Evidence of Early Multistrange Hadron Freeze-Out in High Energy Nuclear Collisions

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Recently reported transverse momentum distributions of strange hadrons produced in Pb(158*A* GeV) on Pb collisions and corresponding results from the relativistic quantum molecular dynamics approach are examined. We argue that the experimental observations favor a scenario in which multistrange hadrons are formed and decouple from the system rather early at large energy densities (at about 1 GeV/fm^3). The systematics of the strange and nonstrange particle spectra indicate that the observed transverse flow develops mainly in the late hadronic stages of these reactions. [S0031-9007(98)07927-7]

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The purpose of the current and forthcoming heavy ion programs at the high energy laboratories CERN (Switzerland) and Brookhaven National Laboratory (US) is to probe strongly interacting matter under extreme conditions, i.e., at high densities and temperatures. The central subject of these studies is the transition from the quark-gluon plasma to hadronic matter. In the early phases of ultrarelativistic heavy ion collisions, when a hot, dense region is formed in the center of the reaction, there is copious production of up, down, and strange quarks. Transverse expansion is driven by the numerous scatterings among the incoming and produced particles. As the medium expands and cools, the quarks combine to form the hadrons that are eventually observed.

On the experimental side, the presence of strong radial transverse flow in the Pb(158*A* GeV) on Pb collisions was deduced from the systematics of nonstrange particle spectra some time ago [1,2]. The long awaited spectra of multiple strange baryons Ξ^- and Ω, measured at midrapidity, were reported during the Quark Matter '97 conference [3]. Quite surprisingly, the reported slopes of these hadrons are much softer than expected from an interpolation based on the measured slope parameters of nonstrange particles, hadrons with a single strange quark only and deuterons [2,4]. A compilation of the experimental data as obtained by the NA44, NA49, and WA97 collaborations is shown in Fig. 1.

In this Letter we argue that the transverse momentum spectra encode valuable information on the decoupling process of strange and nonstrange hadrons in the medium and the time development of flow during the evolution [5]. It has been recognized for a long time [6] that hadron momentum spectra reflect the collective flow developing in ultrarelativistic heavy ion collisions. The flows may be related to bulk and transport properties in the ultradense matterlike transient pressure and viscosities. Hydrodynamic behavior may be expected at least for truly large colliding systems such as Pb + Pb.

Concerning the search for the quark-gluon plasma, one would like to identify the regions in energy density at which the equation of state (EOS) softens, presumably due to the phase transition or crossover between hadronic and quark matter. Another topic of interest is to see the EOS becoming hard again at yet higher densities. At temperatures much larger than the critical temperature, the EOS approaches the Stefan-Boltzmann limit, according to recent lattice calculations [7]. The EOS seems to become remarkably ideal although the regime of perturbative quarks and gluons is being reached only at grand unification scales [8]. In the context of ultrarelativistic collisions the EOS dependence on energy and baryon density translates into a pressure dependence on time, because expansion dilutes the matter continuously. Hadrons with varying strangeness content decouple at different times from the system, due to their different reaction rates in the medium. Therefore, we may employ these spectra to get a sequence of snapshots of the transverse flow present at each of the species-dependent decoupling times.

Several scenarios for the unknown earlier stages in ultrarelativistic nucleus-nucleus are imaginable and have been put forward. We will try to use the most recent information on the spectra to eliminate some of them. Let us list some of the possible choices: (i) Harder transverse momentum spectra in heavy ion as compared to pp collisions—collective flow or initial-state scattering [9]? (ii) Is the expanding matter made of weakly interacting quarks and gluons, or of bound states (hadrons)? (iii) Does the flow already appear at an early stage of the collision [10] or rather later [11]? (iv) Does freeze-out occur simultaneously [12] or sequentially [13–16]?

