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PRODUCTION OF J/ψ IN QUARK-GLUON PLASMA *

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ABSTRACT

It was recently proposed by T. Matsui and H. Satz that J/ψ suppression in nuclear collisions will provide an unambiguous signature for the formation of quark-gluon plasma. In this paper, we will discuss the present status of this proposal and make a few remarks about it.

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I. INTRODUCTION

In the past, existence of a new form of matter had been suggested by many different authors [1] i.e. the quark-gluon plasma (QGP). The main goal for colliding large nuclei at high energy is to form this new form of matter. From relativistic heavy ion programs at CERN-SPS and BNL-AGS a flow of data are already coming. At present, it is a very challenging task to analyze such a wealth of data and study the new physics taking place under the extreme conditions provided by these most violent nuclear collisions. Most important of all is to find a clean experimental signature for the formation of quark-gluon plasma. The experimental signatures for the plasma formation proposed so far include [2] real or virtual photons, dilepton production, the relative production rate of strange particles and the p_T distribution of secondary hadrons.

Recently, a new experimental signature was proposed by Matsui and Satz [3]. According to them, a strong and systematic suppression of the heavy quark bound states formation in nuclear collisions may provide a clear signature of quark-gluon plasma formation. Their argument goes as as follows: the dominant mechanism for producing $c\bar{c}$ pairs is hard parton-parton interaction. The production of J/ψ's takes place through resonant interaction of the $c\bar{c}$ system. If, however, the $c\bar{c}$ production occurs in a nuclear collision, and if such collisions result in a quark-gluon plasma, then the produced $c\bar{c}$ finds itself in a deconfining environment. Provided the Debye screening radius $r_D(T)$ is smaller than the binding radius $r_{J/\psi}(T)$ of J/ψ - then the resonance interaction cannot become operative and J/ψ production will be prohibited.

In the next section, we will mention a few known properties of J/ψ and the values of parameters important for our anlysis. In Section III we will discuss the formation of $c\bar{c}$ pair in quark-gluon plasma. In Section IV we will conclude and make some remarks.

II. PRESENT STATUS

The lowest-lying state of psions called ψ or J/ψ, was first observed simultaneously in 1974 in experiments at SLAC [4] and Brookhaven AGS [5]. Since then the following properties of J/ψ have been well established:

$I^G J^P C_n$	Mass (MeV)	Full Width (MeV)	Branching Ratio
J/ψ $0^-(1^-)-$	3096.9 ± 0.1	0.063 ± 0.009	e^+e^- 7.4 ± 1.2%
			$\mu^+\mu^-$ 7.4 ± 1.2%
			Hadrons+Any 85 ± 2%

the bound state of two heavy quarks can successfully be described with the help of Schrödinger's equation and a potential of Coulomb-plus-linear form [6]

$$V(r) = -\frac{\alpha_{eff}}{r} + \sigma r \tag{1}$$

where $\alpha_{eff} = \frac{4}{3}\alpha_s$ and σ is the string tension. For our analysis, important parameters are α_{eff}, σ, mass of the charm quark m_c and mean square radius of $c\bar{c}$ s-state. In the following we give two sets of values for the above parameters obtained by Quigg and Rosner [6] and the Cornell group [7].

Set I: (Quigg and Rosner)

$$\begin{aligned} \alpha_s &= 0.38, \quad \alpha_{eff} = 0.507 \\ \sigma &= 0.17\ \text{GeV}^2, \quad m_c = 1.37\ \text{GeV} \\ \sqrt{\langle r^2 \rangle} &= 0.394\text{fm} \end{aligned} \tag{2}$$

Set II: (Cornell Group)

$$\begin{aligned} \alpha_s &= 0.39, \quad \alpha_{eff} = 0.52 \\ \sigma &= 0.18\ \text{GeV}^2, \quad m_c = 1.84\ \text{GeV} \\ \sqrt{\langle r^2 \rangle} &= 0.47\text{fm} \end{aligned} \tag{3}$$

By using the uncertaintly principle, one can evaluate the formation time τ_f for J/ψ.

$$\tau_f^I \propto \frac{1}{2m_c} = 0.07\text{fm/c}$$

$$\tau_f^{II} \propto \frac{1}{2m_c} = 0.05\text{fm/c} \tag{4}$$

where I and II in the superscripts refer to the set of values I and II. One can also use the Bohr model to estimate the formation time τ_f for J/ψ

$$\tau_f = \frac{\pi \langle r^2 \rangle m_c}{n} \tag{5}$$

where 'n' is the principal quantum number. For $n = 1$, with the help of (2), (3) and (5), one gets

$$\begin{aligned} \tau_f^I &= 3.4\text{fm/c} \\ \tau_f^{II} &= 6.4\text{fm/c} \end{aligned} \tag{6}$$

