QGP fireball explosion

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Abstract. We identify the major physics milestones in the development of strange hadrons as an observable for both the formation of quark-gluon plasma, and of the ensuing explosive disintegration of deconfined matter fireball formed in relativistic heavy ion collisions at 160–200 A GeV. We describe the physical properties of QGP phase and show agreement with the expectations based on an analysis of hadron abundances. We than also demonstrate that the $m_{\perp}$ shape of hadron spectra is in qualitative agreement with the sudden breakup of a supercooled QGP fireball.

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1. Why Quark-Gluon Plasma?

1.1. Strangeness Enhancement

Considering that strangeness and entropy (hadron multiplicity) excess due to QGP formation accompany each other, the appropriate way to measure the global strangeness enhancement is to study the yield of strangeness produced per participant baryon. This can be done in many different ways, one often invoked is to compare proton induced reactions with nucleus-nucleus reactions [1].

The enhanced strangeness yield observed at 158–200 A GeV reactions corresponds according to our study to $O(1)$ $s\bar{s}$-pairs of quarks per participant baryon [2]. This exceptionally high yield is achievable in a short time that the collision is known to last by in-plasma gluon-fusion reactions, $G+G \rightarrow s+\bar{s}$ [3]. Strangeness enhancement alone is a possible QGP signature. However, it is hard to argue that strangeness alone suffices to show formation of QGP phase, as other mechanisms of flavor formation within some other new physics scenarios can be proposed. Quite early on strange antiquaryons have been recognized as being more specific of the deconfined phase (see next section) [4].

However, systematic study of strangeness enhancement offers a relatively simple and powerful tool to find the critical behavior of elementary matter. At low energies the energy threshold behavior of strangeness formation leads to a rapid rise in strangeness yield. As long as onset of deconfinement does not produce excess pions, strangeness per pion yield can appear at lower collision energies to be greater than it is in QGP phase reached at high energies [4].
A comparison of AGS results with CERN higher energy strangeness per pion yield suggests that the lower collision energy yield is higher, as is in fact consistent with the formation of the QGP phase at higher energies. This production pattern of strangeness allows a simple determination of the transition energy to the high entropy phase, presumably QGP, which is the energy at which the strangeness to pion ratio is diluted by melting of color degrees of freedom – this at first enhances the hadron yield, and only when in-plasma temperature and plasma lifespan at higher collision energy is sufficiently high, the strangeness yield picks up, regaining some lost ground in comparison to the pion yield (see Fig. 1 in [5]).

1.2. Multistrange Antibaryon Enhancement

Even though the strange pattern of strangeness excess as function of energy would clearly indicate formation of a new state of elementary matter, more specific signatures are needed to establish the deconfined nature of the new phase.

Strange antibaryons allow to probe mobility and density of individual strange quarks at the time these otherwise rarely produced hadrons (low backgrounds) are formed. In QGP plasma the predicted, and observed, enhancement of strange antibaryons occurs with an unusual pattern: enhancement is increasing with strangeness content, consistent with these particles being emitted from a very dense source with (nearly) completely saturated strangeness phase space. Here, enhancement is defined with a base being the expectation derived from scaled p-N reactions. In models employing cascading interactions to create multistrange particles such a pattern is highly unnatural.

A special feature emerges from the study of strange antibaryons at CERN-SPS: they seem to emerge directly, and without reinteraction in any baryon-rich medium, from the strangeness symmetric deconfined phase. This has led to the suggestion of explosive disintegration of the QGP fireball which we now briefly discuss.

2. Why Explosion?

2.1. Relative Chemical Equilibrium and Absolute Non-Equilibrium

The abundance analysis of relative strange particle abundances shows that they follow a pattern arising when the phase space of strangeness is symmetric between strange and antistrange quarks. This is surprising in a baryon-rich environment. A solution of this mystery calls for both strange and antistrange quarks to be mobile and not bound in hadronic states. Analysis of lower energy 10–14 GeV AGS results clearly shows the expected matter-antimatter asymmetry. This ‘relative chemical equilibrium’ study suggests that there is an important difference in the reaction mechanism arising comparing reactions occurring at CERN and AGS energies. The nature of relative chemical equilibrium at CERN energies allows thus to suppose that the source has deconfined strange quarks, and that the observed strange antibaryons did not rescatter after formation, which is confirmed by the properties of their $m_\perp$-spectra (see below).

