Effects of (inverse) magnetic catalysis on heavy quarkonia in magnetized matter: a QCD sum rule study

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Introduction

In-medium masses of the $1S$- and $1P$- wave states of quarkonia are studied in the magnetized nuclear matter accounting for the effects of (inverse) magnetic catalysis, using the QCD sum rule approach. The masses are obtained from the in-medium scalar and the twist-2 gluon condensates, calculated within the chiral $SU(3)$ model framework. The contribution of the magnetized Dirac sea is incorporated by summing over the nucleonic tadpole diagrams corresponding to the nucleon-scalar mesons interactions for the scalar isoscalars σ, ζ, isovector δ fields. In-medium masses of the charmonium and bottomonium ground states are observed to have considerable modifications with the magnetic field due to the effects of (inverse) magnetic catalysis. There is magnetic field-induced mixing between the longitudinal component of the vector and the pseudoscalar mesons, called PV mixing (spin-mixing) for the $1S$- wave states of charmonia (bottomonia). The magnetic field-induced mixing leads to a rise (drop) in the masses of $J/\psi^{||}$ (η_c) and $\Upsilon^{||}(1S)$ (η_b) states with the magnetic field. These might be observed in the experimental observables e.g., dilepton spectra in the peripheral, ultra-relativistic heavy-ion collision experiments at RHIC and LHC, where huge magnetic fields are estimated to be produced [1].

Theoretical Framework

In-medium masses are calculated using the framework of QCD Sum Rule (QCDSR) by incorporating the medium effects of density, isospin asymmetry, magnetic fields through the scalar and twist-2 gluon condensates as the non-perturbative effects of QCD. The condensates are computed within the chiral $SU(3)$ model, which is based on the non-linear realization of chiral $SU(3)_L \times SU(3)_R$ symmetry in the baryons and mesons degrees of freedom and the broken-scale invariance of QCD [2]. The gluon condensate is simulated through a scale-invariance breaking logarithmic potential in the scalar dilaton field χ within the chiral model. The scalar fields are treated as classical in solving their coupled equations of motion as derived from the chiral $SU(3)$ model Lagrangian. The scalar fields σ, ζ, δ and χ are solved at the given values of baryon number density ρ_B, isospin asymmetry $\eta = \frac{\rho_n - \rho_p}{2\rho_B}$, and magnetic field $|eB|$ (in units of m_π^2). The medium effects are incorporated into the scalar fields solutions via the number densities $\rho_{p,n}$ and the scalar densities $\rho^s_{p,n}$ of the nucleons in the magnetized nuclear matter. The effects of the magnetic field are incorporated through the Dirac sea, the Landau energy levels of the protons, and the anomalous magnetic moments (AMMs) of the nucleons in the Fermi sea [3].

In-medium masses are determined using the moment sum rules. The starting point of QCDSR is a time-ordered product of currents corresponding to the meson state, locally separated and its Fourier transform is referred to as the current correlation function or, $\Pi_{\mu\nu}(q)$ in general. In the phenomenological side, imaginary part of the correlator $\text{Im}\Pi(s)$ is related to the hadronic spectral density, which is parametrized in terms of a resonance pole and perturbative continuum. The current correlator on the other hand is expanded via Wilson's operator product expansion (OPE) in the deep Euclidean region ($Q^2 \equiv -q^2 >> 0$), $\Pi(q^2) = \sum_n C_n \langle O_n \rangle$; which is connected to

