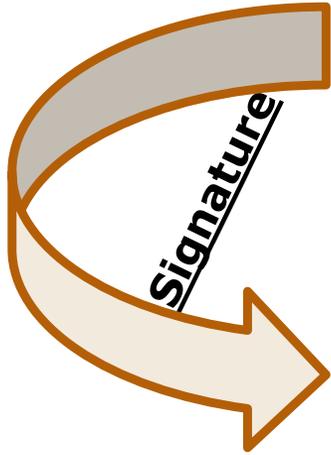


Quarkonium and Thermodynamical Properties in a Baryon-Rich Anisotropic Medium of QGP



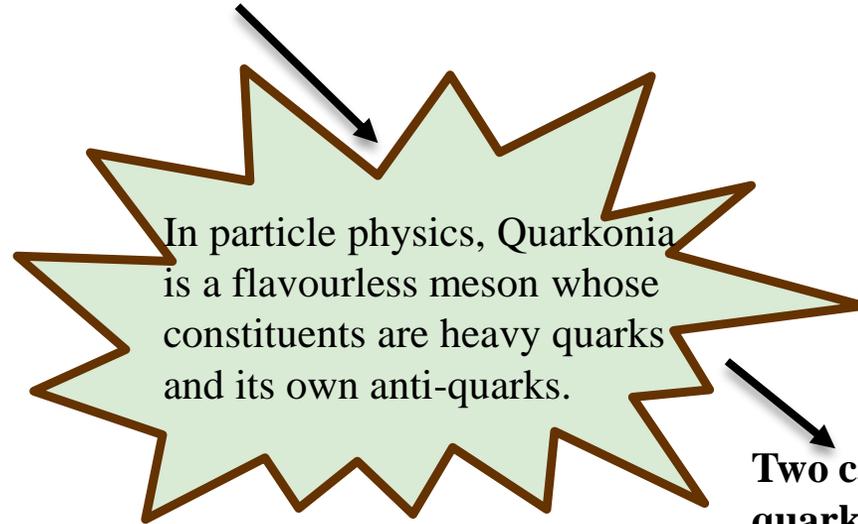
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Quarkonium



We used two types of quarkonium,
❖ Charmonium
❖ Bottomonium

$c\bar{c}$ and $b\bar{b}$



In particle physics, Quarkonia is a flavourless meson whose constituents are heavy quarks and its own anti-quarks.

Two categories of quarks,
❖ Light quarks - U,D,S
❖ Heavy quarks - C,B,T

They are more tightly bound, with binding energies up to 0.5 to 1.0 GeV. Thus, they can survive in a QGP up to temperature above the deconfinement point.

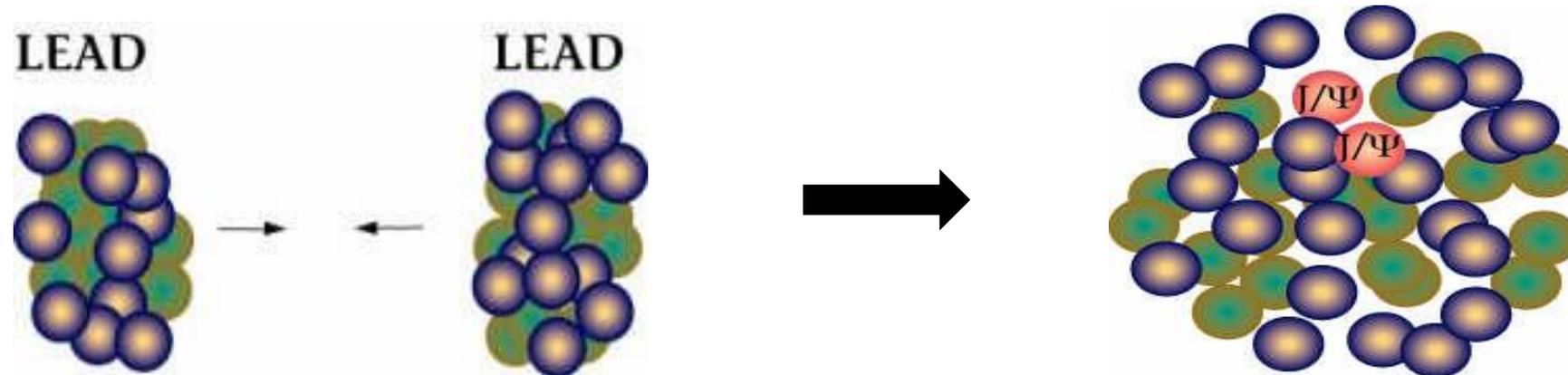
Charmonium	Bottomonium
J/Ψ	γ
Ψ'	γ'
χ _c	χ _b

BASIC FEATURES OF QCD

At low energy, the interaction between quarks and gluon become very small and hence quarks are confined inside the hadrons. so free quarks have never been seen. This is known as **color confinement**

At short distances, the interactions between quarks become weak is known as **Asymptotic freedom**