Analysis of hadron abundances (absolute chemical equilibrium) shows that hadrons (in particular strange) are described much more precisely when the hadron phase space is evaluated allowing for nonequilibrium quark pair yield. This means that a reaction picture should invoke formation of hadrons on a global time scale which is shorter than chemical equilibration for any type of matter considered.
Further and direct evidence for rapid hadron formation comes from HBT correlations analysis, which shows that pions arise within a period of time compatible with zero, and at most 2\(\text{fm/c}\) long. Especially for pions one would expect that continuous emission from an evolving source, thus this result is somewhat unexpected and indicative of a violent end of the fireball of dense matter

It can be imagined that the dense matter fireball formed at CERN breaks up as fast as causality allows: when the sudden hadronization begins, the freeze-out surface propagates at light velocity \(c\). However, the flow velocity we find is smaller, consistent with velocity of sound of relativistic matter \((c/\sqrt{3})\).

2.2. \(m_\perp\)-spectra

Strange antibaryons, specifically \(\Lambda\) and \(\Xi\), \(m_\perp\)-spectra measured by the experiment WA97 at central rapidity averaged over 30% centrality cannot be distinguished from the corresponding shape of \(\Lambda\) and \(\Xi\) spectra. This contradicts the behavior expected should strange antibaryons be evolving when embedded in a baryon rich hadron medium. Furthermore, should the production of strange antibaryons occur in hadron gas medium, there is no reason to expect that these spectra could be equal, as in this scenario fundamentally different processes contribute to the formation of particles and antiparticles.

The \(m_\perp\)-spectra of single and double strange baryons and antibaryons are also found to be nearly identical. This effect sets low limits on formation mechanism involving a gradual build-up due to multi-meson reactions, or continuous emission from a source that is evolving, and not decoupled from these particles.

On the other hand, explosive hadronization picture requires that the thermal and chemical freeze-out conditions of all hadrons (nearly) agree, and that the thermal freeze-out conditions of very different particles are also nearly the same. This is an extraordinarily strong requirement. Thus in order to falsify explosive hadronization picture we either:

1) show that, \(e.g.,\) pion spectra are inconsistent with hyperon spectra in an analysis that applies same methodology including in the thermal freeze-out analysis both temperature and transverse explosion velocity or/and

2) show that \(m_\perp\)-spectra cannot be described by statistical parameters obtained from the chemical freeze-out analysis.

Such an evaluation and comparison of freeze-out conditions involving both chemical and thermal properties of hadronic particles has not been previously performed in a fully consistent fashion, and we will present here the very first results. We find a good agreement with sudden hadronization scenario.

3. Mechanism of Sudden Hadronization

3.1. Chemical Freeze-out

We reported at the last strangeness meeting in Padova that in order to arrive at a statistically significant description of experimental strange hadron abundance results we need to introduce valance quark pair abundance \([10]\), as expressed by the parameters \(\gamma_q\) and \(\gamma_q/\gamma_s\simeq 1\). Our ongoing study of the \(\text{Pb–Pb}\) system final state hadron abundances strongly favors \(\gamma_q \simeq \exp(m_\pi/2T) > 1, \gamma_s \simeq \gamma_i\) \([2]\), confirming and extending the ideas expressed in Padova.
We have now also understood that chemical non-equilibrium arises naturally in explosive fireball breakup. The microscopic processes governing the fireball breakup determine how the physical and statistical properties of the fireball change at the breakup point. The energy $E$ and baryon content $b$ of the fireball are conserved. Entropy $S$ is conserved when the gluon content of a QGP fireball is transformed into quark pairs in the entropy conserving process $G + G \rightarrow q + \bar{q}$. Similarly, when quarks and antiquarks recombine into hadrons, entropy is conserved in the range of parameters of interest here. Thus also $E/b$ and $S/b$ is conserved across hadronization condition. The sudden hadronization process also maintains the temperature $T$ and baryo-chemical potential $\mu_b$ across the phase boundary. What changes are the chemical occupancy parameters. As gluons convert into quark pairs and hadrons $\gamma_g \rightarrow 0$ but the number occupancy of light valance quark pairs increases $\gamma_q > \gamma_{q0} \simeq 1$ increases significantly, along with the number occupancy of strange quark pairs $\gamma_s > \gamma_{s0} \simeq 1$.

