Predictions for $J/\psi$ suppression by parton percolation

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Abstract. Parton percolation provides geometric deconfinement in the pre-equilibrium stage of nuclear collisions. The resulting parton condensate can lead to charmonium suppression. We formulate a local percolation condition viable for non-uniform collision environments and show that it correctly reproduces the suppression observed for S–U and Pb–Pb collisions at the SPS. Using this formulation, we then determine the behavior of $J/\psi$ suppression for In–In collisions at the SPS and for Au–Au collisions at RHIC.

1 Introduction

In recent years, the role of the partonic initial stages of high energy nuclear collisions has attracted increasing interest. While the ultimate aim of the experimental program is the production of the quark–gluon plasma predicted by statistical QCD, it is becoming more and more evident that a thermalized medium consisting of quarks and gluons can be produced only if already the initial state of the collision provides the conditions necessary for deconfinement and thermalization. Dilute initial state parton configurations do not lead to the color connection needed so that partons from different collisions can combine to form a collective medium. On the other hand, if the initial state of primary partons is sufficiently dense, cluster percolation will set in, leading to a condensate of connected and hence interacting partons, which are no longer associated to any “parent” hadrons. Thus parton percolation is a geometric, pre-equilibrium form of deconfinement [1,2]; it must occur in any description based on partons of an intrinsic transverse momentum.

Subsequent interactions can thermalize this interconnected partonic system, turning it into a quark–gluon plasma, so that parton percolation constitutes an essential prerequisite for QGP formation. Moreover, pre-equilibrium deconfinement leads to a further important question. Much of the investigation of high energy nuclear collisions is devoted to the search for quark–gluon plasma signatures. However, some of the features observed in nuclear interactions might be determined by the system present before any equilibration has occurred, and they could be independent of a subsequent thermalization. We must therefore investigate observable consequences of parton percolation, and if possible, show how they can be distinguished from those due to QGP formation.

One of the features of particular interest in this connection is the suppression of $J/\psi$ production in nuclear collisions, predicted as a deconfinement signal for thermal media quite some time ago [3]. If the parton condensate formed through percolation contains partons hard enough to resolve the produced charmonium states, these partons can also dissociate charmonia, so that the onset of $J/\psi$ suppression could coincide with that of parton percolation. It was shown in a first study [4] that for Pb–Pb collisions at the CERN-SPS as a function of centrality the resulting thresholds appear quite reasonable. A more quantitative comparison, which can then also provide the basis for further predictions, requires a formulation of percolation in a non-uniform environment, as given by the partonic source profile in nuclear collisions, and adapted to the local nature of charmonium probes. The aim of this paper is first to formulate percolation for such conditions, then to compare the results to existing SPS data (S–U and Pb–Pb), and finally to present the predictions of this approach for the forthcoming $J/\psi$ production experiments at CERN and BNL. All results are obtained by Monte Carlo simulations taking into account the centrality dependence of the collisions. In closing, we shall consider some features which could distinguish $J/\psi$ suppression by parton percolation from a suppression in a thermal medium.

2 Local parton percolation conditions

Consider a flat two-dimensional circular surface of radius $R$ (the transverse nuclear area), on which $N$ small discs of radius $r \ll R$ (the transverse partonic size) are randomly distributed, allowing overlap to occur. With increasing density $n = N/\pi R^2$, clusters of increasing size

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In high energy nuclear collisions, the incident partons are distributed on a plane transverse to the collision axis. However, since they originate from the nucleons within the colliding nuclei, this distribution is highly non-uniform, with more nucleons and hence more partons in the center than towards the edge of the transverse nuclear plane. If the basic surface is not flat, it is still possible to define the percolation threshold as the point at which the cluster size shows singular behavior in the limit of large $R$ and $N$ [2]. Such a global definition is, however, not always the most useful. Hard probes, such as quarkonia, probe the medium locally and thus test only if it has reached the percolation point and the resulting geometric confinement at their location; they cannot register the global features of the entire cluster area. It is thus necessary to define a more local percolation criterium, and this is in fact quite straightforward.

As mentioned, at the percolation point, $\exp\{-u_c\} \simeq 1/3$ of the surface remains empty. Hence the disc density in the percolating cluster must be greater than $(1.5u_c/\pi r^2)$. Numerical studies show that in fact percolation sets in when the density $m$ of constituents in the largest cluster reaches the critical value

$$m_c = \frac{\eta_c}{r^2},$$

with $\eta_c \simeq 1.72$, slightly larger than $1.5u_c$. This result provides the required local test: if the parton density at a certain point in the transverse nuclear collision plane has reached this level, the medium there belongs to a percolating cluster and hence to a deconfined parton condensate. In Fig. 1b, we illustrate how the percolating cluster grows as a function of the cluster filling factor $\eta = m(r/R)^2$, again with $r/R = 1/100$.

Let us recapitulate: there are two equivalent criteria which can be used to specify the onset of percolation. In the “global” definition, it occurs when the total number of partons distributed over the entire transverse nuclear area reaches $1.13/\pi r^2$. In the “local” definition, percolation sets in when the parton density in the largest cluster reaches $1.72/\pi r^2$. Which of the two is preferable in a given case depends on the physics question addressed, and if we want to study local phenomena such as $J/\psi$ suppression, it is clearly the local parton density which is relevant, not the average over the entire transverse area.

We now turn to the implications of the approach to nuclear collisions [4]; for illustration, we concentrate for the moment on central $A–A$ interactions at a CMS energy $\sqrt{s}$ per nucleon–nucleon collision. The distribution of nucleons in the colliding nuclei is specified by a Glauber calculation using Woods–Saxon nuclear distributions [5]; this provides the density $n_s(A)$ of nucleons in the transverse collision plane. The parton content of a nucleon is given by parton distribution functions $dN_q(x, Q^2)/dy$ determined in deep inelastic scattering experiments; here $x$ denotes the fraction of the nucleon momentum carried by the parton and $Q$ the momentum resolution scale. At central CMS rapidity $y = 0$, we have $x = k_T/\sqrt{s}$, where $k_T$ denotes the average transverse momentum of the parton. In nuclear collisions, $k_T$ defines the transverse size of the partons and thus also sets the resolution scale, $k_T \simeq Q$. Using these quantities, we have for the “global” percolation condition in nuclear collisions

$$n_s(A) \left( \frac{dN_q(x, Q^2)}{dy} \right)_{x = Q_c/\sqrt{s}} = \frac{u_c}{(\pi Q_c^2)};$$

where $u_c \simeq 1.13$ of the “filling factor” $\nu = n(r/R)^2$ is determined by numerical studies. For finite $N$ and $R$, percolation sets in when the largest cluster spans the entire circular surface from the center to the edge. The resulting cluster growth is illustrated in Fig. 1a for a ratio $r/R = 1/100$; we show the percolation probability, defined as the relative size of the largest cluster, as a function of the filling factor $\nu$. Because of overlap, a considerable fraction of the surface is still empty at the percolation point; in fact, at that threshold, only $1 - \exp\{-u_c\} \simeq 2/3$ of the surface is covered by discs.

![Cluster growth and corresponding derivative as a function of the overall filling factor $\nu$ a and of the cluster filling factor $\eta$ b](image)