

Percolation Approach to Quark-Gluon Plasma and J/ψ Suppression

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It is shown that the critical threshold for percolation of the overlapping strings exchanged in heavy ion collisions can naturally explain the sharp strong suppression of J/ψ shown by the experimental data on central Pb-Pb collisions, which does not occur in central O-U and S-U collisions. [S0031-9007(96)01526-8]

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The NA50 Collaboration [1] has reported a strong suppression of J/ψ production in Pb-Pb central collisions at 158 AGeV/ c . The suppression is much stronger than the expected one due to J/ψ absorption corresponding to a cross section of 6.3 mb, by which the NA38 data for O-U and S-U central collisions [2,3] and the hadron-nucleus data can be explained. The NA50 data show a clear deviation from the previous situation [4]. The J/ψ suppression in peripheral Pb-Pb collisions is similar to the one corresponding to central S-U collisions, but a sharp enhancement occurs as the centrality of the Pb-Pb collisions increases.

In this paper we draw attention to the fact that the continuum percolation of color strings can naturally describe the sharp difference in the J/ψ suppression at present energies between O-U, S-U, and peripheral Pb-Pb collisions on the one side and central Pb-Pb collisions on the other side. Predictions for relativistic heavy-ion collisions (RHIC) and Large Hadron Colliders (LHC) energies are given. The idea of applying a percolation approach to strongly interacting matter is not a new one. In fact, it was suggested already many years ago [5,6].

The continuum percolation of color strings takes place when the density of strings rises above a threshold, which can be calculated on geometrical grounds. In this picture, the region where several strings fuse can be considered a droplet of a nonthermalized quark gluon plasma, in which the J/ψ is suppressed as predicted by Matsui and Satz [7]. Percolation means that these droplets overlap and the quark gluon plasma domain becomes comparable to the nuclear size.

In many models of hadronic collisions [8–13], color strings are exchanged between projectile and target. The number of strings grows with the energy and with the number of nucleons of the participant nuclei. When the density of strings becomes high, the string color fields begin to overlap and eventually individual strings may fuse [14–18], forming a new string which has a higher color charge at its ends, corresponding to the summation of the color charges located at the ends of the original strings. The new strings break into hadrons according to their higher color. As a result, heavy flavor is produced more efficiently, and there is a reduction of the total multiplicity

[15]. Also, as the energy-momenta of the original strings are summed to obtain the energy-momentum of the resulting string, the fragmentation of the latter can produce some particles outside the kinematical limits of nucleon-nucleon collisions if the original strings come from different nucleons [19,20]. The fusion of strings has been incorporated in several Monte Carlo codes. In particular, in the quark gluon string model (QGSM) it is assumed that strings fuse when their transverse positions come within a certain interaction area a [15]. The value of a is determined to reproduce $\bar{\Lambda}$ rapidity distributions in S-S and S-Ag central collisions at $p_{\text{lab}} = 200$ GeV/ c and in Pb-Pb central collisions at $p_{\text{lab}} = 158$ GeV/ c .

Cascade reactions like $\pi^+\bar{p} \rightarrow K^0\bar{\Lambda}$, $\pi^0\bar{n} \rightarrow K^0\bar{\Lambda}$, $\pi^+\bar{\Lambda} \rightarrow K^+\bar{p}$, and $p\bar{\Lambda} \rightarrow \pi^+\bar{K}^0$ also contribute to the $\bar{\Lambda}$ rapidity distribution but their effects are smaller than the ones due to string fusion, generating uncertainties in the value of a of around 10%. From the value of a , the radius r of the transverse dimension of the string can be obtained, $a = 2\pi r^2$ [21]. In our code only fusion of two strings is considered, so the obtained r value, $r = 0.36$ fm, is an effective one, somewhat larger than the real transverse radius of the string. Denoting by N_j the number of strings which fuse into j -fold strings and N'_2 and r_{eff} the number of all fused strings and the effective transverse size of the string, respectively, we will have