In this Letter we argue that the systematics of the transverse momentum spectra find their natural explanation in a reaction scenario in which the multistrange baryons freeze out in the Pb on Pb reactions before most of the finally observed transverse flow has developed. In order to go beyond a qualitative interpretation we utilize

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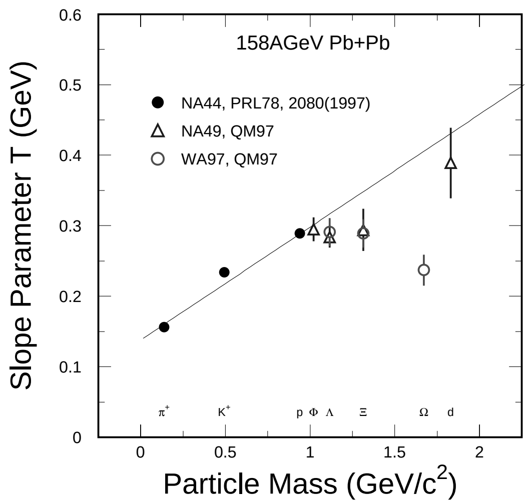

FIG. 1. Measured slope parameters as a function of particle mass. Preliminary results of the slope parameters of strange particles are shown with open symbols. The line serves to guide the eye with respect to the nonstrange data.

a transport theoretical approach—relativistic quantum molecular dynamics (RQMD)—whose predictions agree well with the observations. Furthermore, we are going to address the question whether data from heavy ion experiments allow one to make statements about the existence of strange hadrons in a medium of high energy density $\epsilon > 1$ GeV/fm^3.

Let us turn now to the recent data as presented in Fig. 1. We may draw several conclusions from the compilation of slope parameters. We do not believe that the existence of strong transverse flow in the Pb(158*A* GeV) on Pb reactions belongs to the unresolved questions. The difference between flow—a space-momentum correlation—and excitations purely in momentum space (temperature or random kicks) shows up in observables which are sensitive to the phase-space densities of the finally emitted hadrons (such as nucleon cluster formation [17] and pion interferometry [18]). Indeed, transport calculations [16] and fits to experimental data based on the fireball model [19] consistently give transverse flow velocities in the range of $\sim 0.4c - 0.6c$ for the Pb on Pb reactions.

The frequently employed picture—one-fluid flow until breakup of the matter at a common freeze-out state—is untenable in view of these data. It is impossible to reconcile the proton and deuteron values with the smaller Ω slope parameter in such a scenario. In contrast to the Ω baryon, the Ξ^- spectrum displays a slope which has a value very similar to the proton and Λ spectrum. All of them cluster around 290 MeV. The common freeze-out temperatures and underlying flow velocities would mean that these spectra are purely thermal and collective flow is completely absent. Such a large freeze-out temperature, well above the quark-gluon plasma transition temperature, seems very unlikely.

Furthermore, the apparent softness of the multi-strange baryon spectra points to a dynamics in the hadronic stages that causes the nonuniversal pattern. Early work on strangeness as a quark-gluon plasma signal [20] showed that strange flavor impacts reactions in quark matter rather differently than in a hadron gas. Interactions among quarks at temperatures of several hundred MeV are only mildly affected by quark mass variations at about 5–160 MeV. On the other hand, transport properties of the heavy omega baryons with mass of 1672 MeV are expected to differ completely from the almost massless pions (140 MeV) [21]. A smaller collective component in the final transverse momentum spectrum of multistrange baryons, rather than for pions, kaons, and nucleons, is corroborated by an analysis of the chemical composition. The slope parameter 237 ± 24 MeV of the omega is consistent with the "temperature" value extracted from the particle ratios [22].

We now turn to the RQMD calculations in order to go beyond qualitative statements. The RQMD model [23] provides a microscopic description of heavy ion collisions which has been highly successful in predicting most of the observed features over a wide range of conditions. We generated 1600 events for Pb(158*A* GeV) on Pb employing an RQMD model (version 2.3) and analyzed the final spectra in the same fashion as has been done with the measurements. Before we analyze the aspects of the RQMD evolution dynamics which are pertinent for our discussion we present the results for the slope parameters of the various species in Fig. 2. Very good agreement is found between RQMD predictions and preliminary data.

