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The parton to hadron phase transition observed in Pb+Pb collisions at 158 GeV per nucleon

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Abstract

Hadronic yields and yield ratios observed in Pb+Pb collisions at the SPS energy of 158 GeV per nucleon are known to resemble a thermal equilibrium population at $T = 180 \pm 10\,MeV$, also observed in elementary $e^+ + e^-$ to hadron data at LEP. We argue that this is the universal consequence of the QCD parton to hadron phase transition populating the maximum entropy state. This state is shown to survive the hadronic rescattering and expansion phase, freezing in right after hadronization due to the very rapid longitudinal and transverse expansion that is inferred from Bose-Einstein pion correlation analysis of central Pb+Pb collisions.

Recent Lattice-QCD theory predicts the disappearance of the hadronic phase of matter once the energy density exceeds a critical value of about 1 to 1.5 GeV per fm^3 [1], giving rise to a continuous, partially deconfined QCD state that is governed by the elementary interaction of quarks and gluons. To recreate this phase in the laboratory one collides heavy nuclei at relativistic energy, with the goal of ascertaining the QCD predictions, and to pin down the decay point from the partonic to the hadronic phase by obtaining estimates for the transition temperature and energy density. The CERN SPS Lead (^{208}Pb) beam facility provides for a top energy of 158 GeV per projectile nucleon, corresponding to a total internal CM-system energy of about $3.5\,TeV$, to heat and compress the primordial reaction volume. In fact calorimetric data [2] show that the average transverse energy density exceeds about $2.5\,GeV/fm^3$ in that volume, in central $Pb+Pb$ collisions. Moreover the study of J/Ψ production [3] demonstrates a suppression of the yield in such collisions, characteristic of the QCD "Debeye" screening mechanism expected in a deconfined partonic medium [4].

If one tentatively takes for granted such indications of a deconfined state at top SPS energy one expects, likewise, to receive signals specific to the bulk parton to hadron phase transformation bound to occur once the primordial high density state expands and cools toward the critical temperature and energy density. In the present letter we shall examine the proposal [5, 6, 7, 8] that such a signal is indeed provided for by the composition of the bulk hadron final state, in terms of the yields and yield ratios of the various mesonic and baryonic species. To this end we proceed in two steps. Firstly, a synthesis is attempted between the observation made in microscopic parton cascade and hadronization models [5, 9, 10] that the nonperturbative mechanism implied in the parton to hadron "coalescence" transition leads to a population of the hadronic species that is dominated by conservation laws and phase space, and, on the other hand, the well known conclusion from thermal equilibrium models [7, 11, 12, 8] that the hadron yields resemble a hadro-chemical equilibrium population. We shall conclude that this apparent equilibrium state is not established by dynamical equilibration amongst the hadronic species; it is an outcome, and a direct fingerprint of the hadronization transition. In the second, main step we address the question of how such a multihadronic population pattern established right at the transition point can survive the extensive rescattering that occurs in the course of subsequent hadronic expansion [13] in central $Pb + Pb$ collisions. This will be answered by confronting the dynamical expansion time scales derived from Bose-Einstein two pion correlation analysis of such collisions [14] with estimates of the hadro-chemical relaxation time scales [15, 16], showing that the "explosive" nature of the expansion [17] prevents major rearrangement of the hadron population.

Turning first to the connection between the hadronization mechanism and the apparent hadro-chemical equilibrium we refer to the partonic cascade model of Ellis and Geiger [9]. They analyzed LEP data, $e^+ + e^- \rightarrow Z^0 \rightarrow$ hadrons at $\sqrt{s} = 91\ GeV$ in a quark-gluon transport model based on perturbative QCD. The cascade ends with quarks and gluons recombining to form colour singlets with matching flavour combinations in a statistical coalescence process which generates heavy "pre-hadrons" that, in turn, decay into the final hadrons and resonances according to their relative phase space weights. No hadronic rescattering is considered. After resonance decay the hadronic spectra and production multiplicities are compared to the data finding good agreement. The authors report a second order sensitivity of the hadron composition to the details of the assumed parton coalescence concluding that, to first order, phase space dominance during the hadronization phase overwhelms other influences. The hadronic final state is thus the most probable, maximum entropy state.