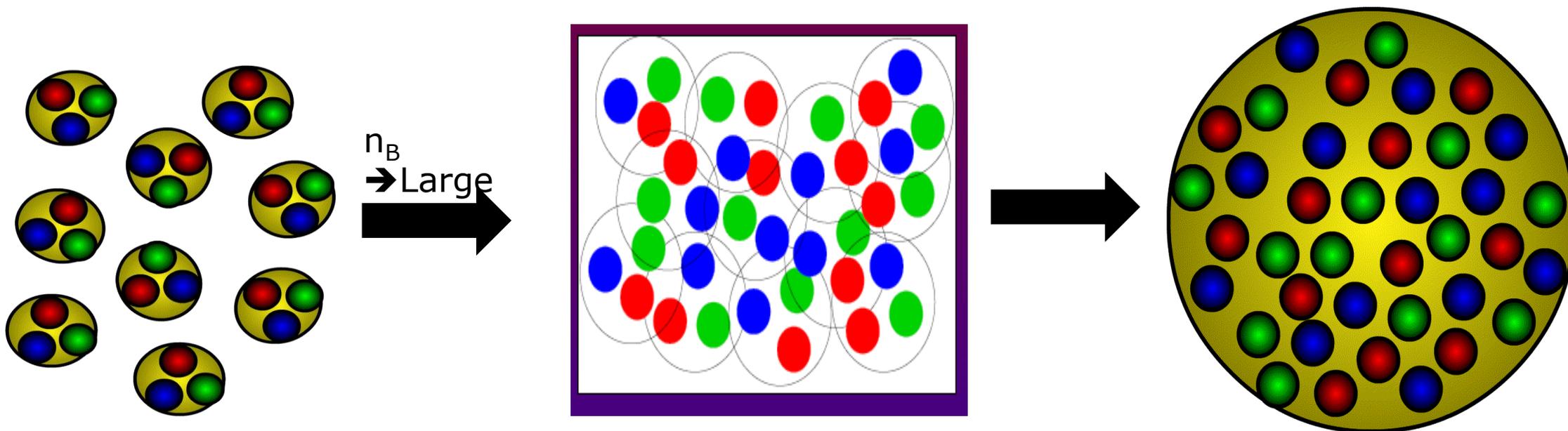
In relativistic nucleus-nucleus collisions, The protons and neutrons in the lead-ions will split up, forming a dense soup of particles so, the system is quark gluon plasma. This is also known as baryon-less plasma. This plasma might have occurred in the early universe, at one microsecond after the big bang.



AT LARGE BARYON DENSITY

- What happens when many hadrons are put in a small volume?

If we increase the baryonic density by 5-10 times of normal nuclear density then baryons overlap with each other and form quark gluon plasma. This plasma is known as baryon rich plasma. This plasma might have occurred inside the core of a neutron star.



DYNAMICS OF QUARKONIUM DISSOCIATION IN ISOTROPIC MEDIUM

- In medium modification of Heavy quark potentials
- The Cornell potential is

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

- The medium modification enters in the Fourier transform of the heavy quark potential as

$$\tilde{V}(k) = \frac{V(k)}{\varepsilon(k)}$$

- The r dependence of the medium modified potential

$$V(r, T) = \left(\frac{2\sigma}{m_D^2(T)} - \alpha \right) \frac{\exp(-m_D(T)r)}{r} - \frac{2\sigma}{m_D^2(T)r} + \frac{2\sigma}{m_D(T)} - \alpha m_D(T)$$

DYNAMICS OF QUARKONIUM DISSOCIATION IN ANISOTROPIC MEDIUM

- ❑ It allows a researcher to investigate the behaviour of quarks and anti-quarks state with in the hot-dense medium.
- ❑ Main effect of the anisotropy is to reduce Debye screening which, in turn has the effect that heavy Quarkonium states can survive up to higher temperatures.
- ❑ The anisotropic parameter is related to shear viscosity to entropy density by:

$$\xi = \frac{10\eta}{T\tau s} = \frac{\langle \vec{k}_T^2 \rangle}{2 \langle \vec{k}_L^2 \rangle} - 1$$

- ❑ The positive and negative values of anisotropic parameter corresponds to the squeezing and stretching of the distribution function in the direction of anisotropy.
- ❑ The phase-space distribution of gluons in the local rest frame is assumed to be,

$$f(\vec{x}, \vec{p}) = f_{iso}(\sqrt{\vec{p}^2 + \xi(\vec{p} \cdot \vec{n})^2})$$

Dimitru et al.,PRD'09

MEDIUM MODIFIED HEAVY-QUARK POTENTIAL IN THE PRESENCE OF ANISOTROPY

❖ We can obtain the modified (or in-medium corrected) potential as,

$$V(r) = \int \frac{d^3 \bar{k}}{(2\pi)^{3/2}} (e^{i\bar{k}\cdot\bar{r}} - 1) \tilde{V}(k)$$

❖ Where $\tilde{V}(k)$ is the Fourier transform of $V(r)$,

$$\tilde{V}(k) = -\sqrt{\frac{2}{\pi}} \left(\frac{\alpha}{k^2} + 2 \frac{\sigma}{k^4} \right)$$

We can write the real part of the potential as,

$$\text{Re}[V(r, \xi, T)] = \left(1 + \frac{\xi}{3}\right) \left(\frac{\sigma}{m_D} - \alpha \left(\frac{1}{s} + \frac{1}{2} \right) m_D \right) + \frac{\xi s}{16} \left(\frac{7}{3} - \cos(2\theta_r) \right)$$

We can write the imaginary part of the potential in the anisotropic medium as,

$$\text{Im}[V(r, \theta_r, T)] = -\left(1 + \frac{\xi}{3}\right) T \left(\frac{\alpha s^2}{3} + \frac{\sigma s^4}{30 m_D^2} \right) \log\left(\frac{1}{s}\right) + \xi T \log\left(\frac{1}{s}\right) \left[\left(\frac{\alpha s^2}{10} + \frac{\sigma s^4}{140 m_D^2} \right) - \cos^2 \theta_r \left(\frac{\alpha s^2}{10} + \frac{\sigma s^4}{70 m_D^2} \right) \right]$$

In this work, we have investigated the properties of quarkonia, in the presence of baryonic chemical potential (μ_b) and anisotropy (ξ).

