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A Novel Mechanism for J/ψ Disintegration in Relativistic Heavy Ion Collisions

ABHISHEK ATREYA, PARTHA BAGCHI* and AJIT M SRIVASTAVA

Institute of Physics, Sachivalaya Marg, Bhubaneswar 751 005, *India*

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In this paper we discuss the possibility of J/ψ disintegration due to the $Z(3)$ domain walls that are expected to form in QGP medium. These domain walls give rise to localised color electric field which disintegrates J/ψ, on interaction, by changing the color composition and simultaneously exciting it to higher states of $c\bar{c}$ system.

Key Words : Domain Wall; QCD; Topological Defect; SUSY Models; CP Violation

Introduction

The ongoing relativistic heavy ion collision experiments at RHIC (BNL) and LHC (CERN) have provided very valuable insights in understanding certain aspects of QCD. One such aspect is the existence of a new phase of matter known as quark-gluon plasma (QGP). QGP is essentially the deconfined phase of QCD, where free quarks and gluons exist in thermal equilibrium. Matsui and Satz (Matsuia and Satz, 1986) proposed that due to the presence of this medium, potential between $q\bar{q}$ is Debye screened, resulting in the swelling of quarkonia. If the Debye screening length of the medium is less than the radius of quarkonia, then $q\bar{q}$ may not form bound states. This is the conventional mechanism of quarkonia disintegration. Due to this melting, the yield of quarkonia will be *suppressed*. This was proposed as a signature and has been observed experimentally (Matsui and Satz, 1986; Abreu *et al*., 2000). However, there are other factors too that can lead to the suppression of J/ψ because of which it has not been possible to use J/ψ suppression as a clean signal for QGP.

In this paper, we propose a novel mechanism of quarkonia disintegration via QCD $Z(3)$ domain walls. These walls appear as topological defects due to spontaneous breaking of $Z(3)$ symmetry in QGP (Bhattacharya *et al*., 1992; West *et al*., 1997; Boorstein and Kutasov, 1995). The thermal expectation value of Wilson loop (Polyakov loop) acts as the order parameter for $Z(3)$ symmetry breaking phase transition

*Author for Correspondence : E-mail: partha@iopb.res.in

(Polyakov, 1978; McLerran and Svetitsky, 1981). RHIC and LHC experiments, hence, provide us with first ever opportunity to study these defects in lab. The formation and evolution of these walls have been discussed in context of RHIC experiments (Gupta *et al.*, 2010: Gupta *et al.*, 2012). In case of early universe, these $Z(3)$ walls can lead to baryon inhomogeneity generation (Layek *et al.*, 2006). *Generalised* $Z(N)$ interfaces can also lead to spontaneous CP violation in SM, MSSM and SUSY models, which, in turn, can lead to baryogenesis in early universe (Altes and Watson, 1995). A detailed quantitative analysis of this spontaneous CP violation was done in (Atreya *et al.*, 2012), in the context of confinement-deconfinement phase transition of QCD. There, the background A_0 profile was calculated from the profile of Polyakov loop, $l(x)$, across the $Z(3)$ interface. It was shown that the quarks have significantly different reflection coefficients than anti-quarks and the effect is stronger for heavier quarks. In this paper, we discuss the effect of this spontaneous CP violation on the mesons, in particular, the J/ψ meson. J/ψ are produced in the initial stages of relativistic heavy ion collisions. As these are heavy mesons $(m \sim 3GeV)$, they are never in equilibrium with the QGP medium ($T \sim 300$MeV at RHIC). However,there are finite T effects (like Debye screening etc.) affecting its motion in a thermal bath. We ignore them initially and comment on it towards the end. Note that if the Debye length is larger, then the conventional mechanism of J/ψ melting does not work. As we will argue, for large Debye screening, our mechanism of J/ψ disintegration works better as any possible screening of the domain wall over the relevant length scale of J/ψ will be small. If a domain wall is present in the QGP, then a J/ψ moving through the medium will interact with it. Due to the CP violating effect of the interface on quark scattering, c and $\bar{c}$ in J/ψ experience different color forces depending on the color of the quark and color composition of the wall. This not only changes the color composition of $c\bar{c}$ bound state but also facilitates it's transition to higher excited states (for example χ states). As these states have large sizes, they will dissociate in the QGP medium.

