Effect of Magnetic Field on 1P States of the Heavy Quarkonia

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ABSTRACT

We determine the properties of 1P state of the charmonia and bottomonia in the presence of the strong magnetic field. Here we have employed the medium modified form of the potential which has both columbic as well as string part. This enables us to study the properties of the heavy quarkonia even above the critical temperatures. The strong magnetic field generally causes the momentum anisotropy which can be understood from the distribution function of the quarks and its effect has been incorporated through the quasi-particle Debye mass. The binding energies of the χc and χb are strongly affected in the strong magnetic field regime. The dissociation temperatures of the χc and χb are found to decreases with the increasing values of the magnetic field. Although the χb state dissociate at higher values of the temperature and magnetic field because of the larger mass and hence large binding energy of the χb. The dissociation temperature obtained in the presence of strong magnetic field are found to be higher than the estimates when the magnetic field B = 0. Thus the strong magnetic field impedes the early dissolution of the quark antiquark bound states. Mass spectra of the 1P states has also been studied in varying magnetic field. Our results are consistent with the predictions of the current theoretical works.

Introduction and Motivation

- ***The study of the fundamental forces among quark and gluons in the QGP medium is an essential key to the understanding of non-perturbative nature of QCD and the occurrence of different phases.***
- ***Charmonium suppression has long been proposed as a signature of the existence of QGP and has indeed been seen at CERN, SPS and RHIC [1].***
- ***Investigations on J/Ψ Suppression need understanding of not only the dissociation of 1S (J/Ψ) but also 2S (Ψ') and 1P (χ_c) states of charmonium in hot QCD medium [2].***
- ***It is believed that an intense magnetic field produced during the early age of this mysterious universe. This strikes us to study the effect of the magnetic field on the quark gluon plasma.***
- ***The main motivation for our analysis comes from the fact that the phase transition in full QCD appears as a crossover rather than a "true" phase transition (in high-temperature and low density regime).***
- ***The main point of focus of the present article is to study the effect of strong magnetic field on binding energies of the 1P states of charmonium and bottomonium (χ_c and χ_b respectively) by incorporating the non-perturbative effects such as nonzero value of the string tension between the quark-antiquark pair beyond Tc.***

Methodology:

The determination of binding energy of 1p states and their dissociation temperatures is not directly possible by employing the medium modified potential [3]. Here, we extend the analysis of [4] (relativistic two fermion system in QED) to determine the binding energy (BE) of χ_c and χ_b.

At this juncture, we need the understanding of the dissociation of 1S and 2S states of charmonium and bottomonium which follow the Bohr's theory.

Here we use the variational treatment method to avoid the violation of the Pauli's exclusion principle.

BINDING ENERGY OF χ_c AND χ_b

The solution of the Schrödinger equation gives the eigenvalues for the ground states and first excited states in the charmonium and bottomonium spectra. First we determine the binding energy for Ψ' by employing the medium-modified potential. Then we obtain the binding energy for χ_c by adding the correction terms to the binding energy of Ψ'.

The solution of the Schrodinger equation for the potential [7] gives the energy eigenvalues for the ground and the excited states of the charmonium and bottomonium J/ψ, ψ', ϒ and ϒ' as:

$$E_n = -\frac{m_Q\sigma^2}{n^2 m_D^4}$$

where m_Q is the mass of the quarkonium states i.e. the charmonia and bottomonium mass , 'n' is number of the energy levels/ principal quantum number and σ is string tension which is taken as 0.184GeV².

From the literature, total energy up to the 4th order in the fine structure constant α written as:

$$E_{nslj} = 2m_{c,b} - \frac{1}{2}\mu\frac{\alpha^2}{n^2} + \Delta K_{nl} + \Delta V_{nslj},$$

where ΔK_{nl} denotes the α^4 correction to the kinetic energy and ΔV_{nslj} is the spin dependent potential energy correction term [8]. In the current setup the fine structure constant α is replaced by the effective charge $\frac{2\sigma}{m_D^2}$.