- ❑ potential,
- ❑ binding energy,
- ❑ mass spectra, and
- ❑ dissociation temperature (using thermal width and thermal energy criteria).

The real and imaginary part of medium modified Cornell potential is,

$$\text{Re}[V(r, \theta_r, \xi, T, \mu_b)] = \frac{s\sigma}{m_D} \left(1 + \frac{\xi}{3}\right) - \frac{\alpha m_D}{s} \left\{ 1 + \frac{s^2}{2} + \xi \left[\frac{1}{3} + \frac{s^2}{16} \left(\frac{1}{3} + \cos(2\theta_r) \right) \right] \right\}$$

And, $\text{Im}[V(r, \theta_r, T, \mu_b, \xi)]$

$$\begin{aligned} &= \frac{\alpha s^2 T}{3} \left\{ \frac{\xi}{60} (7 - 9 \cos 2\theta_r) - 1 \right\} \log \frac{1}{s} \\ &+ \frac{s^4 \sigma T}{m_D^2(T, \mu_b)} \left\{ \frac{\xi}{35} \left(\frac{1}{9} - \frac{1}{4} \cos 2\theta_r \right) - \frac{1}{30} \right\} \log \frac{1}{s} \end{aligned}$$

DEBYE MASS IN HIGH TEMPERATURE QCD

We consider three possible forms of the Debye masses:

- Leading-order term in QCD coupling
- Lattice parameterized form
- Quasi-Particle Debye Mass

$$m_D^{LO} = g(T)T \sqrt{\frac{N_c}{3} + \frac{N_f}{6}}$$

$$m_D^L = 1.4 m_D^{LO}$$

$$m_D^2 = g^2 T^2 \left(\frac{N_c}{3} \times \frac{6 \text{PolyLog}[2, z_g]}{\Pi^2} \right) + \left(\frac{N_f}{6} \times \frac{-12 \text{PolyLog}[2, -z_q]}{\Pi^2} \right)$$

Here the function Poly Log[2,z] having form:

$$\text{PolyLog}[2, z] = \sum_{k=1}^{\infty} \frac{z^k}{k^2} \quad \{\text{Chandra, Ravishankar, PRD2011}\}$$

- The temperature dependence z_g and z_q has the form given below:

$$z_{g,q} = a_{g,q} \exp\left(-\frac{b_{g,q}}{x^2} - \frac{c_{g,q}}{x^4} - \frac{d_{g,q}}{x^6}\right)$$

- The values of fitting parameters i.e., a,b,c and d are listed in Table for hot QCD EoS1 and hot QCD EoS2 for different number of flavors.

- **VALUES OF FITTING PARAMETERS FOR EOS1**

Flavors	a	b	c	d
$N_f = 0$	0.890052	1.29752	-2.42922	3.60965
$N_f = 2$	0.896023	0.924296	-1.82467	2.08887
$N_f = 3$	0.89414	0.944966	-1.88539	2.14893

- **VALUES OF FITTING PARAMETERS FOR EOS2**

Flavors	a	b	c	d
$N_f = 0$	0.946639	0.847449	-1.14761	2.05096
$N_f = 2$	0.922071	0.963019	-1.77314	2.36538
$N_f = 3$	0.920002	1.12035	-1.95618	2.74009

We used the quasi-particle form of Debye mass (m_D) for the full QCD case and is given by:

$$\frac{m_D^2(T, \mu_b)}{T^2} = \left(\left\{ \frac{N_c}{3} Q_g^2 \right\} + \left\{ \left[\frac{N_f}{6} + \frac{1}{2\pi^2} \left(\frac{\mu_b^2}{9T^2} \right) \right] Q_q^2 \right\} \right)$$

Temperature
and baryonic
chemical
potential
dependent form

In our calculations we used the final expression of quasi-particle Debye mass for the full QCD case in terms of baryonic chemical potential

Results of Real part of potential using baryonic chemical potential and anisotropy

