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Percolation approach to quark-gluon plasma in high-energy pp collisions

J. Dias de Deus and A. Rodrigues*
CENTRA and Departamento de Física (IST), Avenida Rovisco Pais, 1049-001 Lisboa, Portugal

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We apply continuum percolation to proton-proton collisions and look for the possible threshold to phase transition from confined nuclear matter to quark-gluon plasma. Making the assumption that J/ψ suppression is a good signal to the transition, we discuss this phenomenon for pp collisions, in the framework of a dual model with strings.

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In recent years, high-energy heavy ion collision experiments have been trying to collect information on the possible existence of the plasma of quarks and gluon (QGP). One of the strategies has been to look for differences in particle production between high density central heavy ion collisions, and low density ion collisions, nucleon-nucleus collisions, and nucleon-nucleon collisions. At the CENR/SPS ($\sqrt{s} \approx 19$ GeV), and now at Brookhaven/RHIC ($\sqrt{s} \approx 130$–200 GeV), several important general results have been obtained.

The charged particle density was found to increases with energy and the number of participating nucleons. The average transverse momentum also increases with energy and particle density, $\langle p_T \rangle$ increases as well with the mass of the produced particle. Strangeness increases with energy and particle density [1]. All these results, naturally excluding the dependence on the number of participants, are qualitatively similar to results obtained in nucleon-nucleon and nucleon-nucleus collisions [2]. None of them, separately, can then be taken as clear evidence for the formation of the QGP.

On the other hand, the anomalous suppression of the ratio J/ψ over Drell-Yan production [3], at a large associated transverse energy E_T, has been widely accepted as a good signal for QGP formation [4]. In fact, no such effect was seen in lower density nucleus-nucleus, nucleon-nucleus, or nucleon-nucleon collisions.

In this paper, we shall argue that if the J/ψ suppression has its origin in the creation of an extended color conducting region, as in percolation, the same kind of suppression should occur even in nucleon-nucleon (pp or $p\bar{p}$) collisions at high enough energy.

We shall work here in the framework of multicollision models, namely, the dual parton model (DPM) [5], but try to be as general as possible. The basic ideas are the following: (1) nucleus-nucleus collisions can be built, in a nontrivial manner, from nucleon-nucleon collisions; (2) nucleon-nucleon collisions occur with formation of intermediate strings, 2 valence strings and $2k$ sea strings intermediate strings, $k \geqslant 0$ being a function of energy; and (3) sea strings may fuse and percolate [6], a process destroying naive additivity of elementary collisions.

The key parameter in transverse plane string percolation is the dimensionless transverse density η, with

$$\eta = \frac{r_s^2}{R^2} N_s , \tag{1}$$

where r is the transverse radius of the string (we shall take $r = 0.2$ fm), R the radius of the interaction area, and N_s the number of strings. Percolation occurs, in the $R \to \infty$, $N_s \to \infty$ limit, for $\eta \geqslant \eta_c \approx 1.15$.

As fusion and percolation of strings also occur in nucleon-nucleon collisions it is clear that the J/ψ over Drell-Yan (DY) ratio will be strongly affected as η approaches η_c. In the $pp(p\bar{p})$ case (1) becomes

$$\eta = \left(\frac{r_s}{R_p} \right)^2 2k, \tag{2}$$

where R_p is the effective proton radius. As the observed increase of particle densities with energy is mostly due to the increase in the number of formed strings, k is also an increasing function of energy. Thus η may reach η_c and become larger than η_c. This implies anomalous J/ψ suppression.