$$2N'_2\pi r_{\text{eff}}^2 = \sum_{j=2} N_j j \pi r^2, \quad (1)$$

$$N'_2 = \sum_{j=2} N_j. \quad (2)$$

The upper limit of the sum in (1) is determined by the constraint (2). The values of N'_2 and r_{eff}^2 were fixed in our calculation by comparing the results of the string fusion model with the experimental data on $\bar{\Lambda}$ production in central S-S collisions at $\sqrt{s} = 19.4$ AGeV. Computing N_j in our Monte Carlo code we obtain from (1) the value $r = 0.2$ fm both for Pb-Pb and S-Ag collisions.

In nucleus-nucleus collisions many strings are exchanged. In impact parameter space these strings are seen as circles inside the total collision area. As the number of strings increases, more strings overlap. Several fused

strings can be considered as a domain of a nonthermalized quark gluon plasma. Following the arguments of Matsui and Satz [7] the J/ψ cannot be formed inside this domain. Also, the J/ψ will be destroyed by interaction with these fused strings. Above a critical density of strings percolation occurs, so that paths of overlapping circles are formed through the whole collision area. Along these paths the medium behaves like a color conductor. The percolation gives rise to the formation of quark gluon plasma on a nuclear scale. The phenomenon of continuum percolation is well known [22]. It explains hopping conduction in doped semiconductors and other important physical processes [23]. The percolation threshold η_c is related to the critical density of circles n_c by the expression

$$\eta_c = \pi r^2 n_c. \quad (3)$$

η_c has been computed using Monte Carlo simulation, direct-connectedness expansion and other different methods. All the results are in the range $\eta_c = 1.12-1.175$ [24–28]. Taking the above-mentioned value of r , these values imply

$$n_c = 8.9-9.3 \text{ strings/fm}^2. \quad (4)$$

One may introduce a hard core to model a repulsive interaction between the circles, or to substitute circles by squares. The percolation threshold η_c is only slightly reduced in these cases. This enhances the confidence in its value and the application to our case where we do not know the dynamics of the interaction among strings.

In Table I the number of strings exchanged for central p - p , S-S, S-U, and Pb-Pb collisions is shown together with their densities. It is seen that at Super Proton Synchrotron (SPS) energies only the density reached in central Pb-Pb collisions is above the critical density. In Pb-Pb minimum bias collisions the average number of strings at SPS energies is 227, very similar to the value for central S-U collisions, so the density is lower than the critical one.

The J/ψ suppression experimentally observed follows the same pattern. The strong suppression is only observed in central Pb-Pb collisions. According to Table I, a strong J/ψ suppression is also expected in S-U collisions at RHIC energies and in S-S and S-U collisions at LHC energies.

Recently [29] it has been assumed that the produced J/ψ is completely destroyed whenever the energy density ex-

ceeds a certain value and this energy density is taken proportional to the density of participants. The critical value is chosen to lie between the density of participants of central S-U collisions and Pb-Pb collisions. With this choice a good description of the experimental data is obtained. In our model the density of strings is proportional to the number of collisions, and we obtain similar quantitative results. However, in our approach the critical value is naturally explained on geometrical grounds.

In Fig. 1 the distribution of strings fusing into sets of a given number of fused strings is shown for central S-U collisions at $\sqrt{s} = 19.4$ AGeV and $\sqrt{s} = 200$ AGeV and also for central Pb-Pb collisions at $\sqrt{s} = 19.4$ AGeV. The first case is below and the second above the percolation threshold. It is seen that above the percolation threshold we can obtain many sets with a very high number of fused strings.

Referring to ψ' suppression the experimental data reveal the following features [1,30–32]:

- (1) The ratio ψ'/ψ is constant in p - A collisions.
- (2) ψ'/ψ decreases with centrality in S-U collisions. The decrease seems to stop at high centrality.
- (3) ψ'/ψ is almost the same in central Pb-Pb and S-U collisions.

