Strangeness Production via Parton Cascade

Bin Zhang\textsuperscript{1}, Miklos Gyulassy\textsuperscript{1} and Yang Pang\textsuperscript{1}

\textsuperscript{1} Physics Department, Columbia University, New York, NY 10027, USA

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Abstract. We study pre-equilibrium strangeness production at RHIC energies in a new parton cascade. Starting with the turbulent glue HIJING initial conditions we investigate the interplay between mini-jet and soft beam jet gluons for strangeness production prior to hadronization, and show the importance of soft beam jet gluons in the strangeness production.

1. Introduction

In ultrarelativistic heavy ion collisions, qualitatively new phenomena are expected, among which the formation of quark gluon plasma (QGP). One of the challenges for the nuclear physics community is to find signals that can identify the formation of QGP. Based on pQCD and thermodynamic calculations, strangeness enhancement was proposed long ago as one of the signals of QGP formation\textsuperscript{[1]} due to the relatively fast strangeness production process $g + g \rightarrow s + \bar{s}$.

Strangeness production from more realistic initial conditions (HIJING\textsuperscript{[2]} mini-jet initial conditions) has been investigated\textsuperscript{[3]} by following a set of rate equations in a 1-dimensional expanding system and it was out that the system does not reach chemical equilibrium.

Cascade Models can be used to investigate equilibration without the assumption of local thermal equilibrium. Results from Klaus Geiger’s Parton Cascade Code (PCM)\textsuperscript{[4]} show that we can not get chemical equilibrium at RHIC energies.

We investigate the strangeness production using a parton cascade code which we developed recently. In particular, we study the interplay between minijet gluons and soft beam jet gluons and reveal the importance of soft beam jet gluons in the strangeness production.

We’ll first review the argument leading to fast equilibration, followed by a simple discussion of our cascade approach.
Then we discuss the differences between our cascade code and Geiger’s PCM, and estimate the relevant screening scales. Next we present the result of our cascade simulations which shows that chemical equilibrium can not be achieved and the soft beam jet gluons are important in the strangeness production.

2. Parton cascade approach to strangeness production

2.1. Strangeness equilibration rate

It’s not difficult to get an estimate for the strangeness equilibration rate. To solve the rate equation,

\[
\frac{dn_s}{dt} \approx A(1 - \left(\frac{n_s(t)}{n_s(\infty)}\right)^2),
\]

we need the transition rate per unit volume,

\[
A = \frac{dN}{dt d^3x}
\]

\[
= \frac{1}{2} \int_{4m^2}^{\infty} ds \sqrt{s(s - 4m^2)} \delta(s - (k_1 + k_2)^2)
\]

\[
\int \frac{d^3k_1}{(2\pi)^3E_1} \int \frac{d^3k_2}{(2\pi)^3E_2} \frac{1}{2} (2 \times 8)^2 e^{-\beta(E_1 + E_2)} \sigma_{gg \rightarrow s\bar{s}}(s),
\]

in which \(e^{-\beta E_1}\) and \(e^{-\beta E_2}\) are classical phase space distributions, and

\[
\sigma_{gg \rightarrow s\bar{s}}(s) = \frac{\pi\alpha^2}{3s} \left[-(7 + \frac{31m^2}{s})\frac{1}{4} \chi + (1 + \frac{4m^2}{s} + \frac{m^4}{s^2}) \log \frac{1 + \chi}{1 - \chi}\right]
\]

where \(\chi = \sqrt{1 - 4m^2/s}\), and \(\sqrt{\frac{s(s - 4m^2)}{2E_1E_2}}\) is the relative velocity.

The relaxation time is given by:

\[
\tau = n_s(\infty)/2A
\]

and is shown in Fig.1 for \(\alpha = 0.6\). we see that the equilibration time is around several fermis.

Since at central rapidity the freezeout time is also around several fermis, we expect from the above simple estimate that chemical equilibrium may be achieved during the life time of the plasma. Comparing to the relatively slower hadronic strangeness production processes, strangeness signal will be enhanced by the formation of quark gluon plasma.
2.2. Parton Cascade Approach

To study strangeness production at RHIC energies, without the assumption of local thermal equilibrium necessary for the hydrodynamic approach, we develop our own parton cascade code. This new cascade code is different from the one Klaus Geiger developed in several important aspects.

Our initial conditions are taken from HIJING output. We use inside-outside cascade picture in which particle production is a result of the collision of two nuclei. We do not have wee partons interacting before the collision of two Lorentz contracted nuclei, because they are part of a coherent field before the collision of the valance quarks.

In our approach, we have on-shell particles instead of virtual particles so that real parton scattering cross sections can be used. The singularities of cross sections are regulated by a medium generated screening mass; this differs from Geiger’s approach in which a lower momentum cutoff is used.

For the soft beam jet gluons, we use 1000 soft gluons per unit rapidity bin. They have a temperature parameter around 250 MeV to account for the beam energy loss at RHIC.

For parton parton collisions, we use two particle center of mass collision criteria, i.e., two particle collide when their closest approach distance is smaller than \( \sqrt{T} \) (\( \sigma \) is the scattering cross section). The collision point is chosen to be the midpoint of two particles in the two-body center of mass frame at their closest approach point.
We take leading divergent cross sections regulated by a screening mass except for $g + g \rightarrow s + \bar{s}$ which is regulated by the strangeness mass.

2.3. Color screening in heavy ion collisions

In nucleus-nucleus collisions, medium effects manifest as color screening. The color screening mass is important in regulating the forward gluon-gluon scattering cross section. Since the total elastic cross section depends on the screening mass, it is an important factor in determining the strangeness production branching ratio of the gluon-gluon scattering.