Following previous work [6,7], we treat fusion and percolation of strings as a two dimensional continuum percolation problem [8]. We performed computer simulation by throwing N disks (of radius 0.2 fm) into a uniform region (of radius of order of the radius of the proton, 1 fm) and counting the fraction of events $f(\eta)$ with percolation. In the $R \to \infty$, $N \to \infty$ limit $f(\eta)$ becomes a step function with a sharp change at $\eta = \eta_c$. As r/R is not so small, finite size effects are important, affecting mostly the slope (a) of the function at η_c, but the value of η_c itself. The computer simulation results were fitted by the function

$$f(\eta) = (1 + e^{-(\eta - \eta_c)/a})^{-1} \tag{3}$$

and the following values were found for the parameters: $a = 0.1666 \pm 0.0067$ and $\eta_c = 1.3584 \pm 0.0116$ (see Fig. 1)

Assuming now, as in Ref. [7], that the J/ψ production is prevented in a plasma of color charges [4] and that such a situation corresponds to percolation and creation of a large conducting area [6] we obtain for the J/ψ over Drell-Yan ratio,

$$R(\eta) = K[1 - f(\eta)] = K[e^{(\eta - \eta_c)/a} + 1]^{-1}, \tag{4}$$

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*Also at Escola Secundária da Ramada, Portugal.

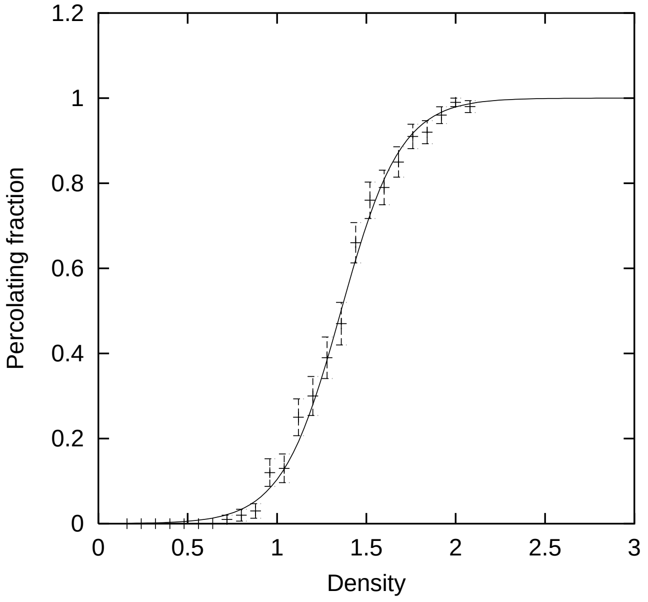

FIG. 1. Percolation probability as a function of the transverse dimensionless density η for pp collisions geometry. The curve shows the fit with Eq. (3). We obtain $a=0.1666\pm0.0067$ and $\eta_c=1.3584\pm0.0116$.

where $K\approx55$ [9] is the value of the ratio at moderate energy.

The problem now is simply the problem of relating η to $\sqrt{s}$, Eq. (2). In other words, we need to obtain a reasonable estimate for the energy dependence of k. This is what we shall attempt now.

If in nucleus-nucleus collisions $\langle\nu\rangle$ is the average number of nucleon-nucleon collisions and $2k$ is the number of strings per nucleon-nucleon collision, the average number of strings N_s is given by

$$N_s=\langle\nu\rangle 2k. \tag{5}$$

In nucleon-nucleon collisions $\langle\nu\rangle=1$ and $N_s=2k$. From Eqs. (1) and (5) the condition for the percolation transition, in the case of $r/R\ll1$, is

$$\eta=\eta_c=\left(\frac{r}{R}\right)^2\langle\nu\rangle 2k\approx1.15. \tag{6}$$

By interpreting the NA50 anomalous J/ψ suppression at $\sqrt{s}\approx19$ GeV as the result of percolation, one can try to estimate the number of formed strings in nucleon-nucleon collisions. The basic information is that anomalous suppression is absent in S-U central collisions, but it is present in Pb-Pb central collisions [3]. This means, $\eta_{\text{S-U}}<1.15$ and $\eta_{\text{Pb-Pb}}>1.15$.