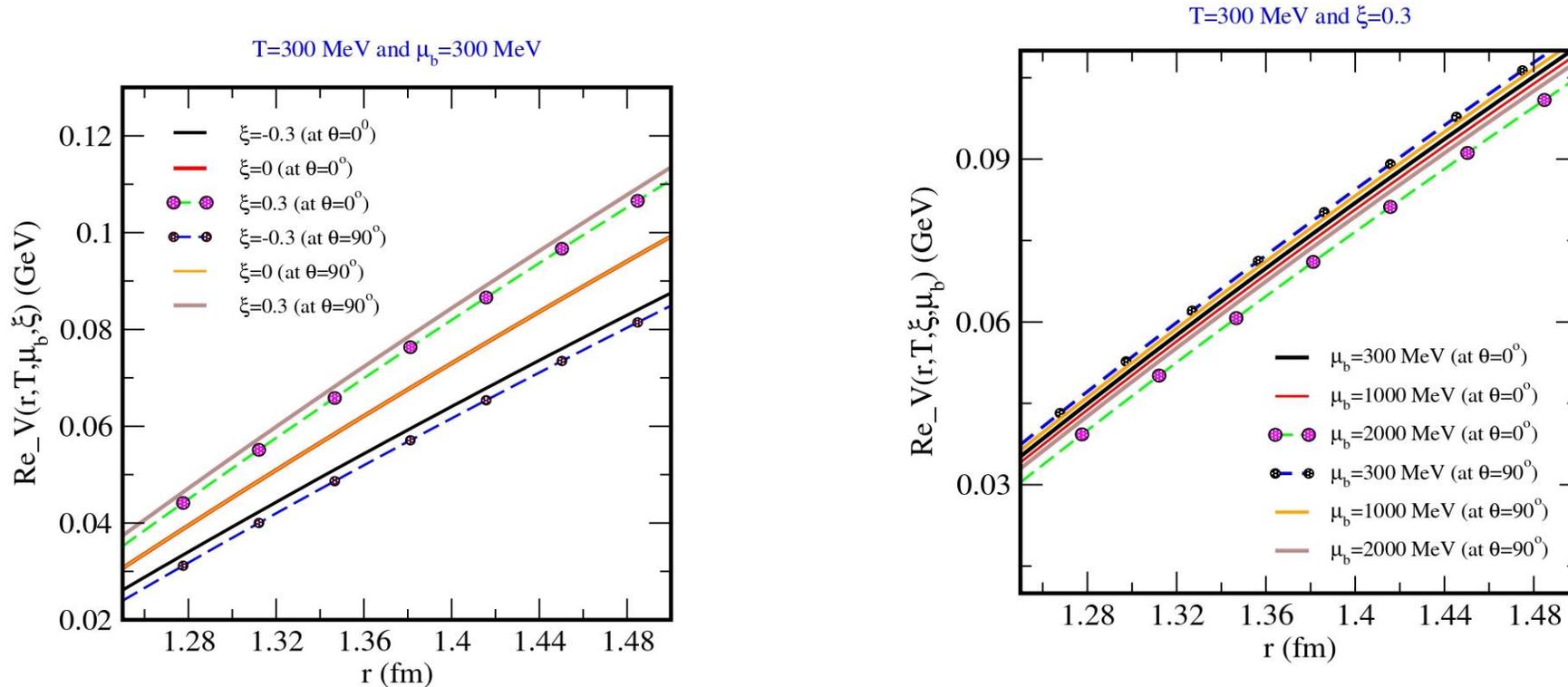


FIG: Variation of real potential with distance (r in Fermi) at different values of anisotropy (left panel) and at different values of baryonic chemical potential (right panel) in both parallel and perpendicular case.

RESULTS OF IMAGINARY PART OF POTENTIAL USING BARYONIC CHEMICAL POTENTIAL AND ANISOTROPY

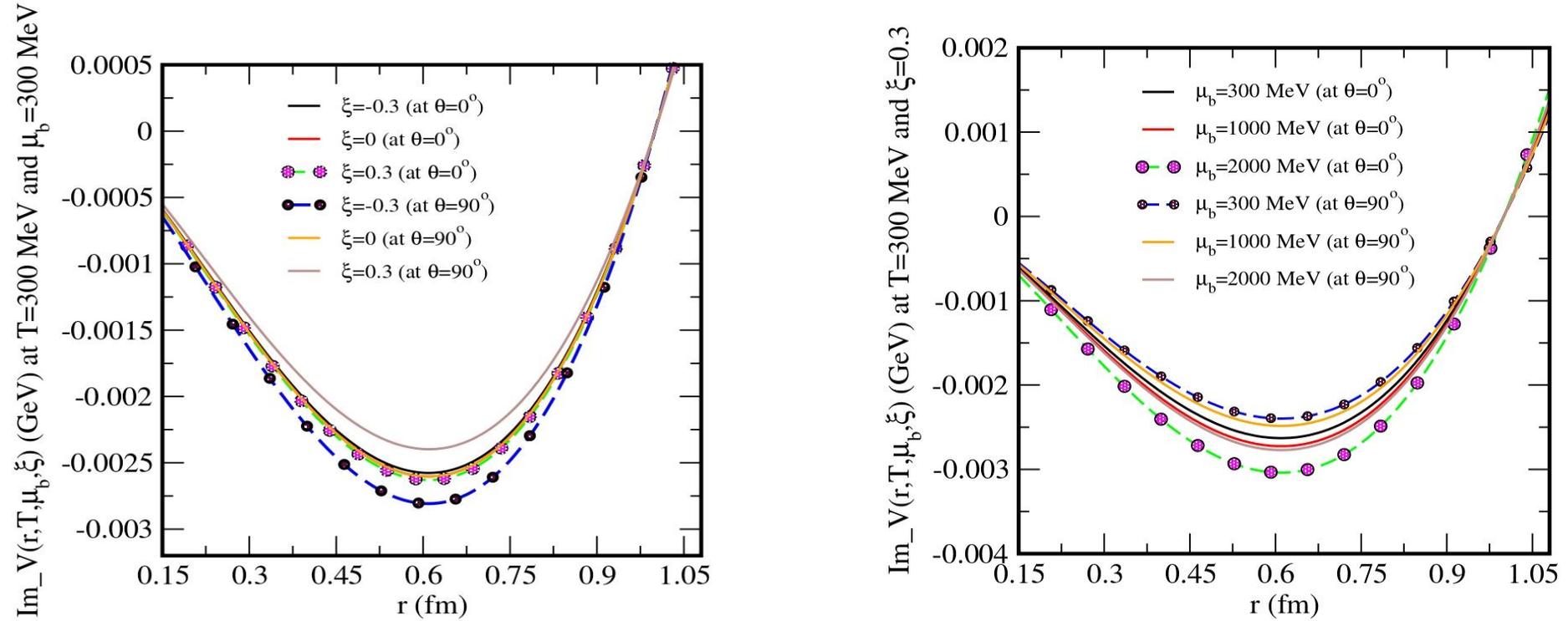


FIG: Variation of imaginary potential with distance (r in Fermi) at different values of anisotropy (left panel) and at different values of baryonic chemical potential (right panel) in both parallel and perpendicular case.

