K^+ and K^- Slope Parameters as a Signature for Deconfinement at Finite Baryon Density

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(Received 25 February 1987)

We propose to study the slope parameters of K^+ and K^- energy spectra from relativistic heavy-ion collisions in the regime of complete nuclear stopping, and suggest a characteristic change of these slopes as a signal for transition into a baryon-rich quark-gluon plasma.

PACS numbers: 25.70.Np, 12.38.Mh

For several years it has been suggested that strange particles produced in relativistic heavy-ion collisions may provide necessary information to prove the creation of a transient quark-gluon–plasma phase (for a review see Koch, Müller, and Rafelski[1]). Unfortunately, the easiest experimentally accessible quantity that involves strange particles, the charged-K/π ratio, turns out to be less determined by the unique flavor composition of the initial quark-gluon plasma than by the general law of entropy conservation during rehadronization,[1,2] and therefore not a direct signature for plasma formation. In this Letter we wish to point out that the kaons still carry valuable information in the form of their *energy spectra.* We argue that these spectra are determined by unique effects of the hadronization phase transition on all strange particles, and that they may thus serve as a signal for the presence of this transition. In contrast to many other proposed signatures of plasma formation, the effect discussed here is particularly suitable for systems with high baryon density (i.e., the nuclear fragmentation regions) and will not be present in the central rapidity region at collider energies. Thus our discussion will be of direct relevance for the upcoming experiments at the Brookhaven Alternating Gradient Synchrotron and the CERN Super Proton Synchrotron.

Our proposed mechanism is based on a detailed thermokinetic investigation[3-6] of the hadronization process which leads to the conclusion[6] that in a finite–baryon-density system the $\bar{s}$ quarks hadronize first from the quark-gluon plasma (predominantly as K^+ and K^0 mesons, with an occasional antihyperon); on the other hand, the s quarks tend to get accumulated in the remaining partial volume which is still in the plasma phase, and hadronize only at the very last moment as K^- and $\bar{K}^0$ mesons and hyperons.[7] We combine this striking strangeness-separation feature with a characteristic change in temperature during hadronization of the system (due to entropy conservation) and mean-free-path considerations[8] to predict characteristic systematic features for the slope parameters of K^+ and K^- energy spectra from heavy-ion collisions, as the beam energy is increased towards and beyond the deconfinement threshold.

We assume that hadronization begins with a thermally and chemically equilibrated plasma of quarks and gluons. Hadronization is described as a set of recombination-dissociation processes (i.e., $3q \leftrightarrow N,\Delta$, $2q+s \leftrightarrow \Lambda,\Sigma$, $q+\bar{s} \leftrightarrow K^+,K^0$, $3\bar{q} \leftrightarrow \bar{N},\bar{\Delta}$, etc.) taken to be in equilibrium. We assign to the hadrons chemical potentials which are written as algebraic sums of their valence-quark chemical potentials μ_q^H and μ_s^H, the conditions for chemical equilibrium with respect to these processes are $\mu_q^H = \mu_q^Q$ and $\mu_s^H = \mu_s^Q$ (i.e., the chemical potentials for valence quarks inside hadrons and for free quarks in the plasma are equal). Obviously, this is a strong assumption which in the future should be replaced by a dynamical solution of rate equations combined with hydrodynamic evolution. However, since the system will always drive towards local equilibrium, the result of our equilibrium calculations will exhibit the basic tendencies of the system during hadronization.

Within our model assumptions, the system has to reheat during hadronization in order to avoid decrease of the total entropy.[9-11] (At fixed T and μ, the entropy per baryon S/A is higher in the plasma than in the hadronic phase, as a result of the presence of gluons.[10]) Alternatively, one may allow the system to go out of equilibrium by the hadronization process itself: In Refs. 1 and 10 hadronization is enforced at constant temperature, and entropy conservation can be guaranteed by adjusting[1] the degree of deviation from chemical equilibrium. The actual evolution of a physical system will lie between these extremes, but can only be determined by a self-consistent simulation of the full dynamics and chemical kinetics.