Becattini has analyzed [7, 11] the same LEP data using a hadro-chemical equilibrium model based on a canonical partition function. With fit parameters temperature T, reaction volume V and a strangeness undersaturation parameter γ_s he finds good overall agreement with the data using $T = 161\ MeV$ and $\gamma_s = 0.67$. The data comprise hadron multiplicities for about 25 species ranging from π to Ω and spread over 4 orders of magnitude. As there is essentially no hadronic rescattering occuring in the reaction the apparent equilibrium state can not have originated from inelastic interactions between the 30 hadrons created per collision event. I. e. there is no chemistry at all *between* the hadrons, they form no stationary state with dynamically maintained population ratios. In accordance with the outcome of the Ellis-Geiger model [9] we conclude that the order seen in the hadronic population is *born into it* by the non-perturbative hadronization mechanism.

Moving on to SPS $Pb+Pb$ collisions at $\sqrt{s} = 17\,GeV$ similar data exist [18] for hadron multiplicity ranging from pions to Omegas, and similar models are successfully applied to these data. Geiger and Srivastava [23] have extended the parton transport model [9] to such low $\sqrt{s}$. They report that the dominant fraction of the hadron yields (near midrapidity) stems indeed from the parton to hadron phase transition. They get a reasonable fit to the NA49 data [18] concerning proton, pion and kaon yields and rapidity distributions, without any consideration of secondary hadronic cascading: a baffling result.

Becattini et al. [12] employ a generalized hadro-chemical equilibrium model based on [7] deducing a temperature parameter of $T = 192 \pm 19\ MeV$ for the NA49 $Pb+Pb$ data set [18] which extends from pions to the $\overline{\Lambda}/\Lambda$ ratio only. Braun-Munzinger et al. [8] address a data set for central $Pb+Pb$ combining all available NA44, NA49 and WA97 information obtaining a satisfactory fit at $T = 170 \pm 11\ MeV$. We note that the two thermal models mentioned here differ in several ways, concerning e. g. the treatment of excluded volume and specific approach to strangeness saturation. The question of a final, "optimal" formulation that avoids an inflation of free parameters is still open [12, 8, 19].

We ignore this question placing prime emphasis on the conclusion that again both the parton cascade hadronization mechanism and the hadro-chemical equilibrium ansatz fit the data, the latter employing "temperatures" that are slightly *higher* than those obtained for elementary $e^+ + e^-$ collision data. The large hadronic system created in $Pb+Pb$ through the hadronization phase transition can thus not "cool" the hadronic population. Although in this case the idea of re-equilibration due to inelastic hadronic rescattering seems applicable, the above data and results indicate that this is not occuring: the state created at hadronization stays essentially frozen-in throughout expansion, and its equilibrium features again appear to have nothing at all to do with inelastic interactions among the 2500 hadrons [18] in the final expansion. Solving this puzzle will help to establish the multi-hadronic population ratios as a fingerprint of a parton to hadron phase transition occuring in SPS collisions.

Hadronic inelasticity is rather weak in a hadronic medium at $T = 180\,MeV$: the mean CM kinetic energy of a pair of baryons is only 270 MeV and we recall that the average pion multiplicity in $p+p$ collisions at this energy [20] is only about 0.2. Only every fifth collision is inelastic. Hadronic equilibration times should thus be well above 1 fm/c at this temperature, growing to about 20 fm/c at $T = 120\ MeV$ [15], the temperature of final hadronic decoupling from strong interaction [14].

To appreciate these relaxation time scales we need to know about the expansion time scale in central $Pb+Pb$ collisions. Fig.1 shows the time profile of pion decoupling [21] from the fireball. The Gaussian with mean $\tau_f = 8\ fm/c$ and width $\Delta\tau = 4\ fm/c$ results from an analysis of Bose-Einstein pion pair correlations in central $Pb+Pb$ by NA49 [14] using a dynamical hadron source expansion model developed by Heinz [22]. The time scale in this model begins after the primordial source is formed, irrespective of its content at this time (partons or hadrons). This time is reached at complete interpenetration, $t \approx R(Pb)\gamma_{CM}^{-1} \approx 1\ fm/c$. Then the emission clock starts ($\tau = 0$ in Fig. 1), correctly so as pions can be emitted from the surface of the fireball right away. We see that the mean decoupling (freeze-out) time of pions is $\tau = \tau_f = 8\, fm/c$ from this analysis. This includes the average life-time of the partonic phase. In order to arrive at an estimate of the mean hadronization time we reproduce in Fig. 2 a result of the partonic cascade model by Geiger and Srivastava [23] that we quoted above to reproduce global features of central $Pb+Pb$ collisions. This shows the time dependence of the average energy density in the vicinity of midrapidity as exhibited by partons and hadrons (plus resonances), in a cylindrical subvolume of $4\, fm$ transverse radius, i. e. in the interior section of the source. The partonic era ends at $t = 6\ fm/c$. We may crudely estimate a mean hadronization time of $3\ fm/c$.