BINDING ENERGY

Real part of the medium modified form of Cornell potential

Used for the solution of Schrodinger equation

We get the form of Binding Energy

$$\text{Re}[B.E] = \frac{m_Q \sigma^2}{m_D^4(T, \mu_b) n^2} + \alpha m_D(T, \mu_b) + \frac{\xi}{3} \left(\frac{m_Q \sigma^2}{m_D^4(T, \mu_b) n^2} + \alpha m_D(T, \mu_b) + \frac{2m_Q \sigma^2}{m_D^4(T, \mu_b) n^2} \right)$$

RESULTS OF BINDING ENERGY USING BARYONIC CHEMICAL POTENTIAL AND ANISOTROPY

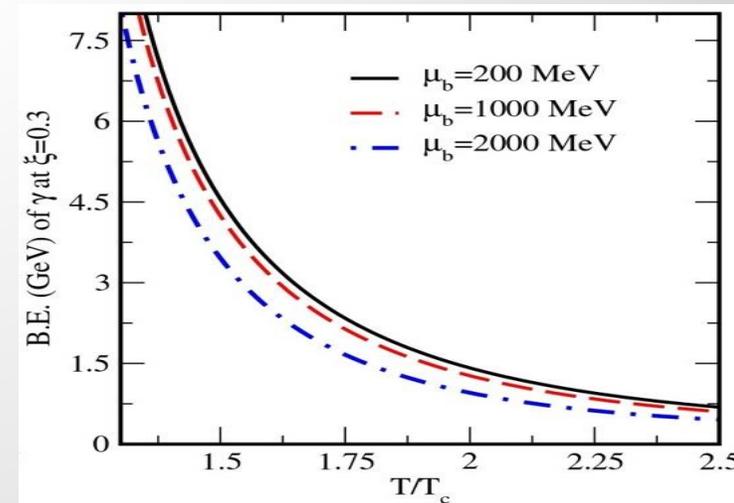
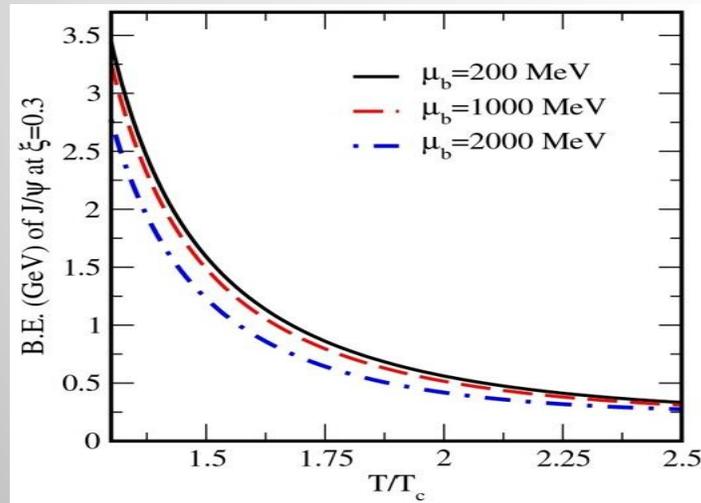


Fig: Shows the variation of binding energy of the J/ψ (left panel) and Υ (right panel) with T/T_c at different values of baryonic chemical potential (μ_b) when the value of ξ is fixed.

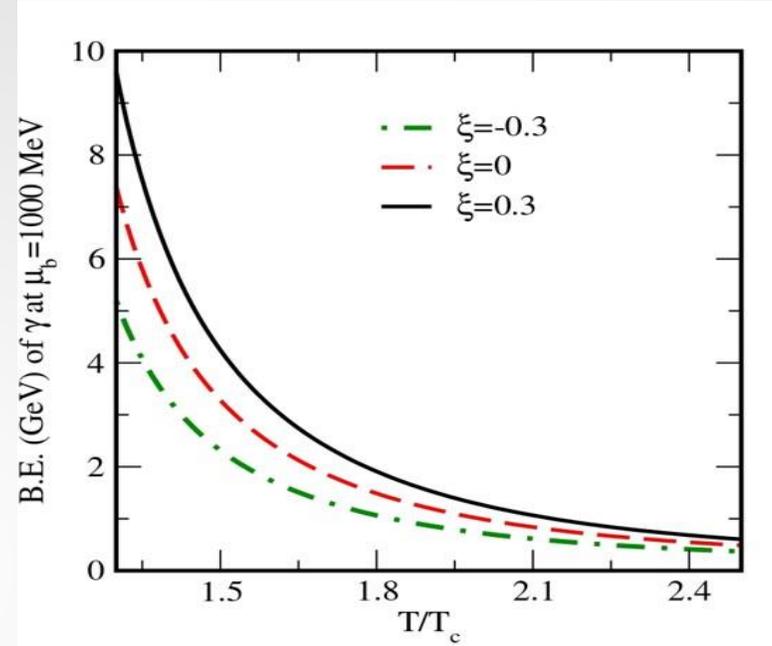
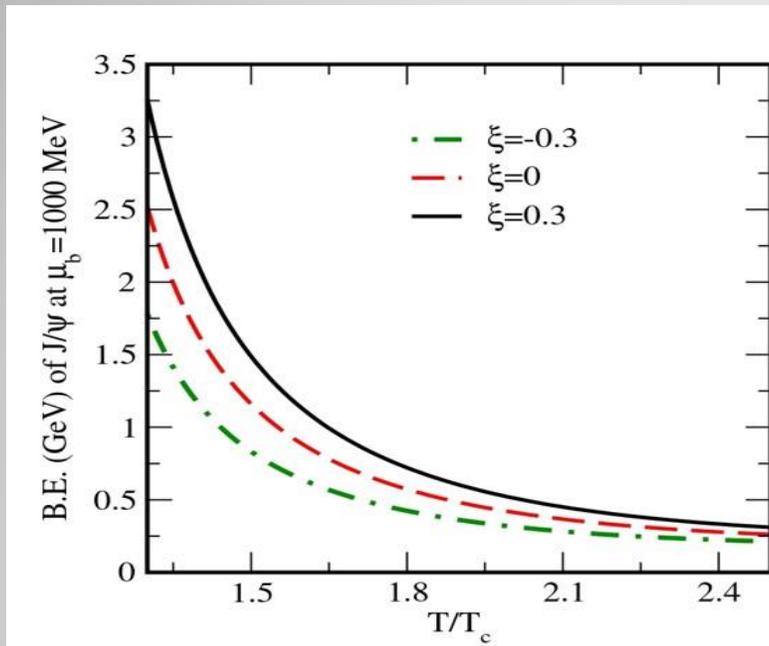
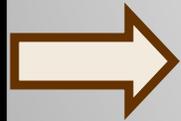


