Disintegration of quarkonia in QGP due to time dependent potential

Partha Bagchi

Institute Of Physics

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Based on:**Bagchi and Srivastava, MPLA 30, 1550162 (2015)**

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Outline of talk

- Review of Conventional Mechanism of quarkonia suppression
- Violation of Adiabatic Approximation
- Quarkonia Suppression Due to Rapid Thermalisation (New Insight)
- Results
- Summery

Conventional mechanism for quarkonia suppression

- Quantum chromodynamics predicts that at extreme high conditions of baryon density and /or temperature there should be a deconfinement of quarks and gluons, and hadrons should undergo a phase transition to quark-gluon plasma (QGP).
- We cannot probe QGP directly.
- Observing quarkonia suppression is one of the several indirect methods to probe QGP.

Conventional mechanism for quarkonia suppression

Continued...

- 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

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

Important points about the conventional mechanism for quarkonia suppression

- 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 from zero temperature (V(T=0)) to the finite temperature one (V(T)).
- Initial quarkonium state evolves to the state corresponding to V(T) which is also a bound state for $T < T_D$, hence no quarkonium suppression for $T < T_D$. $\Longrightarrow$ Adiabatic

Violation of Adiabatic Approximation

- We question this assumption of adiabatic evolution for ultra-relativistic heavy-ion collisions, such as at RHIC, and especially at LHC.

Quarkonia evolution during thermalisation

- At such energies, thermalization is achieved in time scale less than 1 fm (from elliptic flow measurements) and may be as short as 0.25 fm for RHIC and about 0.1 fm for LHC[2]
- For J/ψ and even for Υ, typical time scale of $q\bar{q}$ dynamics will be at least 1-2 fm from the size of the bound state (as can be seen from the extent of the wave function and the fact that $q, \bar{q}$ have non-relativistic velocities).

[2] D.M. Elliott and D.H. Rischke, Nucl. Phys. A 671 , 583 (2000)

Violation of Adiabatic Approximation

Continued

- Also, ΔE between J/ψ and its next excited state (χ) is about 300 MeV (400 MeV for Υ states), leading to transition time scale ~ 0.7 fm (0.5 fm for Υ).
- Thus, the time scale of change in potential from $V(T=0)$ to $V(T)$ is at most the same as the time scale of the dynamics of $q\bar{q}$ in quarkonium, or the transition time scale between relevant states.

Time dependent potential for studying quarkonia wave function evolution

- 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
- Survival probability of quarkonia should be calculated under this perturbation
- Adiabatic assumption has been questioned earlier by Dutta and Borghini[3], but only for the cooling part, they discuss only the case when $T_0 > T_D$.
- Whereas, we discuss violation of adiabaticity for initial thermalisation part, and especially consider the case when $T_0 < T_D$.

[3] Nirupam Dutta, Nicolas Borghini arXiv:1206.2149

Time dependent potential.......continued

- It is clear that even if the final temperature remains less than T_D (above which Debye screening can melt quarkonia), if the change in potential is fast enough invalidating the adiabatic assumption then transition of initial quarkonium state to other excited states, or unbound state, will occur
- These excited states will have larger profile and will easily melt in medium.
- Thus: Quarkonia melting can occur even when QGP temperature remains below T_D.

Quarkonia Suppression Due to Rapid Thermalisation of QGP

- As Thermalisation may happen in very short time, about 0.25 fm for RHIC and 0.1 fm for LHC, it seems reasonable to use the *sudden* perturbation approximation instead of adiabatic approximation.
- The initial wave function of the quarkonium cannot change under this quick change of potential.
- Thus, as soon as thermalization is achieved the initial quarkonium wave function is no longer an energy eigen state of the new Hamiltonian with the $q\bar{q}$ potential corresponding to temperature T of QGP.

Results

- we calculate wave functions for J/ψ and Υ at different temperatures
- Debye screened $q\bar{q}$ potential[4]

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

$$\omega_D = T\sqrt{6\pi\alpha_s}, \quad \alpha = 0.471 = \frac{4}{3}\alpha_s \quad \sigma = 0.192 GeV^2$$

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

Results: Continued....

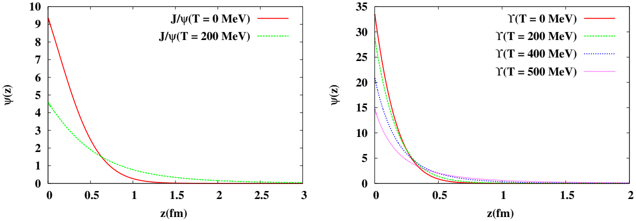

Figure : Wave functions for J/ψ and Υ at different temperatures.

Results: Continued....

- As a result, one can find overlap with the new (instantaneous) eigen states, giving us the survival probability of the quarkonium as well as the probability of its transition to other excited states.
- We note dramatic decrease in survival probabilities down to about 10 % as temperature increases to about 260 MeV and 590 MeV respectively for J/ψ and Υ.

Results: Continued....

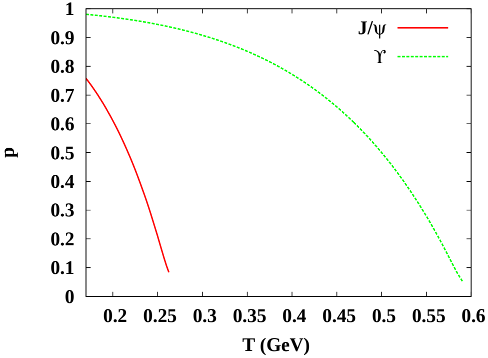

Figure : Survival Probability p of J/ψ and Υ vs. temperature of medium. Plots are given upto the temperature T_D for J/ψ and Υ .

Error Calculation

- We have also estimated the error[5] in using this sudden approximations by calculating the probability ζ of transition of the original quarkonium state to some other state during the time scale τ of the change of the potential.
- $$\zeta = \tau^2 \Delta \bar{H}^2$$
$$\Delta \bar{H} = < \bar{H}^2 > - < \bar{H} >^2$$
$$\bar{H} = \frac{1}{\tau}\int_0^\tau H(t)dt$$
- Here, $<>$ denotes the expectation value in the initial quarkonium state.

[5] A. Messiah, *Quantum Mechanics*, Dover Publications (1999)

Error Calculation

Continued

- This error remains below 8 % for the thermalization time used as 0.5 *fm*.

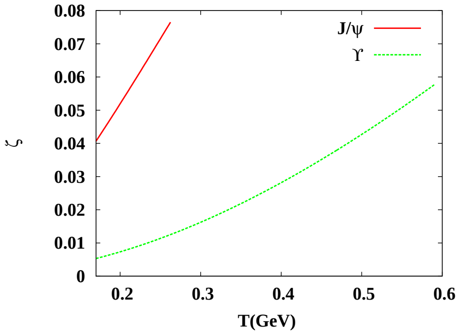

Figure : Plot of the probability ζ encoding the error in making the sudden approximation.

Summery

- It is not reasonable to use the adiabatic approximation for quarkonia wave function evolution in medium in the case of rapid thermalization
- We have used *sudden* perturbation approximation instead of adiabatic approximation.
- Quarkonia melting can occur even when QGP temperature remains below T_D.
- More detailed calculations can be done by modeling initial thermalization in terms of time dependent temperature and using time dependent perturbation theory(We do not expect much change in results).
- This new mechanism has to be incorporated for more accurate calculation of quarkonia suppression in QGP.

Thank You !