III. J/ψ AND QGP

The potential given in Eq.(1) is for $T = 0$. Imagine now that this $c\bar{c}$ is created in the deconfined phase of hadronic matter i.e. QGP. It means T is greater than some critical temperature T_c. In such a deconfining environment, the string tension σ will vanish and the Coulombic part of the $c\bar{c}$ potential will be modified by the plasma screening effect and become short ranged [8]

$$V(r) = -\frac{\alpha'_{eff}}{r} \exp\left(-\frac{r}{r_D}\right) \tag{7}$$

where α_{eff} is replaced by α'_{eff} [9], because of the fact

$$\alpha_s(T) = \frac{g^2}{4\pi} = \frac{6\pi}{(11N_c - 2N_f)\log\left(\frac{4T}{\Lambda_T}\right)} \tag{8}$$

where 'g' is the colour charge, N_c and N_f are the number of colours and flavours present in the plasma respectively. The Debye screening radius r_D in Eq.(7) can be written as [9]

$$r_D^{-1} = 0.38\, C(N_c, N_f)\, \beta^{-1}\left(\frac{g^2}{4\pi}\right)^{1/2} \tag{9}$$

where

$$\beta^{-1} = T \quad \text{and} \quad C(N_c, N_f) = \frac{(2N_c + N_f)^{3/2}(N_c^2 - 1)}{3N_cN_f + 2N_c^2 - 2} \ .$$

Therefore, Eq.(9) determines the behaviour of Debye screening radius r_D with respect to T. At this point, one should note that in the potential of Eq.(7) there is no linear confining part, but sill $c\bar{c}$ bound state can exist as a Coulomb bound state. To find that out we write the Hamiltonian

$$H = 2m_c - \frac{1}{m_c} \nabla^2 + V(r) \tag{10}$$

In the semi-classical approximation one can write [10)]

$$E(r) = 2m_c + \frac{1}{2m_c r^2} + V(r) \tag{11}$$

To find the lowest state, we minimize E(r) and obtain

$$x(x + 1) \exp(-x) = (m_c\, \alpha'_{eff}\, r_D)^{-1} \tag{12}$$

In Eq.(11) we have used the potential given in Eq.(7) and also $x \equiv \frac{r}{r_D}$. There is still one more inequality one can get by using the fact that if E(r) is minimum then $\frac{\partial^2 E}{\partial r^2} > 0$, which gives

$$x(x^2 + 2x + 2) \exp(-x) > 3(m_c\, r_D\, \alpha'_{eff})^{-1} \tag{13}$$

Eq.(12) has a solution if $(m_c\, \alpha'_{eff}\, r_D)^{-1} \leqslant 0.84$, so that

$$r_D^{min} = [0.84\, m_c\, \alpha'_{eff}]^{-1} \tag{14}$$

is the smallest value of the screening radius still permitting a Coulombic bound state.

IV. CONCLUSIONS

The lifetime of the plasma without taking into account the transverse expansion range from 4 to 64 fm/c [11)]. These numbers are obtained by using Bjorken's model [12)], the inclusion of transverse expansion would perhaps shorten the upper limit by a factor of 2 [13)]. At this point, we will make the final remark. An important characteristic of psions lying below the $2M_D$ ($\sim$ 3.73 GeV, where M_D is the mass of a D-meson) limit is the narrowness of their total decay width i.e. of the order of a few hundred keV. This implies a lifetime of a typical psion, lying below $2M_D$ limit, of the order 10^5fm/c. This narrowness of decay width of psions can be well understood on the basis of OZI (Okubo-Zweig-Iizuka) rule. Another important point is the direct production cross section of J/ψ, which requires the fusion of three gluons, is much less than that obtained via production of the intermediate state χ. This fact is supported by the experiments and also explain the small observed ratio of ψ' production relative to J/ψ production i.e. $\sim$ 2% [14)]. Therefore, if the main mechanism for the production of J/ψ is via an intermediate state χ, then it will be produced 10^5fm/c after the formation of χ, by that time the nucleus-nucleus collision is over. So, is it sensible to talk about J/ψ as the formation signal for the quark-gluon plasma?

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