HEAVY QUARKONIUM SUPPRESSION BEYOND THE ADIABATIC LIMIT

Jacob Boyd, Thomas Cook, Ajaharul Islam, and Michael Stricland

Department of Physics, Kent State University, Kent, OH 44242 United States

Abstract

In Ref.[1], we relax the assumption of the adiabatic approximation by solving the 3d Schrödinger equation in real-time in order to compute quarkonium suppression dynamically. We compare results obtained using the adiabatic approximation with real-time calculations for the realistic complex heavy quark potentials.

We find that, for the $\Upsilon(1s)$, the difference between the adiabatic approximation and full real-time evolution is at the few percent level, however, for the $\Upsilon(2s)$, we find that the correction can be as large as 18% in low temperature regions. For the J/Ψ, we find a larger difference between the dynamical evolution and the adiabatic approximation, with the error reaching approximately 36%.

1. Heavy Quarkonium States

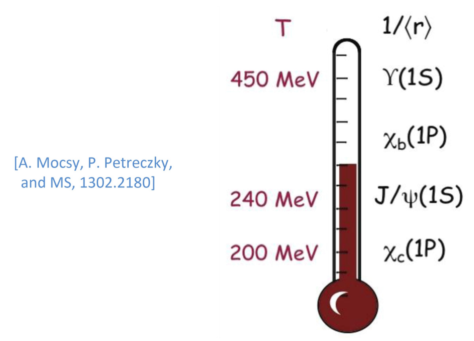
We know that the strong coupling constant decreases with increasing energy. Therefore, at a high energy, the interaction among quarks becomes negligible and quarks behave as free particles. This phenomenon is known as asymptotic freedom.

At temperatures around T =170 MeV, the deconfinement phase transition occurs and quarks and gluons are liberated from light hadronic states and form a state consisting of quasi-free quarks and gluons called the Quark-Gluon Plasma (QGP).

At temperatures below roughly 600 MeV, there still remain some quarkonium states which are bound states of a heavy quark and its antiquark. As the QGP temperature increases, the effective color charge is reduced due to the Debye screening and q and $\bar{q}$ become unbound and the quarkonium state melts in the QGP.

$n^{2s+1}L_J$	J^{PC}	Particle	Mass (MeV)
1^3S_1	1^{--}	J/ψ	3096.90
1^3P_0	0^{++}	$\chi_{c0}\,(1P)$	3414.75
1^3P_1	1^{++}	$\chi_{c1}\,(1P)$	3510.66
1^3P_2	2^{++}	$\chi_{c2}\,(1P)$	3556.20

Charmonium: $c\bar{c}$



$n^{2s+1}L_J$	J^{PC}	Particle	Mass (MeV)
1^3S_1	1^{--}	$\Upsilon(1S)$	9460.30
1^3P_0	0^{++}	$\chi_{b0}\,(1P)$	9859.44
1^3P_1	1^{++}	$\chi_{b1}\,(1P)$	9892.76
1^3P_2	2^{++}	$\chi_{b2}\,(1P)$	9921.21
2^3S_1	1^{--}	$\Upsilon(2S)$	10023.26
1^3P_0	0^{++}	$\chi_{b0}\,(1P)$	10232.50
1^3P_1	1^{++}	$\chi_{b1}\,(1P)$	10255.46
1^3P_2	2^{++}	$\chi_{b2}\,(1P)$	10268.65
3^3S_1	1^{--}	$\Upsilon(3S)$	10355.20

Bottomonium: $b\bar{b}$

Ajaharul Islam, Kent State University

So, now if we can define a term **"suppression"** indicating the probability of melting of a particular state, one expects that the $\chi_c(1P)$ is most suppressed and $\Upsilon(1S)$ is least suppressed in the QGP.

