Effect of Chiral Restoration on Kaon Production in Relativistic Heavy-Ion Collisions

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(Received 26 April 1990)

Kaon production from meson-meson annihilation is enhanced significantly because of the decrease of hadron masses in hot and dense matter as a result of the restoration of chiral symmetry. We show that this can lead to enhanced kaon yield in high-energy heavy-ion collisions.

PACS numbers: 25.70.Np, 11.30.Rd, 21.65.+f

Recently, experiments have been carried out at the Brookhaven National Laboratory Alternating Gradient Synchrotron (AGS) to study kaon production from heavy-ion collisions at an incident energy of 14.5 GeV/nucleon.[1,2] The measured K^+/π^+ ratio is about 20% and is more than 4 times that from the proton-proton interaction at the same energy. There is, however, no significant increase in the K^-/π^- ratio which remains about 4% as in the proton-proton interaction. Of course, enhanced kaon production was first proposed as a signal for quark-gluon plasma formation,[3] but there seems to be little possibility of this at the AGS energies.[4,5]

In hadronic models, kaons can be produced from $NN \rightarrow NYK$, $\pi N \rightarrow YK$, and $\pi\pi \rightarrow K\bar{K}$. Here, Y is a baryon with strangeness $S=1$. Although the initial hadronic matter has zero net strangeness, the decay of Y to $N+\pi$ via the weak interaction after decoupling from the hadronic matter destroys the s quark. Kaons therefore reflect the net strangeness created in the reaction. In the hydrochemical model,[6] it has been shown that for reasonable initial density and temperature the K^+/π^+ ratio is about 10% if a cross section of about 3 mb is taken for the reaction $\pi\pi \rightarrow K\bar{K}$. In calculations based on the transport model, a similar ratio is obtained in Ref. 7 with $\bar{\sigma}_{\pi\pi \rightarrow K\bar{K}} \sim 0.5$ mb, while a ratio comparable to the measured one is found in Ref. 8 with $\sigma_{\pi^+\pi^0 \rightarrow K^+\bar{K}^0} \sim 2$–3 mb.

In these studies, the elementary kaon production cross sections for the two processes $NN \rightarrow NYK$ and $\pi N \rightarrow YK$ are extracted from empirical data[9,10] and should be quite reliable. The process $\pi\pi \rightarrow K\bar{K}$ has recently been analyzed in detail by Lohse *et al.*[11] They have found that its cross section is appreciable only in the isospin-zero channel, where $\sigma(I=0) \sim 9$ mb in the region of the center-of-mass energy $s^{1/2} = 1$–1.4 GeV. Isospin averaging introduces, however, a factor of $\frac{1}{9}$, so that the averaged cross section is $\bar{\sigma}_{\pi\pi \rightarrow K\bar{K}} \sim 1$ mb. The cross sections used in Refs. 6–8 are thus not unreasonable.

According to the transport model,[12] the central density and excitation energy in the initial stage of the collision exceed $6\rho_0$ and 1.5 GeV/fm^3, respectively, where ρ_0 is the normal nuclear matter density. Based on the chiral model for the meson-nucleon interaction, it has been shown that the restoration of chiral symmetry at high density and temperature would lead to the reduction of hadron masses.[13,14] Typical pion energies in the E802 experiment at the AGS are about that of the free kaon mass, so that there is little phase space for the reaction $\pi\pi \rightarrow K\bar{K}$. The phase space increases rapidly with decreasing kaon mass. The cross section for kaon production in hot and dense hadronic matter will thus be substantially enhanced. This effect has not been considered in previous studies.[6-8]

A fundamental approach to the density and temperature dependence of hadron masses requires the solution of quantum chromodynamics (QCD). Although lattice calculations have not reached the stage where reliable results can be obtained, the QCD sum-rule method[15] has confirmed the results of the chiral model that hadron masses decrease with increasing density and temperature and give indications that they may vanish when the chiral symmetry is restored at the critical density and temperature. The temperature dependence of hadron masses can be approximately parametrized by $[1-(T/T_c)^2]^n$, where T_c is the critical temperature at which the hadronic matter transforms into the quark-gluon plasma and is about 195 MeV according to chiral perturbation theory.[16] The exponent n has a value about $\frac{1}{6}$ from the QCD sum-rule approach[15] and about $\frac{1}{2}$ in the chiral models.[17] For our exploratory study, we shall take $n=\frac{1}{3}$. In Ref. 18, the dependence of hadron masses on the nuclear density ρ_N has been parametrized and is given by $1-(\lambda/2)\rho_N/\rho_0$. With $\lambda \approx 0.3$, such density-dependent effective hadron masses can consistently explain recent experimental results on the scattering of kaons,[19] protons,[20] and electrons[21] off the nucleus.