The average time span between hadron formation and freeze-out may thus be estimated to be about $6\, fm/c$ (taking proper account of the fact that $\tau = 0$ in Fig.1 corresponds to $t = 1\ fm/c$ in Fig.2). However, during this time interval any freshly formed hadron experiences a dramatic falloff concerning density and temperature in its local, co-moving environment cell that participates in the overall expansion of the system. A closer look at Fig.2 already reveals the presence of this expansion: the (energy) density of hadrons and resonances in the inner subvolume considered here stays constant throughout the hadronization phase although it is constantly replentished by further, newly created hadrons. This implies that the rate of hadronization inside the cylinder must be compensated by the rate of hadrons escaping, thus preventing a pile up to unreasonable central density beyond $0.6\ GeV/fm^3$. A more quantitative consideration shows that the newly formed hadrons must have left this inner subvolume of maximal density and temperature after about $1.5\, fm/c$ on average, much smaller than the estimated typical hadronic relaxation time of about $4\ fm/c$, that was obtained by Mekjian and Kapusta [15] for kaons in a hadron gas at $T = 180\ MeV$. Travelling outward in longitudinal and (more slowly) in transverse direction the average hadron encounters a rapidly diluting and cooling environment. In fact a combined analysis of pion pair correlation and hadron spectral data for central $Pb+Pb$ SPS collisions [14] has revealed evidence for collective outward velocity fields reaching up to $\beta_\perp \approx 0.55$ (reminiscent of the limiting hydrodynamical fluid velocity of $c/\sqrt{3}$), the temperature falling to $T = 120\ MeV$ at hadronic decoupling. This fall thus occurs during an average time span of 6 fm/c, during which the total reaction volume increases about tenfold [8, 14]. While the average hadron encounters about 6 binary collisions [13], perhaps maintaining local momentum equilibrium, the inelastic fraction fades away rapidly in such an "explosive" hadronic expansion [17]. Thus the primordial population pattern created by the hadronization transition among hadronic and resonance species stays essentially unaltered (the resonances decaying within their proper time), remaining "frozen in" throughout the hadronic expansion phase.

The fingerprint of the parton to hadron phase transformation in central $Pb + Pb$ collisions is thus preserved in the observed bulk hadron yields, and yield ratios. Moreover the models of microscopic parton transport toward the critical QCD conditions of hadronization indicate statistical phase space dominance, according to the spin, mass and flavour spectrum of created hadronic and resonance states. Not surprisingly, the thermal hadrochemistry models [12, 8, 19] thus come up with meaningful accounts of this initial maximum entropy state. This lifts the conceptual qualms ever prevailing since Hagedorns engagement [24] with statistical thermodynamics applied to hadron production data. There is no chemical equilibration occuring at the hadronic level to dynamically *achieve* a state of limiting temperature, neither in elementary $e^+ + e^-$ or $p + \overline{p}$ collisions nor in ultra-relativistic nuclear collisions [25]. Such states are created from partonic energy densities and temperatures *above* the limiting hadronic conditions, the QCD hadronization thus populating a statistically ordered system (to avoid the term "state" as it invites the view of stationary conditions) just at the limiting hadronic energy density. This results in the apparent universality [7] of hadron production as reflected in thermal model analysis from $e^+ + e^-$ to $Pb + Pb$.