Utilizing our earlier work[3,10] on the nuclear equation of state, we here study a model that allows us to follow the dynamics of the colliding nuclei until freeze-out. In our approach, the equation of state of a free quark-gluon gas is matched to a mixture of noninteracting hadron resonances with finite eigenvolume. During the compression state of the collision (assumed to occur between two one-dimensional slabs) the matter is compressed and heated by a shock discontinuity to a point $(T,\mu_q,\mu_s=0)$ in the plasma phase.[12] (For simplicity we assume complete stopping of the two nuclei by each other, which is reasonable at Alternating Gradient Synchrotron energies.[13]) All the entropy at this point has been generated

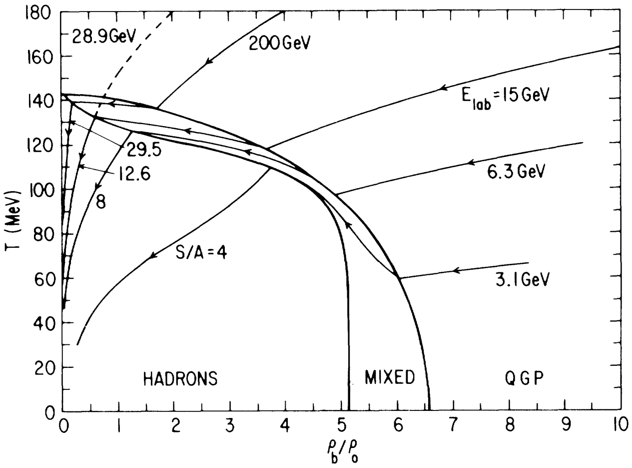

FIG. 1. Isentropic-expansion trajectories for a hadronizing quark-gluon plasma, for several values of entropy per baryon ($S/A=4$, 8, 12.6, 29.5). The corresponding beam-energy values were calculated by solving the relativistic Rankine-Hugoniot equations for a one-dimensional shock, assuming a free quark-gluon gas with bag constant $B=250$ MeV/fm^3 in the shocked region. For comparison, the dashed line shows isentropic expansion with $S/A=12.6$ for a purely hadronic system, i.e., assuming a gas of noninteracting hadron resonances in the shocked region instead. In this case the K^+ mesons, because of their long mean free path, are emitted immediately from the initial shocked region, whereas in the case of a phase transition to quark matter they are emitted from the much cooler mixed-phase region.

by the shock. From here we let the system expand spherically and isentropically (i.e., $S/A=$const). Up to small modifications due to the inclusion of strangeness[3] and the resulting small variation of μ_q during hadronization,[4,6] this reproduces the expansion curves of Ref. 11 (see Fig. 1).

As the system proceeds from the beginning to the end of the mixed phase, the temperature and the chemical composition of both the hadronic and the quark matter subvolumes vary as a function of the conversion parameter $\alpha=V_H/(V_H+V_Q)$. For a system expanding, say, with constant $S/A=8.6$ [a value expected to be reached or exceeded in upcoming experiments at Brookhaven National Laboratory and CERN[14]], we find[5,6] that in the first bubbles of hadronic matter forming at $\alpha\simeq 0$ positive stangeness ($\bar{s}$ valence quarks) is enriched by a factor $(\rho_{K^{+,0}}+\rho_{\bar{\Lambda}})/(\rho_{\bar{K}^{-,0}}+\rho_{\Lambda})=5.6$. As hadronization proceeds, this ratio continuously adjusts back to 1, while in the ever smaller remaining plasma volume the s quarks get distilled[5,6] to a maximum $s/\bar{s}$ ratio of 6.2, just before it completely dissolves into hadrons. From the variation of T and ρ_{K^+} with α we determine the fraction $dN(K^+)/dT$ of positive kaons hadronizing during a temperature interval dT in the mixed phase. Figure 2(a) shows that K^+ are emitted continuously throughout the mixed phase, with a distribution centered at $T_{K^+}=118.5$ MeV. K^-'s and Λ's, on the other hand, hadronize from the plasma only at the very last moment [Figs. 2(b) and 2(c)], i.e., with mean temperatures $T_{K^-}=124.9$ MeV and $T_\Lambda=122.7$ MeV, much closer to the exit temperature from the mixed phase $T_{\rm exit}=127.2$ MeV. These tendencies are seen even more strongly at smaller S/A; there the temperature gap bridged by the mixed phase is larger (see Fig. 1), but the system may not be completely converted to plasma by the initial shock.