Taking both the density and temperature dependence into account simply by multiplying the effects, we can write the ratio of the hadron mass m^* in the medium to its value m in free space as

$$\frac{m^*}{m} \approx \left[- \left(\frac{T}{T_c}\right)^2 \right]^n \left[1 - \frac{\lambda}{2}\left(\frac{\rho_N}{\rho_0}\right) \right]. \tag{1}$$

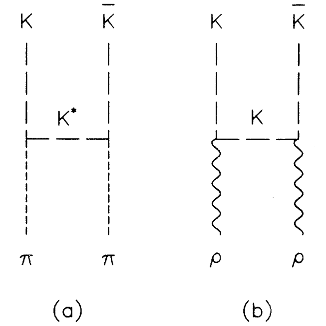

FIG. 1. Feynman diagrams for kaon production from (a) $\pi\pi \rightarrow K\bar{K}$ and (b) $\rho\rho \rightarrow K\bar{K}$.

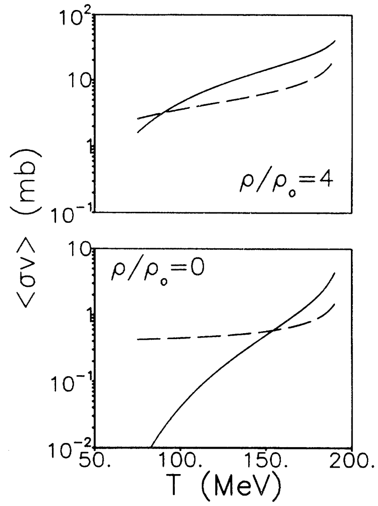

FIG. 2. The temperature dependence of $\langle \sigma v \rangle$ for 4 times normal nuclear matter density, and for zero density. Solid and dashed curves are for $\pi\pi \rightarrow K\bar{K}$ and $\rho\rho \rightarrow K\bar{K}$, respectively.

For the mass of strange hadrons, a substantial part comes from explicit chiral-symmetry breaking which gives a large current quark mass m_s. Therefore, we apply the density and temperature factors only to the dynamically generated masses so that their masses are m_s at $T = T_c$. Kaplan and Nelson[22] noted that chiral Lagrangians with empirically determined coefficients automatically contain a density-dependent kaon effective mass. In extensive calculations[23] to be published separately, we have shown that use of the Kaplan-Nelson expression does not change our results. We would like to emphasize that the parametrization introduced in Eq. (1) is meant to demonstrate the effect of hot and dense matter on hadron masses. The detailed form may be different when improved studies are carried out.

The process $\pi\pi \rightarrow K\bar{K}$ is mainly through the exchange of K^* as shown in Fig. 1(a). To determine the kaon production cross section in the medium, we evaluate the diagram with the density- and temperature-dependent hadron masses. The coupling constant $g^2_{K^*K\pi}/4\pi \sim 0.525$ is taken from Ref. 11. Because of the decreasing hadron masses, heavier hadrons will become important at high density and temperature. We include therefore contributions to kaon production from the annihilation of two ρ mesons, $\rho\rho \rightarrow K\bar{K}$, as shown in Fig. 1(b). Based on estimates from the quark model,[11] we take the coupling constant $g^2_{\rho KK}/4\pi$ to have the same value as that of $g^4_{K^*K\pi}/4\pi$. The contribution from the annihilation of a pion with a ρ meson has been neglected.

Using $n = \frac{1}{3}$, $\lambda = 0.3$, and $T_c = 195$ MeV in Eq. (1), we have evaluated the thermal average $\langle \sigma v \rangle$ of the product of the cross section σ and the relative velocity v. Their temperature dependence is shown in Fig. 2 for two different densities. The solid and dashed curves are for $\pi\pi \rightarrow K\bar{K}$ and $\rho\rho \rightarrow K\bar{K}$, respectively. We see that both $\langle \sigma_{\pi\pi}^{K\bar{K}} v_{\pi\pi} \rangle$ and $\langle \sigma_{\rho\rho}^{K\bar{K}} v_{\rho\rho} \rangle$ increase with increasing density and temperature. Similar calculations have been carried out for the two processes $NN \rightarrow NYK$ and $\pi N \rightarrow YK$ using the cross sections of Refs. 9 and 10 and it is found that their dependence on density and temperature is less significant. Their contribution to kaon production is thus not as important as that from $MM \rightarrow K\bar{K}$.