At relatively low energy, it is known, from NA49 and WA98, SPS experiments, that the number of nucleon-nucleon collisions in central nucleus-nucleus collisions is, roughly (see, for instance, Ref. [11]),

$$\langle\nu\rangle\simeq1.5\frac{N_p}{2}, \tag{7}$$

where N_p is the number of participants in a central $AB, A\leqslant B$, collision,

$$N_p\simeq A^{2/3}(A^{1/3}+B^{1/3}). \tag{8}$$

On the other hand,

$$R\simeq A^{1/3}\ \text{fm}. \tag{9}$$

By using Eqs. (7)–(9) in Eq. (6) we obtain, from S-U,

$$k(\sqrt{s}\simeq19)\lesssim1.7, \tag{10}$$

and, from Pb-Pb,

$$k(\sqrt{s}\simeq19)\gtrsim1.6. \tag{11}$$

As we are not so confident of these estimates we shall include an error of the order of 15% and study the ratio J/ψ over DY in the range

$$1.4\lesssim k(\sqrt{s}\simeq19)\lesssim1.9. \tag{12}$$

If we look now at the charged particle densities in $pp(\overline{pp})$ collisions, in the spirit of DPM, we have that particles are emitted from two kinds of strings: valence strings (V), always 2 from valence quark interactions and shorter sea strings (S), from sea parton interactions, in a number growing with energy, $2k$. The central charged particle density is written as (see, for instance, Refs. [10,11]),

$$\left.\frac{dN}{dy}\right|_{pp}=2\left.\frac{dN}{dy}\right|_V+2k\left.\frac{dN}{dy}\right|_S. \tag{13}$$

On the right-hand side of Eq. (13) we have both contributions, from V and S strings.

We assume that $dN/dy|_V$ and $dN/dy|_S$ are constant (“Feynman scaling”) and that the observed rise of the plateau is determined by the increase in the number of strings, i.e., by increase of k. In the low energy limit, $k\rightarrow1$, we thus have Feynman scaling with, from data [11,12],

$$\left.\frac{dN}{dy}\right|_{pp}\underset{k\rightarrow0}{\rightarrow}2\left.\frac{dN}{dy}\right|_V\simeq1.43\pm0.05. \tag{14}$$

In order to determine the energy dependence of k we do the following. Solve Eq. (13) for k,

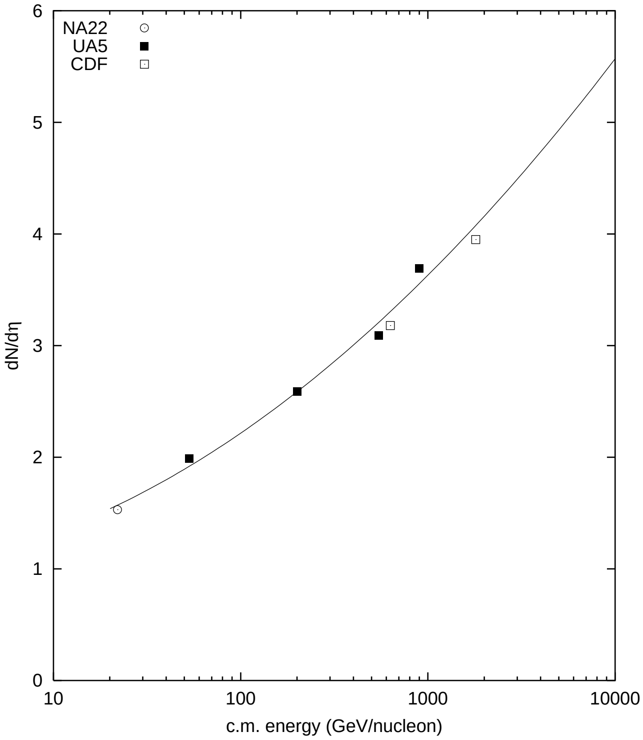

FIG. 2. Pseudorapidity density as a function of c.m. energy. The solid line represents parametrization used to fit the data.