After complete hadronization we assume that the gas of hadron resonances continues to expand hydrodynamically until freeze-out; that is until the scattering time scale of individual hadron species becomes larger than the rarefaction time constant of the collective expansion, leading to their decoupling from the hydrodynamic flow. The scattering time of a given hadron species is estimated by $\tau_{\rm scatt}=\lambda/v_{\rm th}=1/\rho_{\rm tot}\sigma_{\rm tot}v_{\rm th}$, where $\rho_{\rm tot}$ is the total density of all particles interacting with the one under consideration, $\sigma_{\rm tot}$ is its appropriately averaged cross section with these particles, and $v_{\rm th}$ is its thermal velocity. (More properly, the mean free path of species i should be written as $1/\lambda_i=\sum_j \rho_j\sigma_{ij}$.) Since we are in a baryon-rich environment, the mean free paths are dominated by the interaction cross section with nucleons, and we adopt the rough estimates $\sigma_{\rm tot}(\pi)\simeq\sigma_{\pi N}\simeq 100$ mb, $\sigma_{\rm tot}(p)\simeq\sigma_{NN}\simeq 40$ mb, $\sigma_{\rm tot}(K^-)\simeq\sigma_{K^-N}\simeq 50$ mb, and $\sigma_{\rm tot}(K^+)\simeq\sigma_{K^+N}\simeq 10$ mb, neglecting any temperature dependence.

To estimate the rarefaction time scale, we assume a velocity profile of the expanding fireball $\beta(r)=(r/R)\beta_s$ (borrowed from the study of self-similar solutions to the hydrodynamic equations[15]); here $R=(3A/4\pi\rho_b)^{1/3}$ is the radius of the expanding sphere, determined from the baryon density (with use of baryon-number conservation) at a given point of the expansion trajectory in Fig. 1. β_s is the expansion velocity of the surface, which is obtained from energy conservation, i.e., by equating the total E/A available in the c.m. system with $(4\pi/A)\int_0^R T_{00}r^2dr$ at a given point of the expansion [where $T_{00}=\gamma^2(\epsilon+P)-P$ is evaluated with the above velocity profile]. The rarefaction time scale is then given by $R/3\beta_s$ (the 3 is due to the spherical symmetry). Hence our decoupling criterion reads $(3A/4\pi\rho_b)^{1/3}/3\beta_s < 1/\rho_{\rm tot}\sigma_{\rm tot}v_{\rm th}$.

Calculated values for the freeze-out temperatures for several particle species, obtained from isentropic expansion trajectories for a series of beam energies, are given in Table I for both cases, with and without a transition to quark-gluon plasma. The freeze-out temperatures for K^+ are larger than those for protons as a result of the larger mean free path.[8] On the other hand, the pion and K^- temperatures are not lower than T_p, contrary to naive mean-free-path arguments[8]; since, after the nucleons have decoupled, their temperature stays constant, any further interaction of the pions and K^- with the nucleons cannot lead to further cooling of these particles, although they decouple from the nucleons only consider-

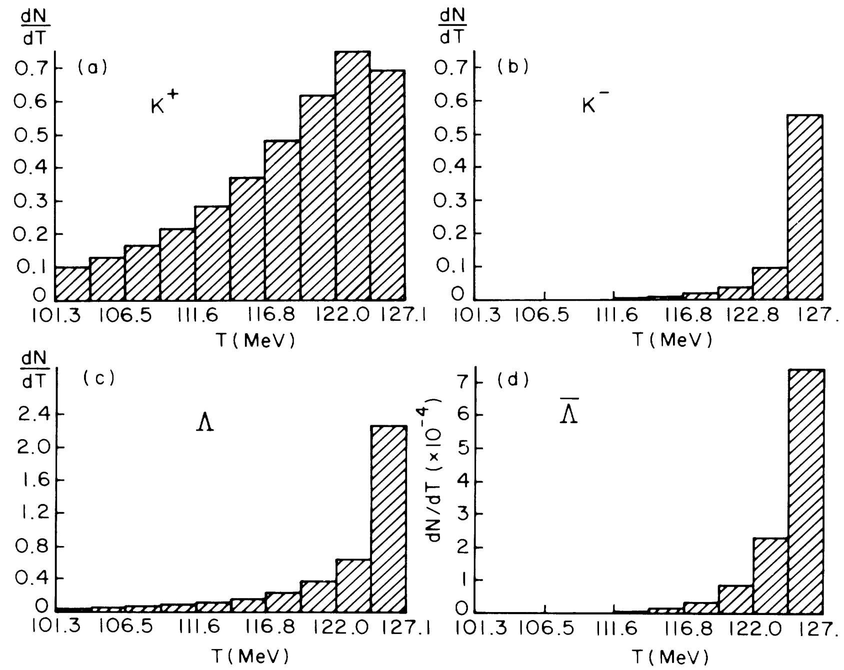

FIG. 2. Hadronization rates as a function of temperature during the mixed-phase region for several hadrons. Isentropic expansion of a system with $S/A = 8.6$ and a baryon number $A = 100$ has been assumed. Note that whereas K^+ are being hadronized already at a rather early stage, K^- and Λ hadronize only near the end of the mixed-phase region.

ably later.[16] An important consequence of this study is that the K^+ hadronizing in the mixed phase are already frozen out, i.e., they escape with the energy spectrum with which they are produced in hadronization (up to modifications as a result of collective flow, see below).