Fig: Shows the variation of binding energy of the J/ψ (left panel) and Υ (right panel) with T/T_c at different values of anisotropy (ξ) and when value of μ_b is fixed.



If μ_b is **increases** then values of Binding energy **decreases**.



If ξ is **increases** then values of Binding energy also **increases**.

DISSOCIATION TEMPERATURE USING THERMAL WIDTH CRITERIA

Imaginary part of the medium modified form of Cornell potential

$$\Gamma(T) = - \int d^3r |\Psi(r)|^2 \text{Im} V(r)$$

We get the Thermal width expression

Results for the calculation of Dissociation temperature using thermal width criteria

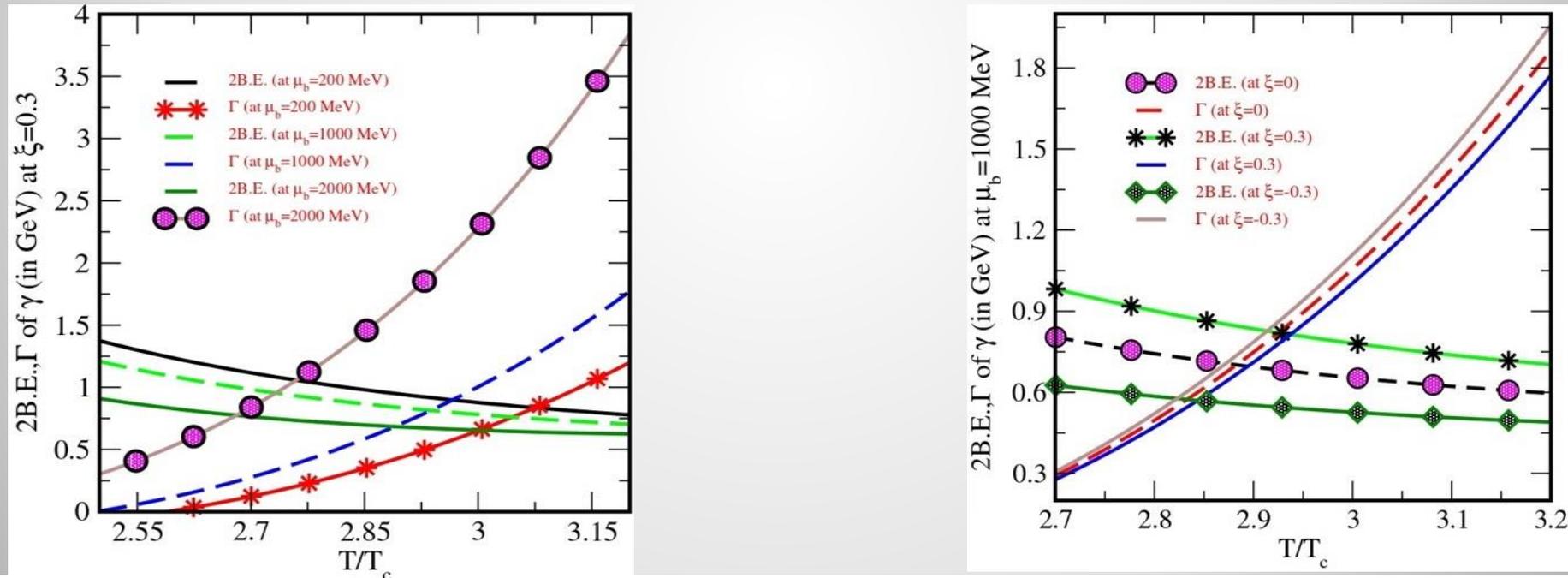


Fig: Shows the variation of 2B.E., Γ of γ with T/T_c at different values of μ_b (left panel) and at different values of ξ (right panel).