The suppression factor can be defined as

$$R_{AA} = \frac{\text{number produced in}AA}{\langle N_{\text{bin}}\rangle_b\,(\text{number produced in } pp)}\,,\quad \langle N_{\text{bin}}\rangle_b = \text{number of nucleonic collisions}$$

$$\begin{aligned} &= 1\,,\ \text{No effect} \\ &> 1\,,\ \text{Enhancement} \\ &< 1\,,\ \text{Suppression} \end{aligned}$$

2. Adiabatic approximation (KSUa)

Previous works have used the adiabatic approximation to obtain the suppression factor or survival probability. In this approach, they first solved the SWE with a complex-valued potential numerically in order to obtain the real and imaginary parts of the binding energy and then they folded this together with the QGP's hydrodynamic evolution.

In the adiabatic approximation, one ignores the mixing of various excited states which emerge in a time-dependent potential. The result is that in this approximation the time-evolution of each state is governed solely by the time-dependent imaginary part of the states energy, i.e.

$$N_n(t) = N_n(0)\exp\left(2\int_{t_0}^{t_f} dt\, \Im[E_n(t)]\right), \tag{1}$$

where

$$N_n(t) = |c_n(t)|^2\,, \tag{2}$$

is the modulus-squared overlap states of type n at time t. Finally, they used equation (1) to obtain the survival probability i.e., $|c_n(t)|^2$.

3. Real-time evolution (KSUr)

In the improved method we use the real-time quantum evolution instead of adiabatic approximation.

At first, we solve the real-time 3D SWE with a complex-valued potential. For this purpose, we make use of a complex Karsch-Mehr-Satz (CKMS) type potential based on the internal energy

$$V(r,t) = \Re[V] + i\,\Im[V]\,, \tag{3}$$

where,

$$\begin{aligned} \Re[V] = &-\frac{\alpha}{r}(1+m_D r)\exp(-m_D r) + \frac{2\sigma}{m_D}[1-\exp(-m_D r)] \\ &-\sigma\, r\,\exp(-m_D r) - \frac{0.8\,\sigma}{m_Q^2\, r}\,, \end{aligned} \tag{4}$$

and

$$\Im[V] = -\alpha_s T\phi(\hat{r})\,,\ \phi(\hat{r}) \equiv 2\int_0^\infty dz \frac{z}{(z^2+1)^2}\left[1-\frac{\sin(z\,\hat{r})}{z\,\hat{r}}\right]. \tag{5}$$

where $\sigma = 0.210$ GeV^2 is the string tension, and m_D is the QGP Debye mass $m_D^2 = (1.4)^2 \cdot N_c(1+N_f/6)\,4\pi\alpha_s T^2/3$ with $N_c = 3$ and $N_f = 2$; $\alpha = 4\alpha_s/3 = 0.385$, and $\hat{r} \equiv m_D r$, $\alpha_s = 0.289$.