3.2. Mechanical Instability and Deep Supercooling

We found that sudden breakup (hadronization) into final state particles occurs as the fireball super-cools, and in this state encounters a strong mechanical instability. Deep supercooling requires a first order phase transition, and this in turn implies presence of a latent heat. The total pressure and energy comprise particle (subscript $p$) and the vacuum properties:

$$P^{(i)} = P_p - B, \quad \varepsilon = \varepsilon_p^{(i)} + B. \quad (1)$$

The upper index $(i)$ refers for the intrinsic energy density $\varepsilon$ and pressure $P$ of matter in the frame of reference, locally at rest, i.e., observed by a co-moving observer. We omit the superscript $(i)$ in the following.

The surface normal vector of exploding fireball is $\vec{n}$, and the local velocity of matter flow $\vec{v}_c$. The rate of momentum flow vector $\vec{P}$ at the surface is obtained from the energy-stress tensor $T_{kl}$:

$$\vec{P} = P\vec{n} + (P + \varepsilon)\frac{\vec{v}_c \cdot \vec{n}}{1 - \frac{v_c^2}{c^2}}. \quad (2)$$

For the fireball expansion to continue, $P = |\vec{P}| > 0$ is required. For $P \rightarrow 0$ at $v_c \neq 0$, we have a conflict between the desire of the motion to stop or even reverse, and the continued inertial expansion. Expansion beyond $P \rightarrow 0$ is in general not possible. A surface region of the fireball that reached it but continues to flow outwards must be torn apart. This is a collective instability and thus the ensuing disintegration of the fireball matter will be very rapid, provided that much of the surface reaches this condition. We adopt the condition $\vec{P} = 0$ at any surface region to be the instability condition of an expanding hadron matter fireball.

4. QGP fireball

4.1. Equations of State

In order to quantitatively evaluate supercooling of a QGP fireball, we need a model of equations of state of the deconfined phase that comprises interactions, and specifically, the freezing of the color degrees of freedom, as temperature decreases. We have developed a model which agrees well with the lattice results and have presented it elsewhere. The key ingredients of our model are:
(i) We relate the QCD scale to the temperature $T = 1/\beta$, we use for the scale the Matsubara frequency $\mu$ (we are following the notation convention and thus $\mu$ without a subscript is not a chemical potential, it is the QCD scale):

$$\mu = 2\pi\beta^{-1}\sqrt{1 + \frac{1}{\pi^2}\ln^2\lambda_q} = 2\sqrt{(\pi T)^2 + \mu_q^2}. \quad (3)$$

This extension to finite chemical potential $\mu_q$, or equivalently quark fugacity $\lambda_q = \exp \mu_q/T$, is motivated by the form of plasma frequency entering the computation of the vacuum polarization function $\langle 16 \rangle$.

(ii) We obtain the interacting strength $\alpha_s(\mu)$ integrating numerically the renormalization group equations

$$\mu \frac{\partial \alpha_s}{\partial \mu} = -b_0 \alpha_s^2 - b_1 \alpha_s^3 + \ldots \equiv \beta_2^{\text{pert}}. \quad (4)$$

$\beta_2^{\text{pert}}$ is the beta-function of the renormalization group in two loop approximation, and

$$b_0 = \frac{11 - 2n_f/3}{2\pi}, \quad b_1 = \frac{51 - 19n_f/3}{4\pi^2}.$$  

$\beta_2^{\text{pert}}$ does not depend on the renormalization scheme, and solutions of Eq. (4) differ from higher order renormalization scheme dependent results by less than the error introduced by the experimental uncertainty in the measured value of $\alpha_s(\mu = M_Z) = 0.118 + 0.001 - 0.0016$.

(iii) We introduce, in the domain of freely mobile quarks and gluons, a finite vacuum energy density:

$$B = 0.19 \text{ GeV fm}^3.$$  

This also implies, by virtue of relativistic invariance, that there must be a (negative) associated pressure acting on the surface of this volume, aiming to reduce the size of the deconfined region. These two properties of the vacuum follow consistently from the vacuum partition function:

$$\ln Z_{\text{vac}} \equiv -BV\beta. \quad (5)$$

(iv) The partition function of the quark-gluon liquid comprises interacting gluons, $n_q$ flavors of light quarks $\langle 17 \rangle$, and the vacuum $B$-term. We incorporate further the strange quarks by assuming that their mass in effect reduces their effective number $n_s < 1$:

$$\frac{T}{V} \ln Z_{\text{QGP}} \equiv P_{\text{QGP}} = -B + \frac{8}{45\pi^2} c_1(\pi T)^4$$

$$+ \frac{n_q}{15\pi^2} \left[ \frac{7}{4} c_2(\pi T)^4 + \frac{15}{2} c_3 \left( \mu_q^2(\pi T)^2 + \frac{1}{2}\mu_q^4 \right) \right]$$

$$+ \frac{n_s}{15\pi^2} \left[ \frac{7}{4} c_2(\pi T)^4 + \frac{15}{2} c_3 \left( \mu_s^2(\pi T)^2 + \frac{1}{2}\mu_s^4 \right) \right], \quad (6)$$

where:

$$c_1 = 1 - \frac{15\alpha_s}{4\pi} + \cdots, \quad (7)$$

$$c_2 = 1 - \frac{50\alpha_s}{21\pi} + \cdots, \quad c_3 = 1 - \frac{2\alpha_s}{\pi} + \cdots.$$
4.2. Properties of QGP

We show properties of the quark-gluon liquid in a wider range of parameters at fixed entropy per baryon $S/b$ in the range $S/b = 10$–$60$ in step of 5 units. In the top panel in figure 1, we show baryo-chemical potential $\mu_b$, in middle panel baryon density $n/n_0$, here $n_0 = 0.16/\text{fm}^3$, and bottom left the energy per baryon $E/b$. In top and middle panel the low entropy results are top-left in figure, in bottom panel bottom left. The highlighted curve, in figure 1, is for the value $S/b = 42.5$. The dotted line, at the minimum of $E/b|_{S/b}$, is where the vacuum and quark-gluon gas pressure balance. This is the equilibrium point and indeed the energy per baryon does have a relative minimum there.

Since little entropy is produced during the evolution of the QGP fireball, lines in the lower panel of figure 1 characterize the approximate trajectory in time of the fireball. After initial drop in energy per baryon due to transfer of energy to accelerating expansion of the fireball, during the deep supercooling process the motion is slowed...
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Figure 2. Thin solid and dashed lines: equilibrium phase transition from hadron gas to QGP liquid without and with excluded volume correction, respectively. Dotted: breakup condition at shape parameter $\kappa = 0.6$, for expansion velocity $v_2^c = 0, 1/10, 1/6, 1/5, 1/4$ and $1/3$, and thick line for $v_c = 0.54$. The experimental point denotes chemical non-equilibrium freeze-out analysis result [2].

and thus energy per baryon increases. However only at the entropy 10 the two processes balance and the collective motion slows. At higher entropy content the vacuum pressure is not sufficient to stop the explosion of a fireball. The thick line is our expectation for the fireball made in Pb–Pb interactions at the projectile energy 158A GeV. The cross shows the result of chemical freeze-out analysis.

We also have compared the chemical freeze-out conditions with the phase transition properties. The thin solid line in the $T, \mu_b$ plane in figure 2 shows where the pressure of the quark-gluon liquid equals the equilibrated hadron gas pressure. The hadron gas behavior is obtained evaluating and summing the contributions of all known hadronic resonances considered to be point particles. When we allow for finite volume of hadrons [18], we find that the hadron pressure is slightly reduced, leading to some (5 MeV) reduction in the equilibrium transition temperature, as is shown by the dashed line in figure 2. For vanishing baryo-chemical potential, we note in figure 2 that the equilibrium phase transition temperature is $T_{pt} \simeq 172$ MeV, and when finite hadron size is allowed, $T_{hp} \simeq 166$ MeV. The scale in temperature we discuss is result of comparison with lattice gauge results. Within the lattice calculations [19], it arises from the comparison with the string tension.

The dotted lines, in figure 2, correspond to break up velocity for (from right to left) $v_2^c = 0, 1/10, 1/6, 1/5, 1/4$ and $1/3$. The last dotted line corresponds thus to an expansion flow with the velocity of sound of relativistic noninteracting massless gas. The thick solid line corresponds to an expansion with $v_c = 0.54$. The hadron analysis result is also shown [2]. Comparing in figure 2 thin solid/dashed with the thick line, we recognize the deep supercooling as required for the explosive fireball disintegration. The super-cooled zero pressure $P = 0$ QGP temperature is at $T_{sc} = 157$ MeV, (see
5. Thermal freeze-out

As noted earlier on, it is essential for the idea of sudden freeze-out of hadrons that all spectra are well described by the same parameters obtained in chemical analysis of (strange) hadrons produced. Some spectacular results related to this objective are shown in the following. These were obtained taking chemical freeze-out temperature value for the thermal freeze-out temperature: $T_f = 143 \text{ MeV}$, with a freeze-out surface velocity $0.99c$, as expected for sudden break-up of an unstable fireball.