Interaction of J/ψ with a Z(3) Wall

In our model, J/ψ interacts with the gauge field A_0 corresponding to the $l(x)$ profile of the Z(3) wall. This allows for the possibility of color excitations of J/ψ as well as the spatial excitations of its wave function. First we discuss the possibility of color excitations of J/ψ. Subsequently, we will discuss spatial excitations of J/ψ.

Possibility of Color Excitation of J/ψ : We work in the rest frame of J/ψ and consider the domain wall coming and hitting the J/ψ with a velocity v along z-axis. The gauge potential and coordinates are appropriately Lorentz transformed. We assume that there is no background vector potential, $A_i(z) = 0\,; i = 1, 2, 3$. A'_3 (Lorentz transformed A_3) has only z dependence, so it does not produce any color magnetic field but it does produce a color electric field , which is proportional to v^2 as A_0 has the form $p \tanh(qz + r) + s$ (see ref (Atreya *et al.*, 2012)). For a low energy particle $v^2 << 1$, so this electric field can be neglected. We use first order time dependent perturbation theory to study the excitation of J/ψ due to the background A_0 profile and consider the transition of J/ψ from initial energy eigenstate ψ_i with energy E_i to the final state ψ_j with energy E_j. The transition amplitude is given by

$$\mathcal{A}_{ij} = \delta_{ij} - \ i \int_{t_i}^{t_f} \langle \psi_j | \mathcal{H}_{int} | \psi_i \rangle e^{-i(E_j - E_i)t} dt. \tag{1}$$

We take incoming quarkonia to be a color singlet state. The interaction of the quarkonia with the wall is written as

$$\mathcal{H}_{int} = V^q(z'_1) \otimes \mathbb{1}^{\bar{q}} + \mathbb{1}^q \otimes V^{\bar{q}}(z'_2) \quad \text{with} \ \ V^{q,\bar{q}}(z'_{1,2}) = g A_0'^{q,\bar{q}}(z'_{1,2}) \tag{2}$$

where $A_0'^{q,\bar{q}}(z'_{1,2})$ is the background field configuration in the rest frame of J/ψ. z'_1 and z'_2 are the coordinates of q and $\bar{q}$ in quarkonia and g is quark coupling. The gauge potential A_0 is taken in the diagonal gauge. $A_0 \to -A_0$, hence $A_0^{\bar{q}} = -A_0^q$. Now, both the initial and the final states have a spatial, spin and color part. The incoming quarkonia is a color singlet while outgoing state could be a singlet or an octet. Using eqn. (2) and extracting only the color part of interaction, we get

$$\langle \psi_{out} | \mathcal{H}_{int} | \psi_{singlet} \rangle = \langle \psi_{out} | g A_0'^q(z'_1) \otimes \mathbb{1}^{\bar{q}} | \psi_{singlet} \rangle + \langle \psi_{out} | \mathbb{1}^q \otimes g A_0'^{\bar{q}}(z'_2) | \psi_{singlet} \rangle. \tag{3}$$