To demonstrate the effect of decreasing hadron masses on kaon production in relativistic heavy-ion collisions, we use the model of Ref. 6 which assumes that the two nuclei are fully stopped in the collision, leading to the formation of a fireball with baryon number given by the number of participants. For the collision between Si and Au at 14.5 GeV/nucleon that is currently available at the AGS, the initial baryon and energy densities have been estimated to be about $4.5\rho_0$ and 1.9 GeV/fm^3, respectively, if one assumes that the fireball volume is given by the arithmetic mean of two Lorentz-contracted volumes. In reality, these numbers could be smaller.

The fireball expansion is then described by the hydrochemical model of Birö *et al.*[24] in which the fireball is assumed in thermal equilibrium and the thermal energy is converted into collective flow energy via a simplified relativistic hydrodynamical equation with a linear scaling ansatz for the velocity profile. In Ref. 6, chemical equilibrium is not assumed. Because of the enhanced interactions among hadrons as a result of decreasing hadron masses in hot and dense hadronic matter, it is reasonable to assume that they are also in chemical equilibrium. This includes chemical equilibrium among the antikaon and strange baryons such as Λ, $\Sigma(1193)$, and $\Sigma(1385)$. We do not assume, however, that the kaon is in chemical equilibrium and its abundance is thus determined by the rate equation, which includes contributions from $MM \rightarrow K\bar{K}$, $BB \rightarrow BYK$, and $MB \rightarrow YK$, where M and B denote mesons and baryons, respectively.

With initial baryon and energy densities of $4\rho_0$ and 1.3 GeV/fm^3, respectively, which are slightly lower than those estimated above, we have solved the hydrochemical equations. The initial temperature of the fireball is

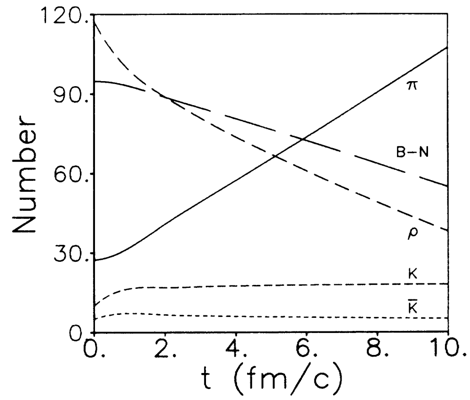

FIG. 3. The time evolution of the particle abundance.

about 170 MeV and is below the critical temperature. The system then expands and cools until freeze-out when particles cease to have significant interaction with other particles. The time when a particle freezes out from the fireball depends on its transport mean free path and is thus different for different particles. In the present study, we assume for simplicity that all particles freeze out at the same time when the fireball density is about $\frac{1}{3}$ the normal nuclear matter density. This occurs at about 10 fm/c after the expansion when the temperature is about 125 MeV and the collective flow velocity is about 0.5c. These values are very similar to those of Lee, Rhoades-Brown, and Heinz,[25] who have treated more carefully the freeze-out conditions in the hydrodynamical model.

In Fig. 3, we show the time evolution of the abundance of baryon resonances (B-N), pion (π), ρ meson (ρ), kaon (K), and antikaon ($\bar{K}$). The number of strange baryons is then given by the difference of the kaon and antikaon numbers while that of the nucleon can be determined by subtracting the number of baryon resonances and strange baryons from the total number of baryons in the fireball which is about 102. As expected, there are initially more ρ mesons and higher baryon resonances than pions and nucleons because of decreasing hadron masses at high density and temperature. The initial number of kaons and antikaons is taken to be about 10 and 4, respectively, to simulate their production from the nonequilibrium stage of the collision. This would give the final ratios $K^+/\pi^+ \sim 10\%$ and $K^-/\pi^- \sim 4\%$ if chemical reactions are neglected in the expansion. These ratios are similar to those from the proton-nucleus interaction at the same energy. Most kaons are produced during the first 1 fm/c when the density and temperature of the fireball are high and are thus mainly from the process $\rho\rho \rightarrow K\bar{K}$ because of the large initial ρ-meson density.