In figure 3, we show how the data of WA97 experiment for $\Xi$ (top) and $\bar{\Xi}$ are understood. We have included as usual the contributions from the decay $\Xi^* (1530) \rightarrow \Xi + \pi$ and similarly for $\bar{\Xi}$. Given the large statistical errors we did not (yet) include in analysis other resonances. Varying the two parameters normalization and the flow velocity $v_c$, we found that $\Xi$ are best described by $v_c = 0.50 \pm 0.03$, while for $\Xi$ we found $v_c = 0.49 \pm 0.05$, both values are consistent with the chemical analysis result $v_c = 0.54 \pm 0.03$. The $\chi^2$/dof for $\Xi$ is 0.6 and it is 1.1 for $\bar{\Xi}$. These results are remarkably consistent with the results of chemical freeze-out analysis [2], and are highly statistically significant. We thus can draw the conclusion that the double-strange baryons and antibaryons which comprise practically all newly made quarks, are produced predominantly in a sudden hadronization process.

We now turn to the pion spectra. We study the $\pi^0$ data in a very wide range of $m_T$ in which the yield changes by 6 orders of magnitude. These results were also obtained at central rapidity by the WA98 collaboration [24]. We use the same set of parameters as for cascades, i.e., $T_f = 143 \text{ MeV}$, chosen at the chemical freeze-out, and with freeze-out surface velocity $0.99c$. We include in the results shown in figure 4 the intercept of the first dashed line to the right in figure 2) and an expanding fireball can deeply super-cool to $T_{dsc} \approx 147 \text{ MeV}$ (see the intercept of thick solid line) before the mechanical instability occurs.
Figure 4. Central rapidity data of experiment WA98 for $\pi^0$ are compared to the spectra expected in a sudden freeze-out reaction picture. See text for details.

Aside of directly produced pions the two body decay of the $\rho$. However, noticing the large range of yield here considered, we allow a direct hard parton QCD component contribution [21], of the form $E d^3N/d^3p \propto 1/\kappa\perp^\tau$. Thus, we vary four parameters two normalizations, and also $\kappa = 5.6\pm 1.2$, $v_c = 0.55\pm 0.02$. This yields again an extremely good description of the data as seen in figure 4, with $\chi^2/dof < 1.4$. Considering that only statistical error is being considered, and we were not evaluating contributions of 3-body decay resonances, we see this as a highly significant result. We note that the hard scattering contribution is at 1–20% level, and thus one must make a more precise model of this contribution before searching for a precise description.

Our analysis is not contradicting results shown in [20], for these authors did not consider that the freeze-out surface velocity is different from the flow velocity, and they did not allow for direct parton-parton scattering contributions in their analysis of pion spectra. Moreover, we confirm the finding that the apparent temperature hierarchy for different mass particles is due to a collective expansion of the source [22].

6. Discussion and Conclusion

We recall here the conclusion of Cs"orgo and Csernai [23] who required as verification for the presence of a deeply super-cooled state of matter and sudden hadronization: i) short duration and relatively short mean proper-time of particle emission, now seen in particle correlations [13]; ii) clean strangeness signal of QGP [1]; iii) universality of produced particle spectra which are the remarkable features of strange particle production [1]; v) no mass shift of the phi-meson; despite extensive search such a shift has not been found by the NA49 collaboration [24]. All this has been found true, and more.

Is our picture of fireball evolution compelling? We found that particle production occurred at condition of negative pressure expected in a deeply super-cooled state and have shown internal consistency with (strange) hadron production analysis involving
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chemical non-equilibrium. Moreover, these chemical freeze-out conditions agree with thermal analysis, allowing the conjecture that the explosive quark-gluon fireball breakup forms final state hadrons, which do not undergo further re-equilibration.

Our first glance at the thermal hadron spectra is clearly showing consistency of thermal freeze-out between very different hadrons. Moreover, we find consistency of thermal and chemical freeze-out conditions. Both results are required if hadrons are formed in sudden hadronization of a supercooled quark-gluon plasma.

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