Equilibration and Particle Production in an Increasingly Strongly Interacting Parton Plasma

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We report on a new equilibration scenario in relativistic heavy ion collisions, the scenario of the Increasingly Strongly Interacting Parton Plasma, and the effects of this scenario on equilibration and open charm, photon and dilepton production. The parton plasma is shown to be a very special kind of many-body system, which contains new physics concerning the approach towards equilibrium. This is likely to be unique to the parton plasma.

1. Introduction

In this talk, we present a new equilibration scenario, which emerges out of the initially gluon dominated hot gluon and progressively gains importance in time, this is the scenario of the Increasingly Strongly Interacting Parton Plasma (ISIPP). The new scenario arises out of the previously neglected running of the coupling. In high energy nuclear collisions, the interactions in the early stage are pretty hard, so perturbative QCD is applicable. It is common therefore to choose a small fixed coupling of $\alpha_s = 0.3$, with $\Lambda_{QCD} = 200$ MeV, this corresponds to a fixed average momentum transfer of $2$ GeV. Now for a very typical interaction, a simple t-channel exchange for parton 1 and 2 with 4-momenta $p_1$ and $p_2$ and final parton 3 and 4 with 4-momenta $p_3$ and $p_4$, respectively, the momentum transfer $Q^2$ would be bounded between $0 < Q^2 < 4p_1p_3$. For very typical partons, the upper limit would be given by $4p_1p_3 = 4\langle \epsilon \rangle^2$, essentially the squared of the average parton energy. In ref. \cite{1}, we showed that the time evolution of $\langle \epsilon \rangle$ in a plasma time-evolved with a fixed $\alpha_s = 0.3$ at LHC and at RHIC energies. The change of $\langle \epsilon \rangle$ from the beginning to the end of the evolution is a decrease of at least $1$ GeV and nearly $2$ GeV at LHC. So the average momentum transfer $Q$ in the system will decrease in time. This leads to an increase in the strength of the interactions and the interactions in the parton plasma will become stronger and stronger as the system evolves. This is the origin of the new scenario of ISIPP. In the following, we discuss but not show, due to lack of space, the effects on equilibration of the parton plasma in the new scenario. We show that the parton plasma is a special kind of many-body system unlike ordinary matter and is probably unique. To end, we have three news to report on three different particle productions.

\textsuperscript{*}The author is grateful for local financial support from the Yamada Science Foundation during the attendance of this conference.
2. Effects of ISIPP on Equilibration

By combining Boltzmann equation with the relaxation time approximation for the collision terms,

\[ C(p, \tau) = -\frac{f(p, \tau) - f_{eq}(p, \tau)}{\theta(\tau)} \]  

and construction of the latter again explicitly from QCD matrix elements of the simplest elastic and inelastic interactions, we can solve for the distribution function \( f(p, \tau) \) and hence find out the time evolution of the parton plasma. This has been done in ref. [2] for a plasma with fixed interaction strength. For ISIPP, one must take into account also the decrease of the average energy of the system so this is accompanied by using \( Q = \langle \epsilon \rangle \), a not too unreasonable choice, and inserting this into the one-loop running coupling formula to obtain a time-dependent \( \alpha_s \). With this approach, we found that both chemical and kinetic equilibration of quarks and gluons in the plasma are speeded up but only for quark and antiquark are there any improvements [1] towards the end of the time evolution. We refer the readers to [1] for details. But still viewed on the whole, the equilibration of the system is faster and improved. The only drawback in the time evolution of the system is the more rapid cooling and hence shortened duration of the parton phase due to energy sharing from enhanced particle creation and longitudinal expansion. This reduction when going from the standard plasma to ISIPP is rather large. This is determined by the moment when the estimated parton temperatures reach \( T_c = 200 \text{ MeV} \), the end point of the time evolution. The reduction at LHC is as much as 5.0 fm/c and 3.5 fm/c at RHIC. These are the main effects on equilibration in ISIPP.