The expansion dynamics generated by RQMD for central Pb on Pb reactions may be schematically decomposed into three stages. The prehadronic stage which lasts about 1.5 fm/c is modeled by initial excitation and fragmentation of color strings and ropes. After hadronization, the produced ultradense hadron matter needs some time for chemical and kinetic equilibration (3–4 fm/c). Multistrange baryons such as Ξ's are clearly involved in the

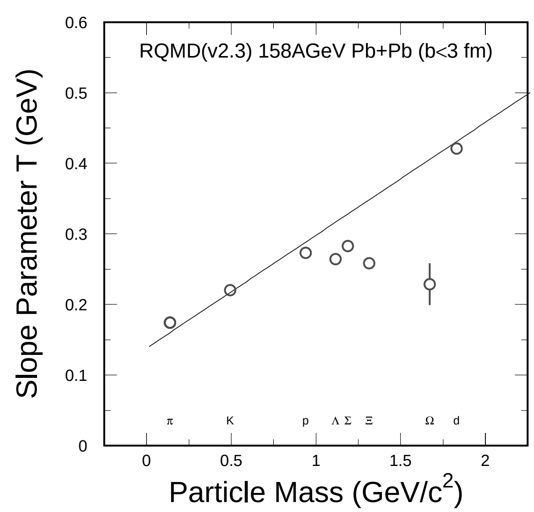

FIG. 2. The RQMD version 2.3 model prediction of the slope parameters.

equilibration process as demonstrated already for the case of light ion S on W reactions [24]. The effective transverse pressure is ultrasoft during these preequilibrium stages [11]. The state when local kinetic equilibrium is finally achieved (after 5 fm$/c$) is soon followed by a breakdown of equilibrium due to the diluteness of the hadron gas and the finite size of the system. In equilibrium, the RQMD evolution is governed by a "resonance matter" EOS. It has been shown that the RQMD evolution of the multicomponent hadronic fluid is characterized by nonideal effects, even in the dense regime [16]. The pions accelerate quite easily, their motion more or less governed by their own EOS. In contrast, the rarer heavy particles cannot keep up with the pion "fluid" and are left behind.

The developing flow of matter according to the RQMD calculations is illustrated by plotting the mean transverse distance of hadrons from the center of the collision region (see Fig. 3). We see from Fig. 3 that the baryon matter does not expand at all during the first 5 fm$/c$. The baryons develop collective flow only after the soft stage has elapsed, which is reflected in the increase of their spatial distribution.

Why are the multiply strange particles not dragged with the heavy particle flow? Their interactions in the expansion stage are dominated by resonance formation which is built into the RQMD approach (for details see [23]). A good measure of the reaction rates is therefore the decay widths of the baryon resonances to which the baryons couple. We see from the Particle Data Group tables that the decay widths of resonances are a strong function of their flavor content [25]. Approximately, the trend is 0.45:0.62:0.85:1 for Ω^*:Ξ^*:Y^*:N^*. We expect from these numbers that the Ξ collision rates will be suppressed by on the order of 30% to 40% compared to Λ's and nucleons. The Ω is basically not involved in forming these resonances. The π-Ω system does not match any of their flavor quantum numbers. Collisions of Ω's with η and K mesons which may form such resonances are suppressed as these collision partners of the Ω are much rarer than pions. Relativistic quantum molecular dynamics predicts considerably earlier freeze-out of Ω baryons (and Ξ's) than nucleons (and Λ's). The time and spatial distributions of nucleons and Ω's are displayed in Fig. 4. Most of the Ω's freeze-out between 2 and 8 fm$/c$ while the nucleon freeze-out distribution is centered around 20 fm$/c$. Note that the freeze-out time spectra are characterized by sizable differences between median and averages. Very soft collisions between particles of almost equal velocities lead to the long tails in the distributions but are of no importance for the reaction kinetics.

The corresponding transverse distance distribution which is also shown in Fig. 4 reveals that the Ω source at freeze-out is very similar to the initial source. In contrast, nucleons are transported by the collective flow to larger radial distances nearer the surface of the system. We can analyze the RQMD results concerning the local energy densities at which the multistrange hadrons decouple from the system. Typically, these local energy densities cluster around 1 GeV$/$fm^3. Clearly, if true, these values would just set a lower limit for the densities at which quarks may bind to form these particles. So far, experimental information about survival or "melting" of quark bound states was restricted to charmonium states only [26]. Our studies, like the work done in [22], seem to imply that Ω baryons exist at energy densities and temperatures which are significantly larger than the preferred lattice values for the quantum chromodynamics (QCD) phase transition. We find this possibility intriguing. The nature of strongly interacting matter around T_c is still badly understood. Most recently, Witten has conjectured that QCD with large number of colors may be expressed as a certain string theory [27]. This has stimulated enormous activities to put the old idea of duality between hadronic (or string) degrees of freedom and quarks and gluons on solid ground. It may also provide an incentive to look closely for quasihadronic modes in the quark-gluon plasma.

