Evolution of quarkonium states in rapidly varying magnetic field at Relativistic Heavy Ion Collision Experiment

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EMERGENT TOPICS IN RELATIVISTIC HYDRODYNAMICS, CHIRALITY, VORTICITY AND MAGNETIC FIELD

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Outline of Talk

- Review of Conventional Mechanism of quarkonia suppression
- Non Adiabaticity: An Important Aspect of Evolution of Quarkonia
- Quarkonia in Magnetic Field
- Results
- Summary

Conventional Mechanism for Quarkonia Suppression

- Matsui and Satz[1] proposed J/ψ suppression as a signal for QGP due to Debye screening of the potential between $q\bar{q}$.
- If at a temperature T_D, the Debye screening length of the medium becomes less than the radius of quarkonia, then $q\bar{q}$ may not form bound states.
- In the above picture, suppression of quarkonia occurs when the temperature of QGP achieves a value higher than T_D.

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[1] T. Matsui and H. Satz, Phys.Lett. B178,416 (1986)

Adiabatic Approximation

- If the QGP temperature remains below T_D, no quarkonia suppression is expected due to color screening(?) in the conventional mechanism.

Description of quarkonia through effective potential

- $q\bar{q}$ potential changes slowly from initial temperature $(V(T = T_i))$ to the final temperature $(V(T_f))$.
- Initial quarkonium state evolves to the state corresponding to $V(T_f)$ which is also a bound state for $T_f < T_D$ with same quantum number as initial state, hence no quarkonium suppression for $T < T_D$. $\Longrightarrow$ Adiabatic

Evolution of Fireball Created in Heavy Ion Collisions

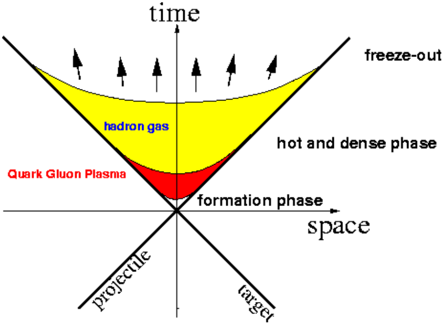

Figure: Nuclear collision evolution epoch.

Some Important Observations

- The fireball created in Heavy Ion Collision is rapidly evolving with time.
- If quarkonia is described in potential model then $q\bar{q}$ potential is no-doubt time dependent.

Note:

Matsui and Satz picture considers the static QGP only.

- **One need to solve Schrödinger equation for time-dependent Hamiltonian.**

Adiabaticity Violation: An Important Aspect of Quarkonia Evolution

Several possible Example of Adiabaticity Violation

- During Thermalisation [1]
- Cooling Phase [2]
- In presence of initial fluctuation [3]
- During Freeze-out
- Non adiabatic evolution of quarkonia in $p - p$ collision
- **In presence of transient magnetic field**
  - Spin Mixing [4]
  - **Spacial Excitation** [5]

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[1] Bagchi and Srivastava, Mod.Phys.Lett. A30 (2015) no.32, 1550162

[2] Dutta and Borghini, Mod.Phys.Lett. A30 (2015) no.37, 1550205

[3] Bagchi et al.,Springer Proc.Phys. 203 (2018) 493-495

[4] Dutta et al.,Eur.Phys.J. C78 (2018) no.6, 525

[5] Basgchi et al., arXiv:1805.04082

During Thermalisation

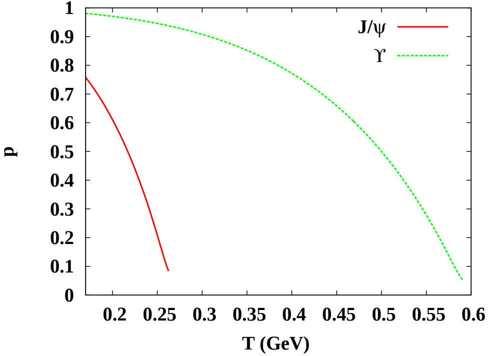

Figure: Survival Probability p of J/ψ and Υ vs. temperature of medium. Plots are given upto the temperature T_D for J/ψ and Υ .

Initial Fluctuation in Heavy Ion Collisions

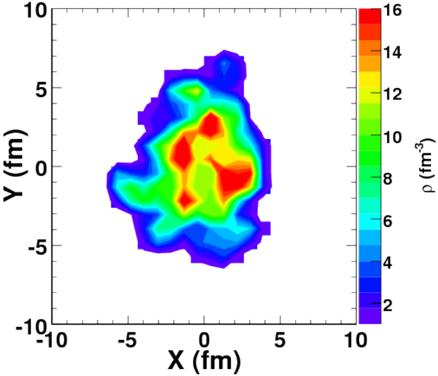

Figure: Initial energy density fluctuation (Phys.Rev. C92 (2015) no.5, 054902).