In order to relate[17] these emission temperatures to the *slope parameter* of the measured energy spectra ("apparent temperature"), it should be taken into account that the thermal distribution is boosted by the collective-expansion

TABLE I. Values of S/A and the initial temperature T_{shock} for different beam energies, and the emission temperatures (in megaelectronvolts) for kaons, pions, and protons from our one-dimensional dynamical model, with and without us assuming the existence of a phase transition to a quark-gluon plasma. (Note that a one-dimensional model overestimates the initial compression and heating, as a result of neglect of transverse degrees of freedom.) For the case *with* a phase transition T_{K^+} is given by the average K^+ *hadronization* temperature as determined from Fig. 2(a). All other temperatures are determined from the freeze-out condition described in the text, for a fireball with $A = 100$. The entries for 60 and 200 GeV should only be taken qualitatively, since their complete nuclear stopping is doubtful.

E_{lab}/A (GeV)	S/A	T_{shock}	T_{K^+}	$T_{p,K^-,\pi}$
		With phase transition		
4	5.6	90	104	88
7	8.6	129	118	110
15	12.6	179	127	121
60	20.7	279	134	128
200	29.5	392	136	135
		Without phase transition		
4	6.7	180	126	93
7	8.3	220	145	106
15	10.8	272	162	118
60	16.4	379	178	127
200	22.4	519	183	130

velocity $\beta(r)$. This raises the apparent temperature above the freeze-out temperature, which affects heavier particles more than lighter ones.[17] Consequently, $T_p^{app} > T_{K^-}^{app} > T_\pi^{app}$ although all these particles freeze out with (nearly) the same temperature. A detailed study of the dynamical flow effects on the slope parameters for our scenario is under way and will be published in a more detailed account of this work.

Summarizing the information contained in Table I, the K^+ are seen to be messengers from the early stages of the collision.[8,18] If no plasma is formed, the K^+ escape much earlier than protons, K^-, and pions, and with a considerably higher temperature; their energy spectra will fall off more slowly than K^- as well as proton and pion spectra. This expectation is supported qualitatively by the experimental evidence gained at the LBL Bevalac,[18] where the slope parameters of K^+ spectra are 30%–50% larger than those of p, K^-, and π. On the other hand, if a phase transition to a quark-gluon plasma occurs, for the same beam energy the temperature in the shocked region is lower, since the latent heat of the transition[10] is not available for excitations. While the plasma expands towards hadronization it cools further, and the K^+, which by our argument are emitted from rather early stages of the mixed phase, escape with a spectrum determined by a much *lower* temperature than in the purely hadronic scenario. Furthermore, because (for beam energies larger than ~7 GeV/nucleon where in our one-dimensional case complete initial conversion to plasma is expected[9,14]) the produced entropy per baryon is higher with than without phase transition, the freeze-out temperatures for p, K^-, and π are also slightly *higher:* In the T-ρ plane of Fig. 1 the hadronic part of the expansion trajectory for a hadronizing quark-gluon plasma lies *above* the one for an expanding hadron gas produced at the same beam energy in absence of the plasma.

Altogether the large gap between the K^+ and the K^- (and p, π) slope parameters, which is expected in a purely hadronic collision scenario and observed at the LBL Bevalac,[18] is predicted to become considerably narrower as the beam energy threshold for quark-matter production is crossed. If the difference between freeze-out temperatures becomes small enough (as predicted in Table I as a consequence of strangeness separation in the mixed phase), the K^+ slope parameter will (as a result of the smaller effect[17] from collective flow at the earlier freeze-out point) actually be lower than both the proton *and* K^- ones! Thus the difference between K^+ and K^- slope parameters observed[18] at LBL Bevalac energies can even change its sign when a quark-gluon plasma is formed at higher beam energies. For extremely high energies, *all* slope parameters will be limited by the critical transition temperature at zero baryon density (T_{crit} ~150 MeV in our model), as first pointed out by Olive.[19]

We thank Professor Stöcker and Professor Zimányi for valuable discussions. This work was supported by the U.S. Department of Energy under Contracts No. DE-AC-2-76CH00016 and No. DE-AC02-76ER13001.

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