In summary once we take for granted the tentative evidence from J/Ψ suppression, and from estimates of primordial energy density, in favour of the hypothesis that SPS $Pb + Pb$ collisions reach beyond the limit of the hadronic phase of matter (as predicted by lattice QCD theory) the system has to rehadronize upon expansion. And, second, the properties of this long-sought parton to hadron phase transition are reflected in characteristic features of the bulk hadronic phase that survive the rescattering and expansion phase because they freeze-in right at, or near the phase transition. Our focus was placed on the regularities of hadronic yield ratios because they are allowing for an estimate of the critical transition temperature (and the corresponding value of the baryo-chemical potential μ_B that we did not comment about) owing to the applicability of thermal model analysis to this maximum entropy state that we have tried to establish. One now expects a convergence among the various thermal model approaches [12, 8, 19], to finally pin down T and μ_B

of the phase transition. At present we may conclude that the QCD transition temperature $T_c = 170 - 180\ MeV$, at $\mu_B \approx 0.25\, GeV$.

A final question requires attention: does universality of hadronization imply that small and large systems hadronize by the identical same QCD mechanism? The author is not aware of a rigorous QCD argument. The colour and flavour composition of the partonic phase should reflect in the hadronization outcome (if there are mostly gluons, if strange quarks are far underpopulated or near-equilibrated etc.). Moreover there are rather straight forward effects of increasing system size. In the phenomenological coalescence approach Ellis and Geiger [9] have studied the step from $e^+ + e^- \rightarrow Z^0 \rightarrow$ hadrons to $e^+ + e^- \rightarrow W^+W^- \rightarrow$ hadrons (at LEP 2). In the latter case, the two parton cascades may overlap. This merging of the decaying subvolumes leads to total multiplicity increases, and the transverse momentum spectra exhibit some softening. The LEP 2 data have not been analyzed yet to demonstrate such effects. However, comparison of elementary $p+p$ data with central $Pb+Pb$ collisions shows a drastic effect in the hadronic strangeness composition: the ratio of strange to nonstrange quarks contained in the hadrons increases by a factor 2 [12, 18], the ratio of double strange cascade hyperons to nucleons by a factor of about 10 [26], the same ratio for Ω hyperons by a factor approaching 20 [27]. Thus there is no flavour scaling from the elementary nucleon-nucleon to central $Pb + Pb$ collisions. A certain fraction of this effect has been explained in the hadro-chemical model [12, 28] to arise from the so-called "canonical suppression" (e. g. of strangeness) dominating the small system, due to local difficulty of energy and quantum number conservation [29]. This effect disappears with increasing system size, a precursor seen in the overlapping W^+W^- cascade decay mode [9], and plays no role in central $Pb + Pb$ collisions which thus receive a grand-canonical treatment in these models. However, there is still further strangeness enhancement beyond this mechanism, which may be traced to before the phase transition assuming a higher relative strangeness content in the partonic $Pb + Pb$ collision phase than in $p + p$ collisions [28]. Primordial flavour or gluonic composition levels, perhaps characteristic of a symmetric partonic phase approaching the ideal QCD plasma state [28] may thus survive even the processes occuring during the hadronization phase transition [30]. This then reflects in additional (e. g. flavour) parameters in the hadrochemical model. This new aspect (see, however, ref. [5]) adds further significance to bulk hadronic signals from SPS nucleus-nucleus collisions.

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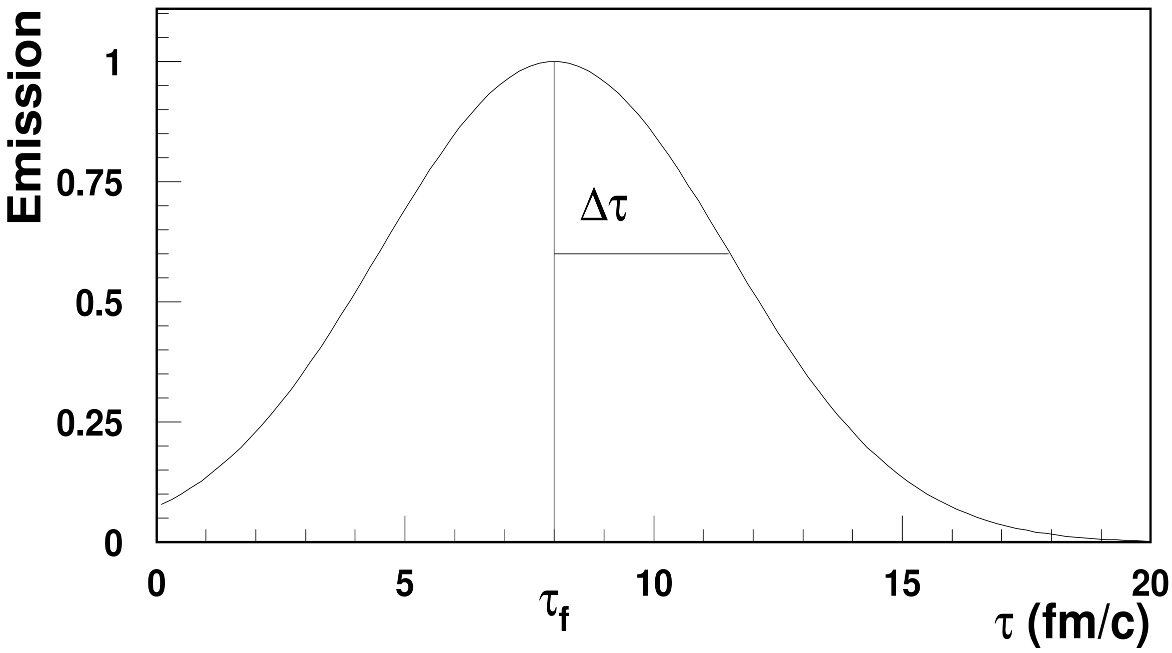