The correction energy term with the appropriate quantum number and coefficient of the ψ′, χ_c, χ_b and ϒ′ thus becomes:

$$E_{c,b}^{corr} = \frac{m_{c,b}\alpha^4}{96} = \frac{m_{c,b}\,\sigma^4}{6m_D^8}$$

So the binding energy of the χ_c and χ_b with the addition of the correction energy term to the binding energy of the ψ′ and ϒ′ can be written as:

$$E_{(\chi_c,\chi_b)} = E_{(\psi',\Upsilon')} + E_{(\chi_c,\chi_b)}^{corr} = \frac{m_{c,b}\,\sigma^2}{4m_D^4}\left(1+\frac{2\,\sigma^2}{3\,m_D^4}\right)$$

Since the magnetic field has no effect on the gluons, so we study the effect of magnetic filed here only for the ll QCD case , $N_f = 3$.
The Debye mass depending on the temperature and the magnetic field[6] can be written as:

$$m_D^2(T, eB) = 4\pi\alpha_s\left\{T^2 + \frac{3eB}{2\pi^2}\right\}$$

The QCD coupling constants α_s (T) [7] at finite temperature is given as

$$\alpha_s(T) = \frac{6\pi}{(33-2N_f)\ln\left(\frac{T}{\lambda_T}\right)}\left(1 - \frac{3(153-19N_f)}{(33-2N_f)^2}\frac{\ln\left(2\ln\left(\frac{T}{\lambda_T}\right)\right)}{\ln\left(\frac{T}{\lambda_T}\right)}\right)$$

where λ_T is the QCD renormalization scale

Upper bound on the dissociation temperatures for χ_c and χ_b using Quasiparticle Debye Mass at different magnetic field

States	eB=0.3GeV²	eB=0.4GeV²	eB=0.5GeV²
χ_c	1.4225	1.1322	----------
χ_b	2.056	1.8903	1.7129

Lower bound on the dissociation temperatures for χ_c and χ_b using Quasiparticle Debye mass at different magnetic field

States	eB=0.2GeV²	eB=0.3GeV²	eB=0.4GeV²	eB=0.5GeV²
χ_c	1.2451	0.9064	-------	---------
χ_b	1.7729	1.51	1.2774	0.9706

Results

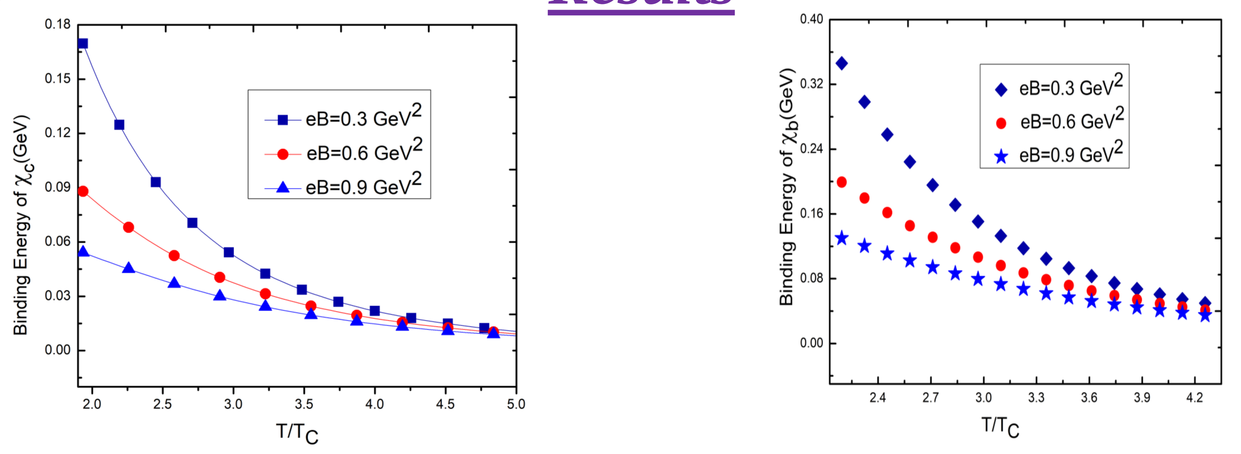

Fig.1 Shows the variation of the binding energy of χ_c and χ_b with the temperature at different magnetic fields.

