Condensation of a Strongly Interacting Parton Plasma into a Hadron Gas in High Energy Nuclear Collisions

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We examine the effects of color screening on the transition of a parton plasma into a hadron gas at RHIC energies. It is found that as expected, color screening posed itself as a significant barrier for hadronization. Parton-hadron conversion would therefore be delayed and prolonged when compared to that occurring in a vacuum. Due to the on-going expansion, the resulting hadron densities are lowered. Parton equilibration is also shown to be seriously disrupted in the process.

1. Introduction

Heavy ion collision experiments at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven are going to study the possibility of the recreation of a deconfined parton plasma. This plasma consists of gluons, quarks and antiquarks which can roam freely in a region of sizable spatial extent. This is made possible by the high energies of the partons through the asymptotic freedom property of QCD and the color screening property of a dense medium of color charges. The latter weakens the otherwise very strong color fields responsible for keeping the partons well hidden inside hadrons under normal circumstances. This same screening property has the additional advantage of removing the infrared divergence in the parton interactions and thus there is no need to introduce an ad hoc and somewhat arbitrary momentum cutoff as in the usual studies within perturbative QCD in a vacuum setting. This signals important differences of a dense parton system in comparison to an extremely dilute system as found in deep inelastic scattering or in $e^+e^-$ annihilation. Because the latters have been studied for well over a decade, it is tempting and certainly easiest to apply all the acquired knowledge or understanding in exactly the same way as done in these studies to heavy ion collisions. In view of the above mentioned differences in the environment, this cannot be entirely correct. It is clear that one has to bear in mind these differences when building numerical models.

The time evolution of a parton plasma has been studied in various models [1–5]. What we have learned are that gluon equilibration tends to be fast in both thermal and chemical aspects but this is not so for quarks and antiquarks. But regardless of the state of the system, that is whether it is fully equilibrated or not, hadronization will take place once the conditions are right. The medium effects such as the Landau-Pomeranchuk-Migdal

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effects of gluon emission and the shielding of infrared divergence have been considered in [3–5] and in [1,2] only the former has been incorporated. All were done, however, within the deconfined phase. In this talk, we are concerned with the next stage in the time evolution of the parton system, that is the transition into hadrons and the medium effects on that. In [3] a hadronization scheme was introduced at the end of the time evolution of the parton cascades but the role of the medium on hadronization, which we will consider here, has been totally neglected.

In our previous investigation, the interaction strength in a parton plasma was found to increase in time due to the decreasing average energy of the system [5], this has the consequence of an increasing screening mass \( m_D \) with time at least at RHIC for the duration that we have investigated. The screening length therefore behaved in the opposite manner. We got a screening length \( l_D \sim 0.4 \) fm at the end of our time evolution when the temperature estimates fell to 200 MeV. This is unfavorable for hadronization because this \( l_D \) value is comparable to the typical common hadron size. This fact is further reinforced by the lattice calculation of \( m_D \) up to \( \mathcal{O}(g^3) \) in [7]. They found that it was larger than the leading order result with \( m_D \sim 3.3 \) \( m_D^{LO} \). Using their results and choosing \( \Lambda_{QCD} \sim 234 \) MeV, at \( T \sim 200 \) MeV

\[
m_D^{LO} \sim 405 \text{ MeV} \implies l_D \sim l_D^{LO}/3.3 \sim 0.16 \text{ fm}
\]
and at \( T \sim 150 \) MeV

\[
m_D^{LO} \sim 332 \text{ MeV} \implies l_D \sim l_D^{LO}/3.3 \sim 0.20 \text{ fm}.
\]

These are small sizes compared to most hadrons. So it is clear that the color screening barrier to hadronization is not small in a parton plasma found at RHIC.

2. Time Evolution Equations for the Parton-Hadron Conversion

In [4], we wrote down the equations for the time evolution of a parton plasma undergoing one-dimensional expansion. The main ingredient of our scheme is to combine the reduced Boltzmann equation, the relaxation time approximation for the parton collision terms \( C_i^p \) and their explicit perturbative construction. The resulting equations are

\[
\frac{df_i^p}{d\tau} \bigg|_{p_z,\tau=\text{const.}} = -\frac{f_i^p - f_i^{p\,eq}}{\theta_i^p} = C_i^p.
\]

With this combination, the distributions \( f_i^p \) which describe completely the time development of the system can be solved.

To extend the time evolution beyond the parton phase and to try to learn something about the medium effects on the parton-hadron conversion, it is not necessary to have the full three-dimensional expansion. There is also no need for a full set of hadrons. So we will continue with one-dimensional expansion and only consider pions and kaons. Moreover these hadrons or resonances will be assumed to consist of only a quark and an antiquark \( qq' \) and thus their formation will be from the clustering of \( q \) and \( q' \). Since the parton plasma is gluon dominated, the gluons must be converted somehow into \( q \) and \( q' \). Perturbative conversion is highly inefficient so a non-perturbative mechanism must be introduced. In [4], exactly such a gluon splitting mechanism was introduced for this very
purpose in the context of $e^+e^-$ annihilations. Although our parton plasma is different from a parton shower, a term of similar nature $C_{i, g\rightarrow q}^p$ will be introduced in the time evolution equations. Together with some new confining terms $C_{i, p\rightarrow h}^p$ which describe the clustering of color singlet $qq'$ pairs into resonances and the subsequent decay into hadrons, the time evolution equations become

$$\frac{df_i^p}{d\tau} \bigg|_{p_\perp=\text{const.}} = -\frac{f_i^p - f_i^{p, \text{eq}}}{\theta_i^p} = C_i^p + C_{i, g\rightarrow q}^p + C_{i, p\rightarrow h}^p.$$  (4)