To obtain the momentum distribution of particles, we fold their thermal distribution at freeze-out with the collective flow velocity.[26] In Fig. 4(a), we show the rapidity

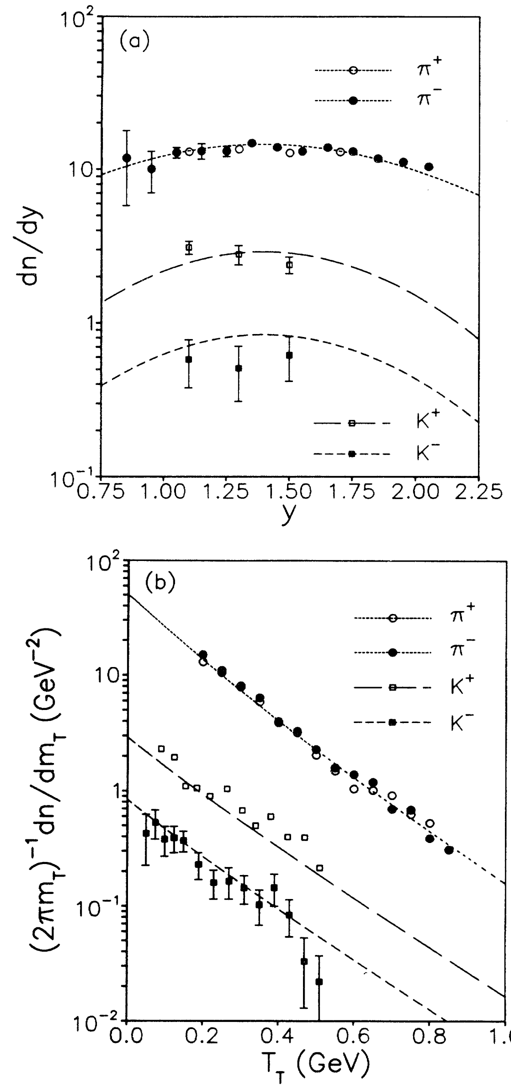

FIG. 4. The (a) rapidity and (b) transverse-kinetic-energy distributions of kaons and pions. Curves are from the theoretical calculations, while data are from Refs. 1 and 2.

distribution of pions and kaons. Only pions from the decay of ρ mesons are included, as pions from the decay of baryons have transverse momenta largely below the experimental cutoffs.[27] Both pion and K^- distributions are comparable to the measured data of Refs. 1 and 2. The calculated kaon distribution centers, however, at the central rapidity, while the measured one centers at lower rapidity. This discrepancy will disappear if we allow some of the initial kaons to be produced from the interaction of pions with the target spectator nucleons. In Fig. 4(b), the transverse-kinetic-energy distributions are shown. All have essentially exponential distributions with slopes of about 126 and 160 MeV for pions and kaons, respectively, which agree with the measured ones. Although both are assumed to freeze out at the same temperature of about 120 MeV, the collective flow has a larger effect on kaons than pions because of their larger masses. Details of our study will be published elsewhere.[23]

At the freeze-out, hadron effective masses are still below their bare masses. The energy required to bring the particles on shell has to come from the kinetic energy of the particles. This would somewhat reduce the flow velocity. We neglect this effect here as the correct treatment of hadron effective masses requires the inclusion of both scalar and vector field energies which, according to the relativistic transport model,[28] allow the nucleons to regain their masses after two-body interactions cease to be effective. Such a consistent study is being carried out.[29]

In conclusion, the cross section for the process $MM \to K\bar{K}$ increases significantly in hot and dense hadronic matter as a result of the restoration of chiral symmetry. In the hydrochemical model, we show that this leads to an enhancement of kaon yield in high-energy heavy-ion collisions. The enhanced K^+/π^+ ratio observed recently at AGS thus offers the possibility of determining the properties of hadrons and their interactions in hot and dense matter.

The work of C.M.K., Z.G.W., and L.H.X. was supported in part by the National Science Foundation under Grant No. PHY-8907986 and the Robert A. Welch Foundation under Grant No. A-1110 while that of G.E.B. was supported in part by the Department of Energy under Grant No. DE-FG02-88ER40388.

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