Quark Anti-quark Potential in QGP Medium

- In medium Debye screened potential between quark (q) and anti-quark ($\bar{q}$) [1]

$$V(r) = -\frac{\alpha}{r} exp(-m_D r) + \frac{\sigma}{m_D}(1 - exp(-m_D r)) \qquad (1)$$

- m_D is the Debye mass [2]$\Rightarrow$ Static limit ($p_0 \to 0, |\vec{p}| = 0$) of the longitudinal part of the gluon self energy $\pi_{\mu\nu}$
- m_D for three flavor case [3]

$$m_D = gT\sqrt{1 + N_f/6} \qquad (2)$$

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[1] H. Satz, J. Phys. Conf. Ser. **455**, 012045 (2013).

[2] E. Braaten and A. Nieto, Phys. Rev. Lett. **73**, 2402 (1994)

[3] F. Karsch, M.T. Mehr, and H. Satz, Z. Phys. C **37**, 617 (1988).

Quark Anti-quark Potential in Presence of Magnetic Field

- The effect of magnetic field in the fermion self energy is incorporated through the fermion propagator.
- In the strong field limit:

$$S_0(k) = i\frac{m + \gamma \cdot k_{\parallel}}{k_{\parallel}^2 - m^2}(1 - i\gamma_1\gamma_2)e^{\frac{-k_{\perp}^2}{|q_f B|}} \tag{3}$$

- B is along Z-axis.
- The self energy is calculated by using thermal propagator in imaginary time formalism.
- Debye mass is then obtained as[1]:

$$m_D^2 = g'^2 T^2 + \frac{g^2}{4\pi^2 T}\sum_f \mid q_f B \mid \int_0^\infty dp_z \frac{e^{\beta\sqrt{p_z^2+m_f^2}}}{\left(1 + e^{\beta\sqrt{p_z^2+m_f^2}}\right)^2} \tag{4}$$

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[1] Hasan et al., arXiv:1802.06874, Nucl.Phys.A 995 (2020) 121688

Quark Anti-quark Potential in Presence of Magnetic Field

Continued....

- First term is the contribution from the gluon loops and this is solely dependent on temperature
- $g'^2 = 4\pi\alpha'_s(T)$ where $\alpha'_s(T)$ is the usual temperature dependent running coupling where the renormalization scale is taken as $2\pi T$
- $$\alpha'_s(T) = \frac{2\pi}{\left(11 - \frac{2}{3}N_f\right)\ln\left(\frac{\Lambda}{\Lambda_{QCD}}\right)} \tag{5}$$

  Where $\Lambda = 2\pi T$ and $\Lambda_{QCD} \sim 200$ MeV

Quark Anti-quark Potential in Presence of Magnetic Field

Continued....

- Second term is the contribution from the fermion loop and this term strongly depends on magnetic field.
- $g^2 = 4\pi\alpha_s^{\parallel}(k_z, q_f B)$, where $\alpha_s^{\parallel}(k_z, q_f B)$ is the magnetic field dependent coupling and doesn't depend on temperature. [1] [2]
- $$\alpha_s^{\parallel}(k_z, q_f B) = \frac{1}{\alpha_s^0(\mu_0)^{-1} + \frac{11N_c}{12\pi}\ln\left(\frac{k_z^2+M_B^2}{\mu_0^2}\right) + \frac{1}{3\pi}\sum_f \frac{q_f B}{\sigma}} \tag{6}$$

where, $\alpha_s^0(\mu_0) = \frac{12\pi}{11N_c \ln\left(\frac{\mu_0^2+M_B^2}{\Lambda_V^2}\right)}$

and, $M_B = 1$ GeV, $\sigma = 0.18\ GeV^2$, $\mu_0 = 1.1$ GeV, $\Lambda_V = 0.385$ GeV.

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[1] Andreichikov et al., Phys. Rev. Lett. 110, 162002 (2013)

[2] Ferrer et al., Phys. Rev. D91, 054006 (2015)

Evolution of Magnetic Field in Non Central Collisions

- In Heavy Ion Collisions there are certain possibilities of production of huge magnetic field for non-central collision.
- The magnetic field will last for only few fm/c time[1].

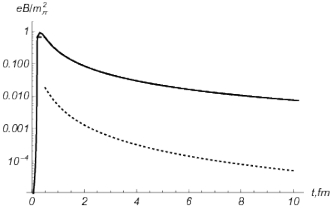

Figure: Magnetic field for $\sigma_e = 5.8MeV$, $z = 0.2fm$, $t_0 = 0.2fm$. Solid, dashed, and dotted lines stand for B, B_{init} and B_{val}, $\gamma = 2000$.