The evolution of the late dilute hadron gas stage should be reliably simulated by RQMD, as it relies upon hadronic cross sections rather than a QCD-based calculation. For

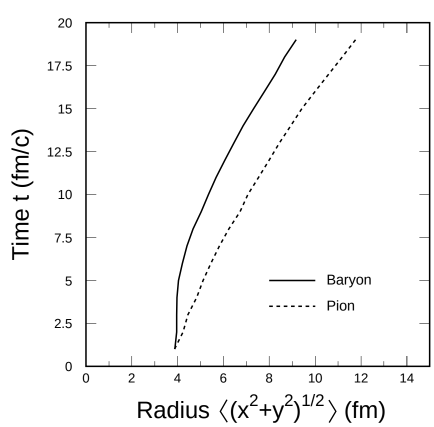

FIG. 3. Time evolution of the transverse source size for midrapidity baryons and pions.

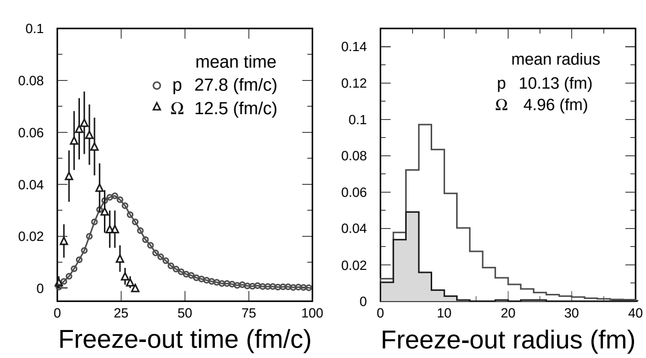

FIG. 4. The time and transverse radius distributions of midrapidity Ω's and nucleons at freeze-out in central Pb + Pb collisions at 158A GeV from RQMD.

the initial stage (and only here) our inability to calculate nucleus-nucleus reactions based on quantum chromodynamics can be compensated. Utilizing the empirical information about the interactions between hadrons, kinetic equations can be set up and solved the same as RQMD and other approaches [23,28–30]. Theoretical justification for semiclassical transport comes essentially from the particlelike behavior with the DeBroglie wavelengths being typically much smaller than the mean free paths. Of course, the final hadron momentum spectra are a product of the time-integrated dynamics, starting with the initial interpenetration of the two nuclei. The agreement between RQMD and experimental data for the final slope parameters indicates that the expansion dynamics in the first ultradense stage is modeled reasonably well in this approach. As a further check, we have simulated Pb on Pb collisions employing the hydrodynamical model. The results confirm our essential conclusion presented here. Agreement with the multistrange baryon data requires a soft evolution before freeze-out of these species and a large decoupling temperature $>T_c$. Detailed results of these studies and the implied constraints on the EOS will be presented elsewhere. Therefore we believe that the dominantly "late" production of the transverse matter flow holds true model independently.

One might be tempted to look for other explanations of the initial "softness" than what is provided by the RQMD model. For instance, Hung and Shuryak have put forward the idea that the system created in Pb + Pb may be close to the so-called softest point of the EOS [31]. Initial conditions for hydrodynamical calculations may be tuned to get good agreement with the nonstrange hadron spectra measured in Pb on Pb reactions [31]. However, this hydrodynamical approach fails to explain the mass dependence of the transverse flow, i.e., the data for S projectiles [32]. On the other hand, the RQMD model provides an explanation for the systematics from $p + A$ and $S + A$ to Pb + Pb [11]. According to the RQMD model the transverse pressure during the early stages is small in all of these systems, implying that equilibrium has not yet been reached at the early stage of the collisions.

In summary, we report the results of the analysis of the particle transverse momentum distributions from the central 158A GeV Pb + Pb collisions. At present, the data seem to favor a scenario in which the main component of the transverse flow develops only rather late, after most of the multistrange particles have already frozen out. We infer from the analysis of RQMD results that characteristic energy densities at which the multistrange hadrons freeze out are at about 1 GeV/fm^3 for central Pb on Pb collisions. Presumably, they may be formed at even larger densities.

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