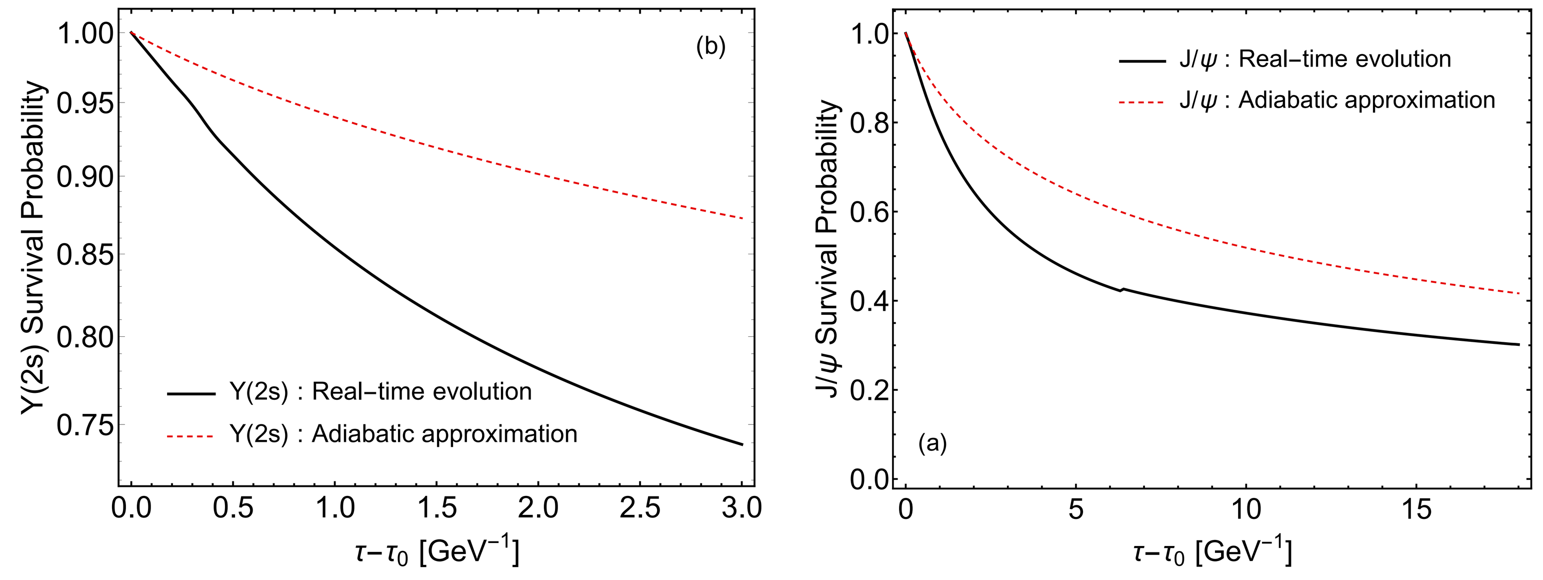
We then expand the wave function, i.e., $\psi(t,x) = \sum_{n=0}^{\infty} c_n(t)\psi_n(t,x)$ and obtain the overlap coefficients $c_n(t)$. Finally, we compute the survival probability i.e., $|c_n(t)|^2$.

We made several case studies using the CKMS potential (3). In all cases, we assumed that the system was undergoing boost-invariant and transversally homogenous one-dimensional Bjorken flow such that $T(\tau) = T_0\left(\frac{\tau_0}{\tau}\right)^{1/3}$, where T_0 is the initial temperature at the proper time τ_0.

We kept the initial time fixed to be $\tau_0 = 1$ GeV^{-1} = 0.197 fm/c and varied the initial temperature to mimic what is seen in a typical Glauber temperature profile in a LHC 2.76 TeV Pb-Pb collision. In all cases shown below, we terminated the evolution when the temperature fell below the freeze-out temperature T_{fo} =150 MeV.

4. Results: Comparison between KSUa and KSUr

In this example, we consider $T_0 = 0.225$ GeV at $\tau_0 = 1$ GeV^{-1} for Υ and $T_0 = 0.4$ GeV at $\tau_0 = 1$ GeV^{-1} for J/ψ.



T_0 [GeV]	State	% correction to primordial R_{AA}
0.6	$\Upsilon(1s)$	-6%
0.225	$\Upsilon(1s)$	+3%
	$\Upsilon(2s)$	-18%
	$\chi_b(1p)$	-4%
0.4	J/Ψ	-36%
0.2	J/Ψ	-0.6%
	$\chi_c(1p)$	-23%

5. Conclusions

- The adiabatic approximation was accurate to the percent level for the $\Upsilon(1s)$.
- At low temperatures, we found large corrections to the adiabatic approximation for the $\Upsilon(2s)$ survival probability.
- In the charmonium sector, we found larger corrections to the adiabatic approximation, with the real-time evolution predicting stronger suppression in all cases.

Acknowledgements and references

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[1] J. Boyd, T. Cook, A. Islam, and M. Strickland, ***"Heavy quarkonium suppression beyond the adiabatic limit,"*** arXiv:1905.05676 [hep-ph].

[2] Michael Strickland, *"Using bottomonium production as a tomographic probe of the quark-gluon plasma"*, arXiv:1906.00888[hep-ph].

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