There are several explanations for the two first features [2,33–36]. The equal absorption of J/ψ and ψ' in p - A collisions can be understood in terms of the breakup of a preresonance charmonium interaction with the nucleons of the nucleus [2,36] considering an absorption cross section

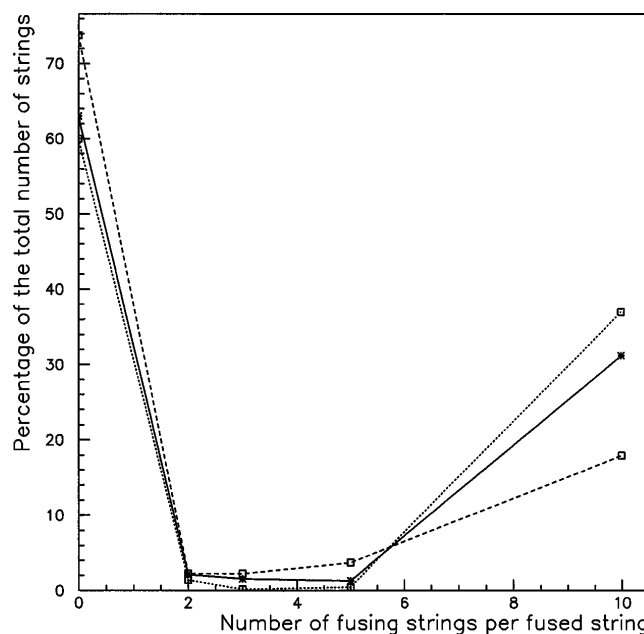


FIG. 1. Percentage of the total number of strings exchanged in the collision which goes into sets of a given number of fused strings, for central S-U collisions at $\sqrt{s} = 19.4$ AGeV (dashed line) and $\sqrt{s} = 200$ AGeV (solid line) and for central Pb-Pb collisions at $\sqrt{s} = 19.4$ AGeV (dotted line). The number 10 in the horizontal axis indicates sets of 10 or more strings.

TABLE I. Number of strings (upper numbers) and their densities (fm^{-2}) (lower numbers) in central p - p , S-S, S-U, and Pb-Pb, collisions at SPS, RHIC, and LHC energies.

\sqrt{s} (AGeV)	Collisions			
	p - p	S-S	S-U	Pb-Pb
19.4	4.2	123	268	1145
	1.3	3.5	7.6	9.5
200	7.2	215	382	1703
	1.6	6.1	10.9	14.4
5500	13.1	380	645	3071
	2.0	10.9	18.3	25.6

value around 6 mb. The interaction of J/ψ and ψ' with the comovers assuming different cross sections explains the behavior of the ratio ψ'/ψ in S-U collisions. In our picture this behavior can be explained by noting that in S-U central collisions the average distance between strings is the order of 0.4 fm, larger than the size of J/ψ (0.2 fm) but less than the size of the ψ' . Therefore one expects that ψ' interacts with the strings or with the particles produced by the strings with greater probability than J/ψ . For central Pb-Pb collisions, with the density above the critical percolation threshold, no additional suppression of ψ' relative to J/ψ is expected, in agreement with the data.

Also it is possible that the percolation process takes place among the produced resonances and particles instead of strings [37]. The two cases can be distinguished by studying the behavior of long range correlations and measuring forward-backward correlations [38].

The percolation of strings can be considered as a smooth way to quark gluon plasma. Around percolation threshold, strong fluctuations in the number of strings with a given color should appear. This will produce large fluctuations in a number of different observables, like strangeness, in an event by event analysis. Also a large number of Ω^- (confirmed by the experimental data [39]) and a copious production of hadronic particles with $|x_F|$ much larger than 1, outside the kinematical nucleon-nucleon limits, may serve as clear signatures. The latter would also distinguish our picture from the percolation of resonances and particles.

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