Because of the parton-hadron conversion, an equation for each hadron will also have to be introduced. Using the same method, we write

$$\frac{df_i^h}{d\tau} \bigg|_{p_\perp=\text{const.}} = -\frac{f_i^h - f_i^{h, \text{eq}}}{\theta_i^h} = C_i^h.$$  (5)

Because they are non-essential to our investigation so no hadron-hadron or parton-hadron interactions are present in Eqs. (4) and (5). These form our basic set of equations for the conversion of a parton into a hadron gas. The explicit forms of the $C_i^p$'s and $C_i^h$'s can be found in [10]. We stress that no medium effect on hadronization has yet been included.

To understand how medium effects such as color screening would affect hadronization, we use the following physical picture. Each hadron must have a certain physical size which can be thought of as the internal separation $b$ of the $q$ and $\bar{q}'$ pair. Because of the internal motion, this separation is not fixed and smaller separations should be more favorable. So this likelihood can be parametrized by a distribution $F(b)$. Therefore for a hadron or resonance existing inside a color screening medium, there is a chance that it will dissolve depending on whether $b < l_D$ or $b > l_D$ which we represent by $P_<$ and $P_>$, respectively. They are related to the distribution by $P_< = \int_0^{l_D} db F(b)$ and $P_> = \int_{l_D}^\infty db F(b)$. They also dictate whether a hadron or resonance can be formed or not. With these probabilities, the parton and hadron time evolution equations with color screening can now be written in the following forms

$$\frac{df_i^p}{d\tau} \bigg|_{p_\perp=\text{const.}} = -\frac{f_i^p - f_i^{p, \text{eq}}}{\theta_i^p} = \left(C_i^p - C_{i, q_a\bar{q}_a}^p\right) + C_{i, q_a\bar{q}_a}' + C_{i, g\rightarrow q}^p + C_{i, p\rightarrow h}^p + C_{i, h\rightarrow p}' ;$$  (6)

$$\frac{df_i^h}{d\tau} \bigg|_{p_\perp=\text{const.}} = -\frac{f_i^h - f_i^{h, \text{eq}}}{\theta_i^h} = C_{i, p\rightarrow h}^h + C_{i, h\rightarrow p}' .$$  (7)

$C_{i, q_a\bar{q}_a}^p$ is the color singlet $qq'$ scattering term and the primed $C'$'s are almost the same terms as in Eqs. (4) and (5) above but are now weighed by either $P_<$ or $P_>$. The new terms $C_{i, h\rightarrow p}$ describe the melting of hadrons as discussed above. Their forms, further details of the above equations and discussions are given in [10].

3. Color Screening Effects on Hadronization in a Strongly Interacting Parton Plasma

Solving for the distributions from the color screened and unscreened equations above, we can compare the effects of the medium on hadronization and vice versa [10]. In Fig. 1, the π and K number densities $n_h$ against time are plotted on the left figure and the
Figure 1. The time developments of the hadron number densities and parton fugacities in a parton plasma going through hadronization with and without color screening.

parton fugacities \( l_g, l_q \) on the right. In the \( n_h \) plot, from top to bottom three pairs of results, color screened (solid) and unscreened (dashed), are shown for the \( \pi^\pm, \pi^0 \) and \( K^\pm,0 \), respectively. Clearly there is a slow start and a delay for forming hadrons in a properly color screened plasma because of the struggle between confinement and color screening. Consequently, the maximum densities are lower because of the expansion. In the second plot on the right, one effect of hadronization on the medium is shown. The top (bottom) three curves are the \( l_g \) (\( l_q \)) results. The long dashed, dotted and solid curves are for the case with no hadronization, with hadronization but no screening and with both included, respectively. So parton equilibration is seen to be seriously disrupted by confinement. Unless equilibration is extremely fast and could finish well before the phase transition which is unlikely, fully equilibrated quark-gluon plasma should not be expected. In the two cases with hadronization, the disruption to the partons is again delayed when screening is included. So any model without screening will not get the hadronization time scale correct. Other effects such as lower hadron densities caused by the delay will affect estimates on the background contributions from the hadron gas to the proposed signatures for the quark-gluon plasma. In view of the imminent operation of RHIC a proper incorporation of medium effects in numerical models with parton-hadron transition is urgently needed.

REFERENCES

1. K. Geiger, Phys. Rev. D 46 (1992) 4965,4986.
2. K. Geiger and J.I. Kapusta, Phys. Rev. Lett. 70 (1993) 1920.
3. T.S. Biró et al, Phys. Rev. C 48 (1993) 1275.
4. S.M.H. Wong, Nucl. Phys. A 607 (1996) 442, Phys. Rev. C 54 (1996) 2588.
5. S.M.H. Wong, Phys. Rev. C 56 (1997) 1075, Nucl. Phys. A 638 (1998) 527c.
6. K. Geiger, Phys. Rev. D 47 (1993) 133.
7. K. Kajantie et al, Phys. Rev. Lett. 79 (1997) 3130.
8. R.D. Field and S. Wolfram, Nucl. Phys. B 213 (1983) 65,
9. B.R. Webber, Nucl. Phys. B 238 (1984) 492.
10. S.M.H. Wong, Minnesota nuclear theory preprint NUC-MINN-99/11-T.