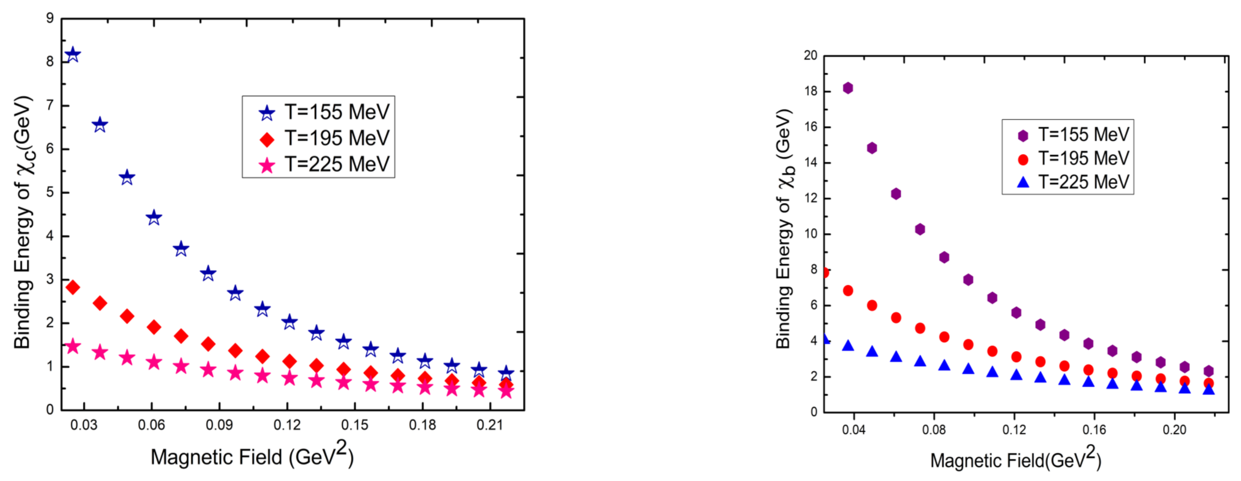

Fig.2 Shows the variation of the binding energy of χ_c and χ_b with the magnetic field at different temperatures.

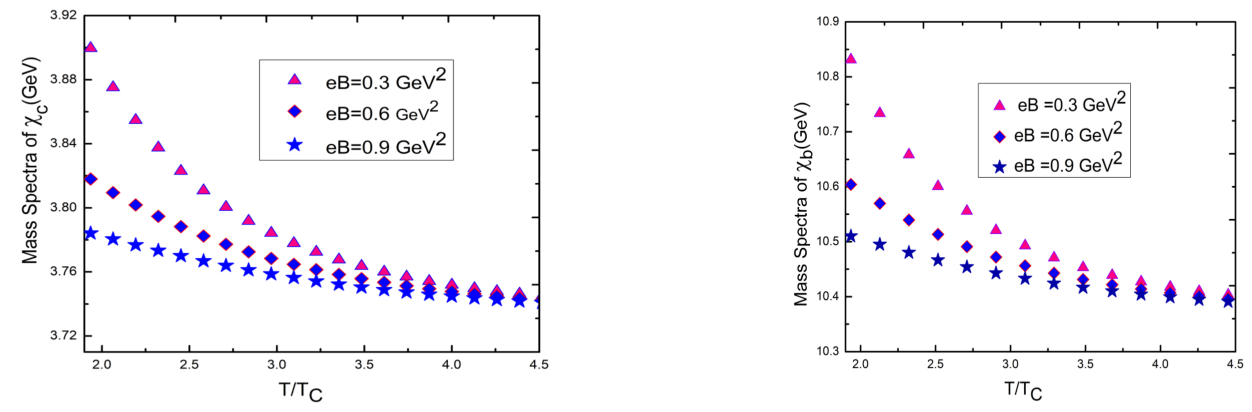

Fig.3 Shows the variation of the mass spectra of χ_c and χ_b with temmperature at different magnetic fields

Calculation of the dissociation temperature of for χ_c and χ_b

The upper bound and the lower bound of the dissociation temperature[5] can be obtained by the following conditions:

$$E_{(\chi_c,\chi_b)} = \frac{m_{c,b}\,\sigma^2}{4m_D^4}\left(1+\frac{2\,\sigma^2}{3\,m_D^4}\right) = \begin{cases} T_D \rightarrow \textit{Upper bound of the quarkonium states} \\ 3T_D \rightarrow \textit{Lower bound of the quarkonkium states} \end{cases}$$

Conclusions

- ***As we move from perturbative to non-perturbative domain, the binding energies and the dissociation temperature are becoming smaller. This is due to the hierarchy in the Debye masses*** $m_D^{LO} < m_D^{L} << m_D^{NP}$
- ***We have obtained the binding energies of the of χ_c and χ_b in the presence of magnetic field.***
- ***The dissociation temperature for the upper and the lower bound of the 1p state of the quarkonium system has also been studied.***
- ***We found that the dissociation temperature of χ_b are larger as compared to χ_c***

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