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the spectral density function through a dispersion relation. $\langle O_n \rangle$ contains the QCD condensates and C_n are Wilson coefficients, are medium independent [4]. The non perturbative nature of QCD enters through these condensates. QCDSR, thus provides a direct link between the various hadronic observables (mass, decay widths) through spectral density to the fundamental QCD quantities. The in-medium hadronic properties can be obtained through the medium modifications of the condensates. The continuum part in the spectral density is suppressed by taking moments i.e., additional derivatives are taken with respect to Q^2. The ratio of M_{n-1}/M_n is considered. Inserting $\mathrm{Im}\Pi(s) = f_0\delta(s-m^2)$ + corrections, [4] the masses of the $1S$ and $1P$ waves quarkonia of i-type [i = vector(V), pseudoscalar(P), scalar(S), axial vector(A)] is given as

$$m_i^{*2} \simeq \frac{M_{n-1}^i(\xi)}{M_n^i(\xi)} - 4m_q^2\xi. \quad (1)$$

Where, ξ = renormalization scale, $m_q(\xi)$ is the running charm/bottom quark mass [3]. In the OPE side $M_n(\xi)$ can be written as,

$$M_n^i(\xi) = A_n^i(\xi)[1 + a_n^i(\xi)\alpha_s + b_n^i(\xi)\phi_b + c_n^i(\xi)\phi_c] \quad (2)$$

Here, $\alpha_s(\xi)$ is the running coupling constant and $A_n^i, a_n^i, b_n^i, c_n^i$ are the Wilson coefficients [3, 4]. In-medium masses are obtained from the medium modified scalar and twist-2 gluon condensates through ϕ_b and ϕ_c, respectively.

Results and Discussion

The effects of the magnetized Dirac sea lead to appreciable modifications to the scalar fields $\sigma \sim (\langle\bar{u}u\rangle + \langle\bar{d}d\rangle)$, $\zeta \sim \langle\bar{s}s\rangle$, $\delta \sim (\langle\bar{u}u\rangle - \langle\bar{d}d\rangle)$ and χ with $|eB|$, as compared to the case with no Dirac sea effect. This leads to the (decrement) increment of the light quark condensates $\langle\bar{q}q\rangle$; $(q = u, d)$ with magnetic field, a phenomena called (inverse) magnetic catalysis. Inverse magnetic catalysis is obtained at the nuclear matter saturation density ρ_0 for non-zero AMMs of the Dirac sea nucleons, and magnetic catalysis is obtained for zero AMM of sea nucleons at ρ_0 and for the vacuum $\rho_B = 0$ (both with and without AMM). Similar behavior are obtained for $\eta = 0$ and 0.5 (pure neutron rich) matter. As the gluon condensates are proportional to the fourth power of the dilaton field and depend on σ, ζ and/or δ (in the limit of finite quark masses), quarkonia masses (decrease) increase considerably with magnetic field due to the effects of (inverse) magnetic catalysis at different medium conditions of ρ_B and AMMs. The magnetic field-induced pseudoscalar-vector mesons or, PV mixing [3] is studied on the $1S$ states: $J/\psi^{||} - \eta_c$ and $\Upsilon(1S)^{||} - \eta_b$. The effects of (inverse) magnetic catalysis are observed on the masses of the $1S$-wave charmonia J/ψ, η_c, bottomonia $\Upsilon(1S)$, η_b, for (non-zero) zero AMMs at ρ_0 and $\eta = 0$.

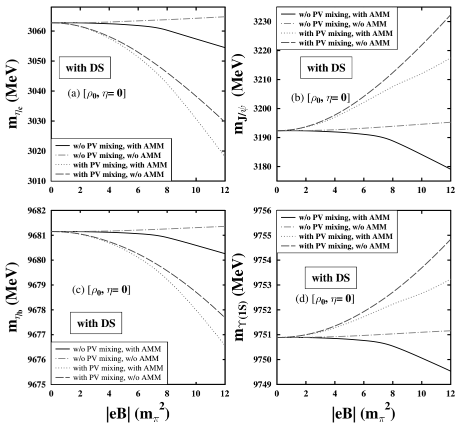

FIG. 1: In-medium masses (in MeV) of $1S$-wave of quarkonia: J/ψ, η_c, $\Upsilon(1S)$, and η_b, as a function of magnetic field, $|eB|$ (in units of m_π^2), at $\rho_B = \rho_0$ for symmetric nuclear matter ($\eta = 0$), accounting for the effects of the magnetized Dirac sea (DS).

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