3. Parton Plasma is a Unique Many-Body System

We show in this section that the parton plasma is a special kind of many-body system. The quantity that allows us to reveal the secret of the parton plasma is the collision time \( \theta \) as appeared in Eq. (1). The inverse of this quantity measures the net interaction rate which is the difference between the rate of the collisions going forward and backward. As the plasma is being driven out of equilibrium, this difference of the collision rate must increase, which is precisely what going out of equilibrium means. So the net reaction rate must go up and \( \theta \) must decrease when the system is going out of equilibrium. When the system is in equilibrium, detail balance means the difference of the collision rate is zero. So when the system approaches equilibrium, the net rate must go down and \( \theta \) must therefore increase. So for our situation, \( \theta \) must first decrease, makes a turn and increases again. In Fig. 1 we show the collision times for quark and gluon at RHIC for various fixed couplings and for ISIPP. As can be seen, for the plasmas with fixed coupling, the behaviour of \( \theta \) follows what we have just described, but for ISIPP, the \( \theta \)'s tend to continue to decrease with time. This decrease is clearly of a different type from the initial drop when the plasma is being driven out of equilibrium. Since \( \theta \)'s for ISIPP are not rising in the later stage in general, it seems to mean that the plasma is not equilibrating. This clearly contradicts what we have already said about ISIPP in Sec. 2. What is happening is, in fact, in the above difference of collision rate, a power of \( \alpha_s \) can be extracted out as a prefactor, the increasing coupling can therefore compensate for the decrease in the
Figure 1. The time evolution of the collision times at RHIC for gluon and quark in ISIPP (long dashed) is different from parton plasma with fixed $\alpha_s = 0.3$ (solid), 0.5 (dotted) and 0.8 (dashed). It shows the unique approach of ISIPP towards equilibrium.

difference as equilibrium is approached. The result is, equilibration proceeds faster and faster in ISIPP whereas, in ordinary many-body system, it is slower and slower. This is a new physics of the parton plasma that, as far as we know, has never been revealed before, which gives the ISIPP a unique status as a many-body system.

4. The 3 News of Particle Production in ISIPP

When we go from the standard parton plasma to ISIPP, there are two categories of effects that make the difference in particle production. They are the direct and indirect effects [3]. The former is where QCD has at least a partial role to play in the production process and hence there will be explicit dependence on $\alpha_s$. The latters are where the coupling effects first act on the time evolution of the system which then get passed onto the production process. The reduced duration of the parton phase already mentioned and enhanced or reduced parton densities [1] are examples of the latter. The first is of importance for particle production because of the need to integrate over spacetime history of the collisions and the second is obvious. We consider 3 types of particle production and we only show the $p_T$ or invariant mass $M$ distributions at LHC.

(i) First News — Dilepton Production
At leading order, this is only subject to indirect effects. As seen in Fig. 2, reduced production time is more important than enhanced fermion densities and therefore the dilepton production in ISIPP is suppressed.

(ii) Second News — Photon Production
Photon production comes from Compton and annihilation contribution. This time both direct and indirect effects are at work. Photon production plot in Fig. 2 shows that negative and positive direct and indirect effects largely cancel out each other so the $p_T$ distribution remains essentially unchanged.

(iii) Third News — Open Charm Production
This process is not subject to direct effect, contrary to appearance, because this is a hard process and is therefore at a different scale, in general, from that for equilibration [3]. As seen in Fig. 2, the total yield is essentially the same in ISIPP over the standard plasma. The ability of open charm as a probe is therefore unaffected.
Figure 2. Comparison of dilepton, photon and open charm production at LHC from ISIPP with the standard parton plasma. For dilepton, the lower curve is from ISIPP. For photon, the total sum (solid), contribution from Compton scattering (dotted) and annihilation (dashed) are essentially the same in the two plasmas. The total (solid) and gluon conversion (dotted) to open charm from ISIPP are the same in the two scenarios, while annihilation (dashed) is slightly down in ISIPP.

5. Summary and Outlook

We have pointed out that the ISIPP scenario is a necessary stage in heavy ion collisions and equilibration is faster and improved as a result but the parton phase is shortened. The approach towards equilibrium for ISIPP is different from other many-body system and contains new physics. Particle productions at leading order in the new plasma have mixed results. In view of the increasing coupling, higher orders are more important for electromagnetic radiations. There is even a chance of enhancement. We have not mentioned the effect of reduction of generated entropy in ISIPP \[\text{?}\], this will lead to a shortened mixed phase in the case of a first order phase transition and therefore reduced final hadron multiplicity and hadron gas density and therefore reduced hadronic signals. So enhanced partonic but reduced hadronic signals, for example the electromagnetic ones suggested here, that follow from ISIPP, if confirmed, would contribute positively towards the possibility of having the quark-gluon plasma outshining hadronic matter.

REFERENCES

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