Figure 1: Time profile of the pion decoupling strength from the hadronic fireball formed in central $Pb+Pb$ collisions (arbitrarily normalized to unity). From two pion correlation analysis [14, 21, 22] we get an average decoupling time $<\tau_f>= 8\ fm/c$, and a mean duration of the decoupling phase characterized by a width $\Delta\tau = 4\ fm/c$ for the assumed Gaussian profile.

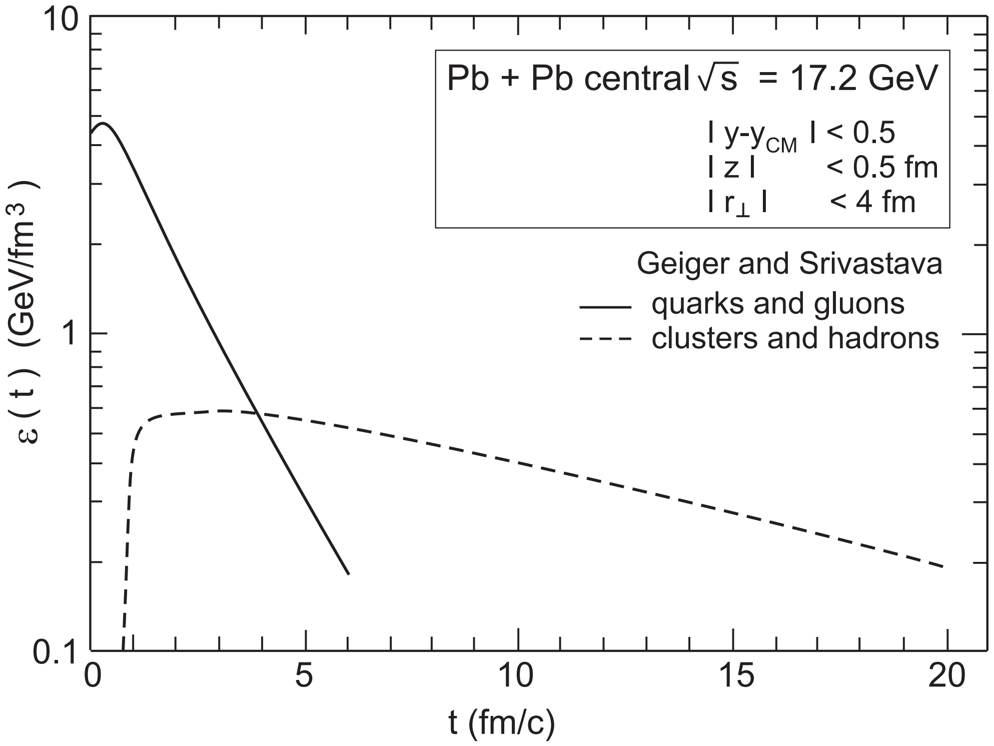

Figure 2: Parton cascade model prediction for the time profile of the energy density contained in partons and hadrons, as found in a central cylinder subvolume of 4 fm/c transverse radius at $|y - y_{CM}| < 0.5$ in central $Pb + Pb$ collisions at $\sqrt{s} = 17.2\, GeV$. Adapted from Geiger and Srivastava [23].