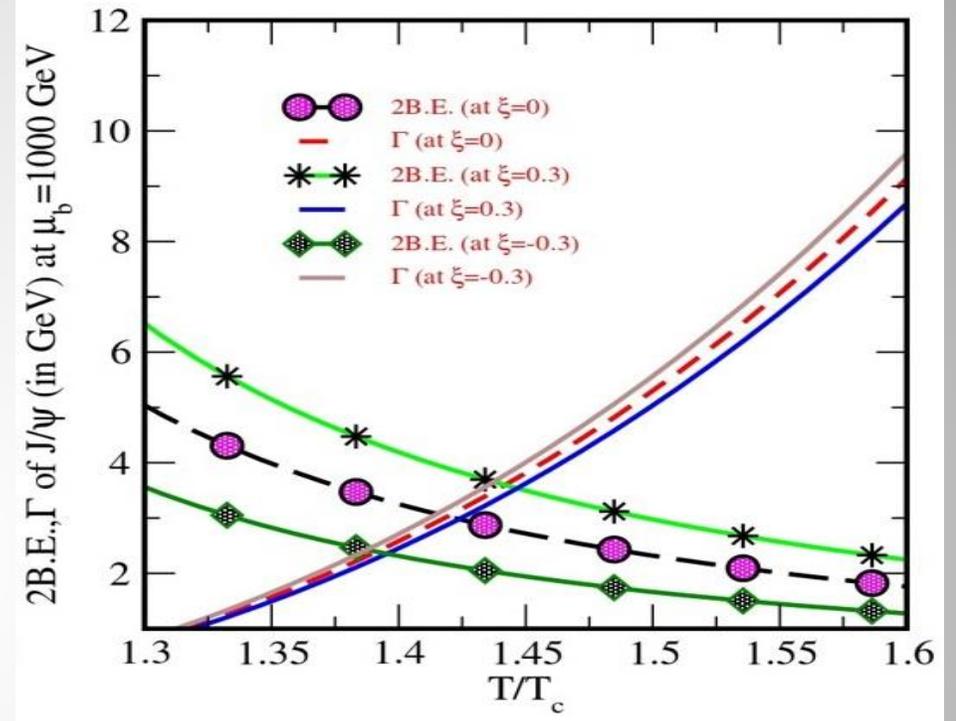
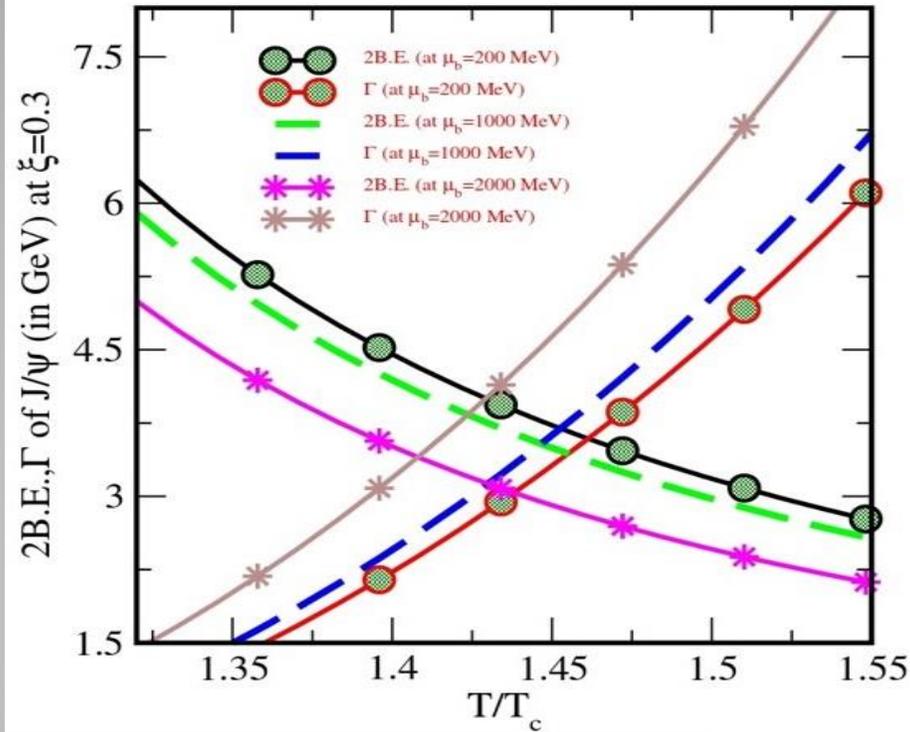


Fig: Shows the variation of 2B.E., Γ of J/ψ with T/T_c at different values of μ_b (left panel) and at different values of ξ (right panel).

➔ If μ_b is increases then the variation of thermal width increases.

➔ If ξ is increases then the variation of thermal width decreases.

DISSOCIATION TEMPERATURE VALUES USING THERMAL WIDTH CRITERIA

Temperatures are in the unit of T_c

Dissociation by thermal width criteria

States	$\xi=-0.3$	$\xi=0$	$\xi=0.3$
J/ψ	1.3879	1.4202	1.4467
Υ	2.8232	2.8857	2.9409
Υ'	1.5644	1.5788	1.5909

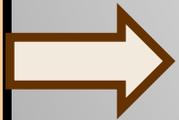
Table: Dissociation for $\mu_b=1000$ MeV at $T_c=197$ MeV.

Temperatures are in the unit of T_c

Dissociation by thermal width criteria

States	$\mu_b=200$ MeV	$\mu_b=1000$ MeV	$\mu_b=2000$ MeV
J/ψ	1.4618	1.4467	1.4082
Υ	3.0775	2.9385	2.6794
Υ'	1.6127	1.5913	1.5379

Table: Dissociation for $\xi=0.3$ at $T_c=197$ MeV.