- σ_e (Electrical conductivity)$= 0$, for $t < t_0$(QGP formation time)

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[1] Kirill Tuchin,Phys. Rev. C 93, 014905 (2016)

Time-Dependent Potential for Studying Quarkonia Wave-Function Evolution

- Magnetic Field is Transient in Nature
- Decays to order of magnitude within few fm/c time.
- The evolution of the wave function, thus, cannot be taken to be adiabatic and it should be treated in terms of a time dependent perturbation theory (**is one of the tool).**
- Survival probability of quarkonia should be calculated under this perturbation.

Results

- We have calculated dissociation energy of J/ψ $(T = 1.4T_c)$ and $\Upsilon(1S)(T = 3.5T_c)$ for different values of magnetic field.
- In the strong field limit, the effect of the temperature is suppressed.
  $\Rightarrow$ strongly bound quarkonia[1], [2]

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[1] Hasan et al., arXiv:1802.06874, Nucl.Phys.A 995 (2020) 121688

[2] Singh et al., Phys. Rev. D 97, 096011

Results

Dissociation Energy

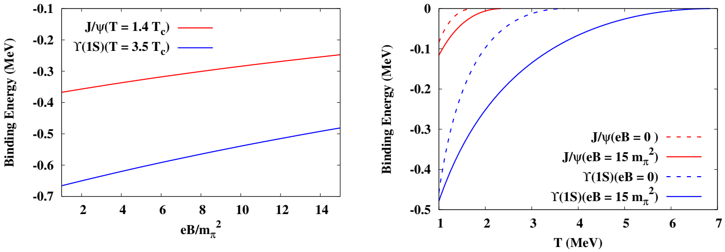

Figure: Left Panel: Magnetic field vs dissociation energy for charmonia. Right Panel: Temperature vs dissociation energy for charmonia.

Results

Evolution of magnetic field

- Considering magnetic field starting from $15m_\pi^2$, decays with time like
  $B = B_0\left(\frac{1}{1+a\tau(1+b\tau)}\right)$
  $a = 1.5$ and $b = 2$
- The temperature starting from $1.4T_c$ for J/ψ ($3.5\ T_c$ for $\Upsilon(1S)$) decays like
  $T(\tau) = T_0\left(\frac{\tau_0}{\tau_0+\tau}\right)^{\frac{1}{3}}$
- Then we have calculated the transition probability of quarkonia from its ground states to continuum states using 1st order perturbation theory.

Results

Evolution of magnetic field

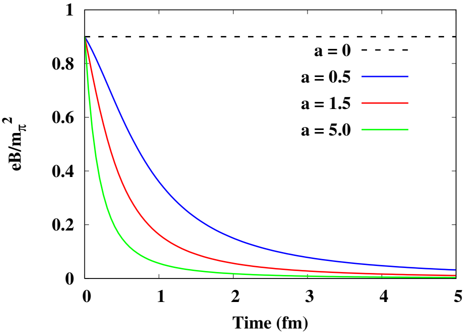

Figure: Decay of magnetic field with time for different "a"

Results

Dissociation Probability

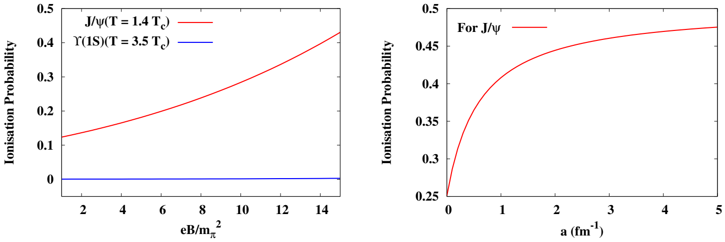

Figure: Left Panel: Magnetic field vs dissociation probability. Right Panel: Dissociation Probability as a function of “a“

Summary

- Here we have not consider the Imaginary Potential, This will provide extra suppression of quarkonia.
- The presence of strong magnetic field makes quarkonia strongly bound .

  $\Rightarrow$ more or less true for all available potential present in the community still now
- Even non-adiabatic evolution can not dissociate $\Upsilon(1S)$ at an initial temperature $T = 3.5T_c$.

  $\Rightarrow$ contradictory with experimental results

Possibilities:

- There will be no(/very weak) magnetic field present when medium formed
- Behavior of quarkonia may be drastically opposite in presence of weak(/intermediate) magnetic field in comparison with the presence of strong field.
- Quarkonia may start dissociating in a transient magnetic field before the medium thermalizes.

Thank You !