If the outgoing state is also a singlet then, each term on RHS of eqn. (3) is zero due to the traceless nature of A_0. Eqn. (1) gives $\mathcal{A}_{ij} = 1$ for ground state ($i = j$). For higher orbital states ($i \neq j$), amplitude is identically zero. For color octet state like $|r\bar{g}\rangle$ each term on RHS of eqn. (3) again vanishes identically because of the diagonal form of A_0, resulting in zero transition probability. There are only two states with non-zero color contribution to transition probability. They are $|r\bar{r} - b\bar{b}\rangle$ & $|r\bar{r} + b\bar{b} - 2g\bar{g}\rangle$ The color part of transition probability for those states are

$$\langle r\bar{r} - b\bar{b} | \mathcal{H}_{int} | \psi_{singlet} \rangle = A_0^r - A_0^b \quad \text{and} \tag{4a}$$

$$\langle r\bar{r} + b\bar{b} - 2g\bar{g} | \mathcal{H}_{int} | \psi_{singlet} \rangle = A_0^r + A_0^b - 2A_0^g, , \tag{4b}$$

where, A_0^r, A_0^b and A_0^g are the diagonal components of the matrix $A'_0\,(z'_1) - A'_0\,(z'_2)$.

Spatial Excitations of J/ψ : We now consider the spatial excitations. The spatial part of the states is decided by the potential between $c\bar{c}$ in J/ψ which is

$$V\left(|\vec{r}_1 - \vec{r}_2|\right) = -\alpha_s / |\vec{r}_1 - \vec{r}_2| + C_d \sigma |\vec{r}_1 - \vec{r}_2| \tag{5}$$

where α_s is the strong coupling constant and σ is the string tension. C_d is the Casimir scaling factor accounting for representation dependence of the potential (Bali, 2000; Cardoso *et al.*, 2000). Since the potential is central, we perform coordinate transformations to $\vec{r}$ (the relative coordinate between q and $\bar{q}$) and $\vec{R}_{cm}$ (the center of mass of J/ψ) and then we get

$$A_0^r = \gamma A_0^{11}\left[\gamma(z_1' + vt')\right] - \gamma A_0^{11}\left[\gamma(-z_2' + vt')\right]. \tag{6}$$

z_1' and z_2' are written in terms of $\vec{R}_{cm}$ and $\vec{r}$. Similar expressions can be obtained for A_0^b and A_0^g. In the above coordinates, the J/ψ wave function is $\Psi(\vec{R}_{cm})\psi(\vec{r})$. For simplicity, we assume that the center of mass motion remains unaffected by the external perturbation. Then $\Psi(\vec{R}_{cm})$ has the plain wave solution, while $\psi(\vec{r})$ can be written $\psi(r,\theta,\phi) = \psi(r)Y_l^m(\cos\theta,\phi)$. When we use eqn. (4) and (6) in eqn. (1), we get one of the terms as

$$\int_{-\infty}^{\infty} \psi_j^* A_0^r \psi_i \, d\vec{r}_1 d\vec{r}_2 = \int_0^{\infty}\int_{-1}^{1}\int_0^{2\pi} \psi_n^*(r) Y_l^m(\cos\theta,\phi)\, A_0^r\, Y_0^0 \psi_{100}(r)\, r^2\, dr d(\cos\theta) d\phi. \tag{7}$$

In the above eqn., we have ignored the motion of the center of mass of charmonium and have considered only the relative coordinate. Under $\cos\theta \rightarrow -\cos\theta, A_0^r \rightarrow -A_0^r$ and ψ_i does not change. So if $Y_l^m(\cos\theta,\phi) = Y_l^m(-\cos\theta,\phi)$ then RHS of eqn. (7) is zero. Thus we do not get any transition to a state which is symmetric under $\cos\theta \rightarrow -\cos\theta$. This has very important significance. While the color part prohibits the transition to singlet final states, the space dependence of interaction forbids the transition to the ground state of an octet. The excitation is possible to the first excited state of an octet (like an 'octet χ' state). As the excited state will have a radius larger than the ground state it is more prone to melting in the medium.