The screening mass is related to phase space distribution through\cite{5}:

$$m^2 = -\frac{3\alpha_s}{\pi^2} \lim_{|\vec{q}| \to 0} \int d^3k \frac{|\vec{q}|}{|\vec{k}|} \vec{q} \cdot \vec{n} f(\vec{k}),$$

in which $f(\vec{k})$ can be parametrized as:

$$f(\vec{k}) = \frac{2(2\pi)^2}{gGV} \frac{1}{|\vec{k}|} g(k_T, y),$$

where:

$$g(k_T, y) = \frac{1}{2Y} g(k_T) [\theta(y + Y) - \theta(y - Y)].$$

For minijet gluons:

$$g(k_T) = N_0 e^{\frac{-k_T}{k_0}},$$

$$m^2_T \approx \frac{3\pi\alpha_s N_G}{R_A^2 \frac{2Y}{Y}}.$$

Take $\alpha = 0.4$, with minijet rapidity density given by HIJING $N_{G\mu} = 300$, we get $\mu \sim 4.5 fm^{-1}$.

For minijet + soft gluons:

$$g(k_T) = N_0 (e^{\frac{-k_T}{k_0}} + \frac{40}{3} e^{\frac{-2k_T}{k_0}}),$$

$$m^2_T \approx \frac{92}{169} \frac{3\pi\alpha_s N_G}{R_A^2 \frac{2Y}{Y}}.$$

For $\alpha = 0.4$, with rapidity density $N_{G\mu} = 1300$, we get $\mu \sim 7 fm^{-1}$.

We’ll use these values\textsuperscript{a} to calculate strangeness production at RHIC energies with only minijets and minijets+soft gluons and show the important role of soft gluons in the strangeness production.

a. There are uncertainties in the screening because color screening is intrinsically non-perturbative.
3. Strangeness production at RHIC energies

By following the time evolution of the strangeness and gluon content, we can monitor the chemical equilibration process. The strangeness to gluon ratio is a very important variable for indicating the degree of chemical equilibration. With chemical equilibrium, we’ll have

\[ n_s = 2 \times 3 \times 2 \times \int \frac{d^3p}{(2\pi)^3} \frac{1}{e^{\beta E} + 1}, \]

\[ n_g = 2 \times 8 \times \int \frac{d^3p}{(2\pi)^3} \frac{1}{e^{\beta E} - 1}, \]

and the ratio

\[ \frac{n_s}{n_g} = \frac{3}{4} \times \frac{3}{4} = \frac{9}{16} = 0.5625. \]

Classically, i.e., without Fermi or Bose statistics, we have \( n_s/n_g = 3/4 = 0.75 \).

![Fig. 2. Strangeness to gluon ratio as a function of proper time. Filled diamonds are for 200 HIJING events with only minijet gluons, screening mass \( \mu = 4.5 fm^{-1} \), and \( \Delta y = 1 \) around central rapidity; filled circles are for 30 HIJING events with both minijet gluons and soft gluons, \( \mu = 7 fm^{-1} \), and \( \Delta y = 1 \).](image-url)

Fig. 2 is the time evolution of the strangeness to gluon ratio. We see that with the soft beam jet gluons, we have a much higher \( N_s/N_g \) than that with only minijet gluons, because the phase space distribution has changed. Fig. 3 gives us the Mandelstam s distributions which reflect the change in the phase space distribution. We see that with the soft gluons, we get an s distribution that has a lower peak and hence more emphasis on the low energy part of the strangeness.
production cross section which is peaked near threshold. So, with the soft gluons, we have larger strangeness to gluon ratio.

**Fig. 3.** The $s$ distribution of collisions. The dashed curve is $\frac{dN}{ds}$ ($N$ is the number of collisions per event) for the case with only minijet gluons ($\mu = 4.5 fm^{-1}$). The solid curve is $\frac{dN}{ds}$ for minijet + soft gluons with $\mu = 7 fm^{-1}$.

For the case with both mini and soft gluons, a more detailed look at the time evolution of rapidity density of strangeness and gluons (see Fig. 4 for the result of 30 HIJING events ($\mu = 7 fm^{-1}, \Delta y = 1$)) shows that at central rapidity, they both increase with proper time. Before 4fms, we get a rapid increase of the strangeness content, but after 6fms, the gluon content rises slowly because of the formation of new particles and the scattering of old particles, but strangeness content freezes out, because the density is too low for the strangeness production process.

**Fig. 5** shows the strangeness production and annihilation rates. If chemical equilibrium can be achieved, the annihilation rate should equal the production rate at some time and then they evolve together till freezeout. This is not the case here. Before 5fm, the production rate is much higher than the annihilation rate. After 5fm, the energy momentum tensor in the local rest frame doesn’t have dominant diagonal elements indicating the system has already frozen out. The system can
not be considered thermal at this later stage of evolution.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{Fig4.png}
\caption{Time development of rapidity density of gluon and strangeness content per event.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{Fig5.png}
\caption{Strangeness production and annihilation rate as a function of time. The collisions are those with at least one produced particle in the central rapidity bin. Filled circles are for the $gg \rightarrow s\bar{s}$ and filled diamonds are for the $s\bar{s} \rightarrow gg$.}
\end{figure}
4. Conclusions

Both the strangeness gluon ratio and strangeness production and annihilation rates indicate that in Au-Au collisions at RHIC, chemical equilibrium is not achieved. Soft gluons play an important role in the strangeness production at RHIC as the minijet gluons and soft gluons together produce a strangeness to gluon ratio around 4 times larger than that produced by the minijet gluons alone.

At this stage, we don’t have inelastic scatterings, and in addition, hadronization may well modify the strangeness to gluon ratio, further investigations are necessary to address this issue.

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