If μ_b is increases then the values of dissociation temperature decreases.



If ξ is increases then the values of dissociation temperature increases.

MASS SPECTRA FOR S-STATES OF QUARKONIA

The main of calculating mass spectra of heavy quarkonia –

- ❖ Is to gain a deep understanding about the strong forces, by predicting the masses of bound states of quarks and anti-quarks and Compare with the experimental data to refining the theoretical model or can check the accuracy of the theoretical model.

The mass spectra of 1S and 2S states of charmonium and bottomonium in anisotropic medium can be calculated by using following conditions:

$$M = 2m_Q + B.E$$

Mass spectra of quarkonium states =

$$2m_Q + \left(\frac{m_Q \sigma^2}{m_D^4 n^2} + \alpha m_D + \frac{\xi}{3} \left(\frac{m_Q \sigma^2}{m_D^4 n^2} + \alpha m_D + \frac{2m_Q \sigma^2}{m_D^4 n^2} \right) \right)$$

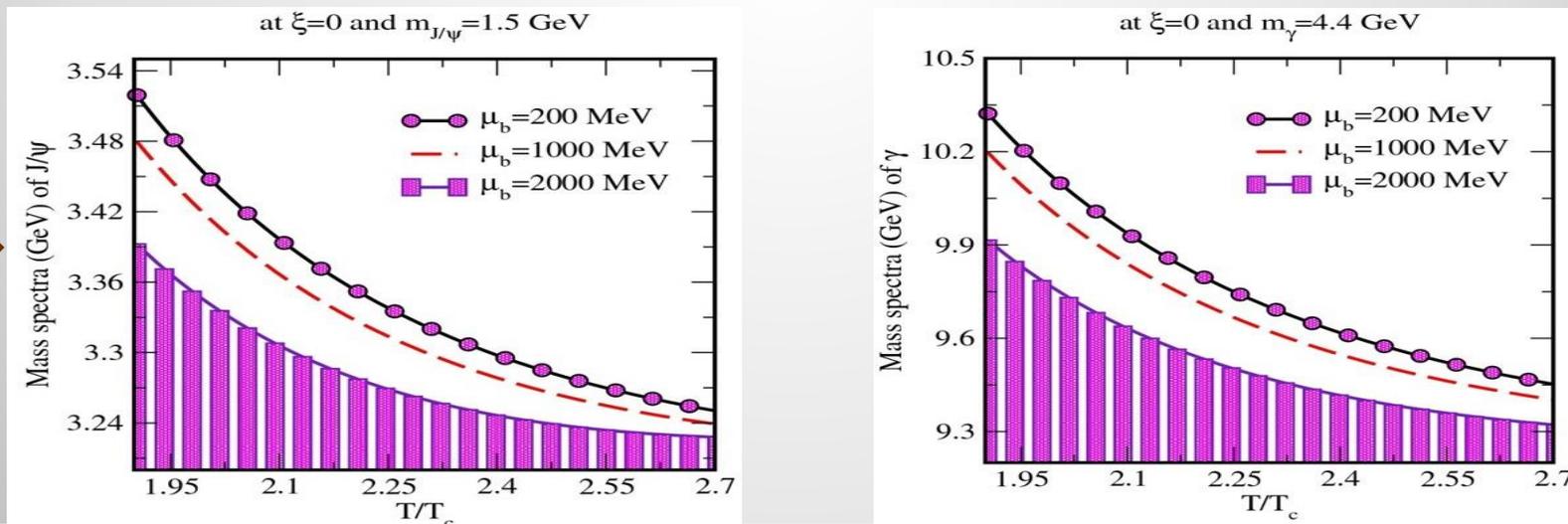


Fig: Shows the variation of mass spectra of the J/ψ (left panel) and Υ (right panel) with T/T_c at different values of anisotropy (ξ) when the value of μ_b is fixed.

COMPARISON OF MASS SPECTRA VALUES WITH EXPERIMENTAL AND THEORETICAL VALUES

Table: Mass spectra of ground state of quarkonium at $\xi=0$.

Mass spectra are in the unit of GeV					
For $m_{J/\psi}=1.5$ GeV and $m_\Upsilon=4.5$ GeV					
States	$\mu_b=200$ MeV	$\mu_b=1000$ MeV	$\mu_b=2000$ MeV	Theoretical Result [39]	Experimental Result [97]
J/ψ	3.520	3.480	3.391	3.060	3.096
Υ	10.32	10.18	9.909	9.200	9.460

Table: Mass spectra of ground state of quarkonium at $\mu_b=1000$ MeV.

Mass spectra are in the unit of GeV					
For $m_{J/\psi}=1.5$ GeV and $m_\Upsilon=4.5$ GeV					
States	$\xi=-0.3$	$\xi=0$	$\xi=0.3$	Theoretical Result [39]	Experimental Result [97]
J/ψ	3.361	3.480	3.597	3.060	3.096
Υ	9.864	10.18	10.53	9.200	9.460

Conclusions

Found a good agreement with the values of recently published experimental and theoretical data.

With Increases
Baryonic Chemical
Potential

- ❖ Binding Energy decreases.
- ❖ Mass spectra decreases.
- ❖ Thermal width increases.
- ❖ Dissociation temperature decreases.

With Increases
Anisotropy

- ❖ Binding Energy increases.
- ❖ Mass spectra increases.
- ❖ Thermal width decreases.
- ❖ Dissociation temperature increases.



Thank you!

Thanks to all audience for
their patience.