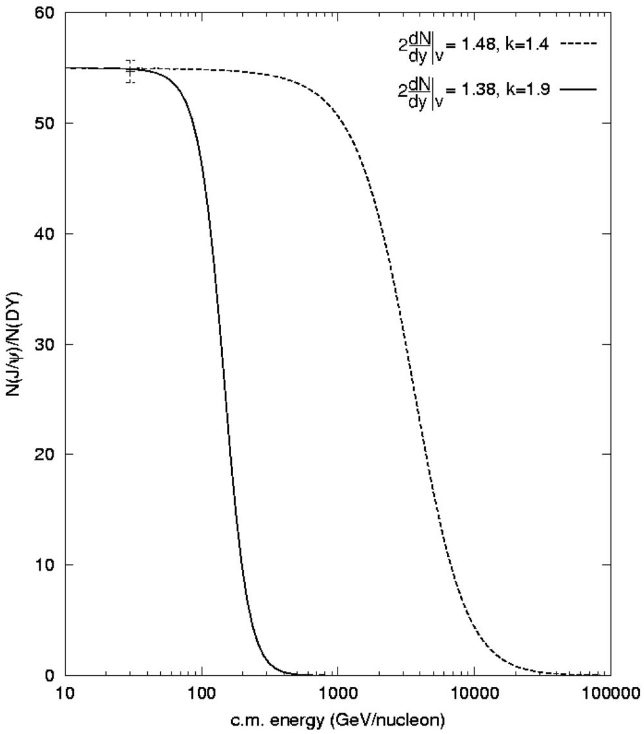

FIG. 3. The ratio of J/ψ to Drell-Yan events as a function of c.m. energy in pp collisions.

$$k = \frac{\left.\frac{dN}{dy}\right|_{pp} - 2\left.\frac{dN}{dy}\right|_V}{2\left.\frac{dN}{dy}\right|_S} \tag{15}$$

with $dN/dy|_V$ fixed by Eq. (14) and using for $dN/dy|_{pp}$ a parametrization to the $pp(p\bar{p})$ data [11],

$$\left.\frac{dN}{dy}\right|_{pp} = 0.957 + 0.0458 \ln\sqrt{s} + 0.0494 \ln^2\sqrt{s}. \tag{16}$$

The fit to $dN/dy|_{pp}$ high-energy data for $\sqrt{s} \geqslant 20$ GeV is shown in Fig. 2. For each of the two limiting values of $k(\sqrt{s} \approx 19)$, combined with the limiting values of $dN/dy|_V$ 14, we adjust the constant $dN/dy|_S$ to obtain agreement with Eq. (12). The energy dependence of k is then fully determined by Eq. (15).

In Fig. 3 we present the $\sqrt{s}$ dependence of J/ψ over DY ratio, Eqs. (4) and (2), for the two limiting values of k. In conclusion, we expect a fast drop of J/ψ over DY ratio in $pp(p\bar{p})$ collisions in the energy range $200 \lesssim \sqrt{s} \lesssim 2000$ GeV/nucleon. These are energies of RIHC, Tevatron, and LHC.

Our work can be criticized from several different points of view.

(1) The J/ψ over DY ratio is also affected by internal absorption and, as the number of strings increases with energy, absorption makes the ratio continuously decrease with energy. This effect was not included, but it should be less dramatic then percolation.

(2) As charm production probability increases with energy the J/ψ over DY ratio should have a tendency to increase with energy. This correction was also not included. One should, perhaps, in future consider the ratio J/ψ over $c\bar{c}$ production as the reference quantity.

(3) As in $pp(p\bar{p})$ collisions the interaction radius increases with energy and $\eta \sim 1/R^2$, the percolation transition taking into account this effect, will tend to occur at higher values of energy.

(4) The model is a purely soft model and hard effects related to the increase of $\langle p_T \rangle$ and changes in multiplicities were not included. These effects can be accounted for with fusion of strings, but were not considered here. They are being studied now.

(5) Nonuniform distributions in impact parameter (such as Gaussian distributions) give rise to an increase of η_c (see last paper in Ref. [6]), and consequently the percolation transition will tend to be displaced to higher energy.

(6) One may question the validity of continuum percolation arguments when the ratio r/R is so large, $r/R \simeq 1/5$. Technically there is no problem, but we are not sure of the validity of the treatment.

While finishing this paper we became aware of the work of Alexopoulos *et al.* [13] dealing with evidence for deconfinement at Tevatron ($\sqrt{s} = 1.8$ TeV).

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