high momenta have mostly escaped the potential well. We already see an enhancement of low-m_t kaons and a weak low temperature component. The steep rise of the extremely low-m_t kaons happens mainly during the time interval from t=4 fm/c to 8 fm/c, as shown in the lower-left panel of the figure. During this time interval, kaons that are initially trapped inside the potential well gradually climb out the well as the system slowly expands. A well-defined low temperature component is visible at this time. Afterwards there is little change in the kaon spectrum, as shown in the low-right panel for t=12 fm/c, as the density of the system is already below $2\rho_0$ and the kaon potential is very weak.

In Fig. 5, we compare our results with preliminary experimental data of the E814 collaboration [1]. The experimental data are in the forward rapidity ($2.2 \geq y < 2.4$), while our results are averaged over the entire rapidity region as mentioned early. Since we do not have a complete dynamical model for the entire process of heavy-ion collisions at AGS energies, we scale our final spectrum such that we fit the data point at $m_t - m_K \sim 7$ MeV. The initial spectrum, given by the dotted histogram, is similarly scaled, and can be characterized by one apparent temperature of about 145 MeV. The final kaon spectrum, obtained after including both propagation in the mean-field potential and rescattering with baryons and pions, is given by the solid histogram and shows clearly a two-component structure. The component corresponding to high transverse masses ($m_t - m_K \geq 0.02$ GeV) has an apparent temperature of about 140 MeV, and is similar to the initial kaon spectrum. The steep rise of low-m_t kaons ($m_t - m_K < 0.02$ GeV) can be fitted by an exponential with an apparent temperature of about 40 MeV. Although this temperature is still about a factor of two larger than the temperature extracted from the experimental data, it is considerably smaller than that of kaons with high transverse masses.

Finally, we compare in Fig. 6 our results for antikaon spectra with preliminary data of Ref. [1]. Again, we scale our final antikaon spectrum such that we fit the data point at $m_t - m_K \sim 7$ MeV. Because of annihilation, the final antikaon multiplicity is smaller than the initial one. For comparison, we have reduced the initial spectrum by the ratio of the final antikaon multiplicity to the initial one. The initial spectrum (dotted histogram) can be fitted by a single exponential with an apparent temperature of about 145 MeV. The final antikaon spectrum again shows a two-component structure. The high-m_t component is similar to the initial spectrum, while the low-m_t component has a much lower temperature of about 30 MeV, which is again about a factor of two larger than that extracted from the experimental data. The K^- temperature is lower than that of K^+ as its potential remains attractive throughout the whole expansion of the fireball while the kaon potential becomes repulsive once the density is below about $3\rho_0$. We note that the reduced annihilation of low-energy K^- in dense matter as discussed in section IV is crucial in obtaining the low-m_t antikaons. Finally, we mention that in our calculation the proton spectrum does not show a two-component structure, which is consistent with the experimental data.

VI. CONCLUSIONS

In summary, we have studied the enhancement of low-m_t kaons and antikaons in heavy-ion collisions at AGS energies in the relativistic transport model. By introducing a density isomer at high densities, the expansion of the fireball is slowed down so that kaons and antikaons can be effectively cooled down by their attractive mean-field potentials. We see clearly a 'cold' low-m_t component in both kaon and antikaon transverse mass spectra, as observed in AGS experiments by the E814 collaboration. To carry out more detail comparisons with the experimental measurements, we need to introduce rapidity cuts in analyzing the kaon and antikaon spectra. Also, it is necessary to extend the relativistic transport model to include more degrees of freedom so that it will be suitable for describing the entire collision dynamics at AGS energies.

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Figure captions:

Fig. 1: Equation-of-state of nuclear matter. The dashed curve is based on the non-linear σ-ω model parameters of Ref. [16]. The solid curve is based on the density-dependent vector coupling constant of Eq. (1).

Fig. 2: Kaon and antikaon potentials (with zero momentum) in nuclear matter as a function of baryon density.

Fig. 3: Baryon density profile of the fireball at different times.

Fig. 4: Kaon transverse mass spectra at different times.

Fig. 5: Initial and final kaon transverse spectra. The experimental data for $2.2 \geq y < 2.4$ are from Ref. [1].

Fig. 6: Same as Fig. 4 for antikaons.

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