Results

We numerically compute the integral given in eqn. (1) with $m_c = 1.3GeV$, $\alpha_s = 0.3$ (Giannuzzi and Mannareli, 2009). The strong coupling is chosen such that $N/g^2 = 0.8$ (Gupta *et al.*, 2010) and the value of σ is chosen to be $0.16\ GeV^2$. The profile of A_0 is of the form $p\tanh(qx + r) + s$ (Fig. 1 A). (Giannuzzi and Mannarelli, 2009). We first calculated the wave-function for the various states of $c\bar{c}$. Fig. 1(B) shows the radial part of the wave function for the $l = 0, 1$ states of charmonium. It is clear from Fig. 1(B), that the radius of J/ψ is about $0.5\ fm$ while that for χ is about $1.0\ fm$. As QGP has Debye length, $r_d \sim 0.6 - 0.7\ fm$, χ state is unstable and it melts easily in the medium. Table 1 lists the probabilities for transition to the color octet χ states for an incoming J/ψ with $E = 3.5\ GeV$ and $4.0\ GeV$, moving normal to the domain wall. The probability for J/ψ to make a transition to χ octet state is $\sim 8\%$ for $3.5\ GeV$. However even for a slight increase in the energy of incoming J/ψ, we find that the probability increases dramatically (almost 60% for $4.0\ GeV$) indicating that almost all J/ψ interacting with the domain wall will dissociate.

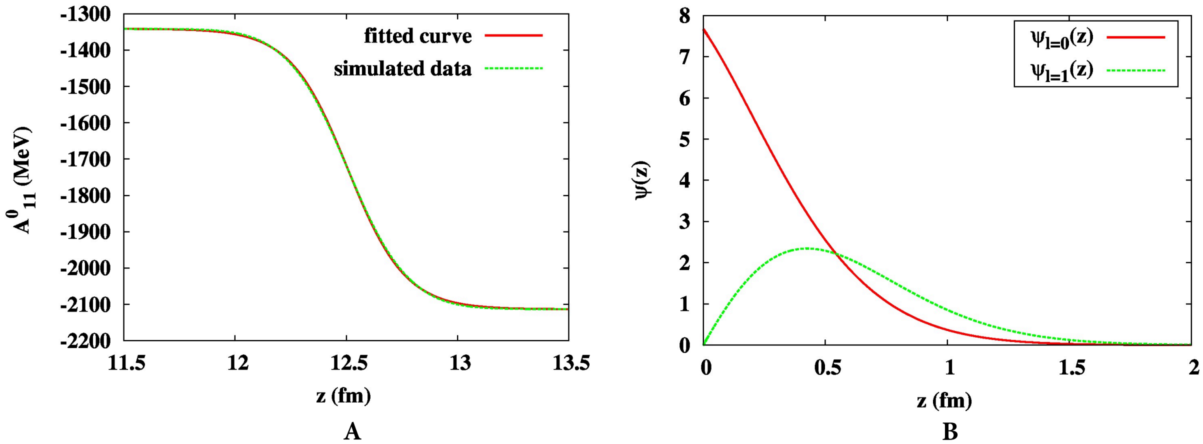

Fig. 1: (A) A_0 profile across the domain wall. Only $(1,1)$ component is shown. Other components are similar too. See ref. (Atreya *et al*., 2012) for details and (B) Wave functions for J/ψ $(l=0)$ and χ $(l=1)$ states

Octet state	$E = 3:5GeV$	$E = 4:0GeV$
$\left\| r\bar{r} - b\bar{b} \right\rangle$	0.05	0.45
$\left\| r\bar{r} + b\bar{b} - 2g\bar{g} \right\rangle$	0.02	0.15

Table 1: **Transition probability for J/ψ to l = 1 state**

Conclusions

These results conclusively show that on interaction with a $Z(3)$ domain wall, a J/ψ particle will make an excitation to a higher orbital of a color octet state which will readily melt in the surrounding QGP medium. At higher energies, the transition probability keeps increasing, making the first order perturbation theory inapplicable and the results are not trustworthy. Nonetheless, this implies that at higher energies, almost all J/ψ are expected to disintegrate in this manner. This strong P_T dependence of J/ψ disintegration probability is a distinctive signature of our model wherein the probability of disintegration of J/Psi is enhanced with higher P_T.

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