Survival of $B_c$ mesons in a hot plasma within a potential model

W.M. Alberico
* Dipartimento di Fisica dell’Università di Torino and
  Istituto Nazionale di Fisica Nucleare, Sezione di Torino,
  via P.Giuria 1, I-10125 Torino, Italy

S. Carignano
Department of Physics, University of Texas at El Paso, El Paso, TX 79968, USA

P. Czerski
The H. Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences,
ul. Radzikowskiego 152, PL-31-342 Kraków, Poland

A. De Pace and M. Nardi
Istituto Nazionale di Fisica Nucleare, Sezione di Torino,
via P.Giuria 1, I-10125 Torino, Italy

C. Ratti
Dipartimento di Fisica dell’Università di Torino,
via P.Giuria 1, I-10125 Torino, Italy

We extend a previous work on the study of heavy charmonia and bottomonia in a deconfined quark-gluon plasma by considering the $B_c$ family of mesons. With the introduction of this bound state of a charm and a beauty quark, we investigate at finite temperature the behavior of the quarkonium, in an energy region between the $\psi$ and the $\Upsilon$ states.

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INTRODUCTION

In the context of relativistic heavy ion collisions the early production of heavy quarkonia and the modulation of their survival while crossing the deconfining medium, created and thermalized afterward in the collision, has been considered as a meaningful test of deconfinement since long ago. The attention has been first focused on charmonia and bottomonia since in a single hard collision (already in p-p scattering) the relevant pairs $c\bar{c}$ and $b\bar{b}$ can be produced and can form one meson in the $J/\psi$ or $\Upsilon$ families (for recent reviews see, e.g., Refs. [1, 2]). Instead the production of a $B_c$ meson ($c\bar{b}$ or $\bar{c}b$) requires, in the p-p case, the simultaneous occurrence of two hard partonic scatterings, which appears to be less favorable.

On the contrary, the $B_c$ formation could be favored in a nucleus-nucleus collision where many more partonic (hard) scatterings can occur simultaneously. Hence the $B_c$ production might be significantly enhanced in A-A collisions with respect to p-p ones.

The number of $B_c$ states coming out from the global process is strongly affected, on the one side, by the melting of the initially formed $c\bar{c}$ and $b\bar{b}$ mesons inside the hot, deconfined plasma; on the other side it is affected by the regeneration process (as foreseen, for example, within a coalescence model) which, according to several authors [3], can be important for hidden-charm and -beauty mesons, while it will certainly dominate over the initial hard production for the $B_c$ case.

Here we will mainly focus on the modifications of the binding energy of a $B_c$ meson due to the increasing temperature of the plasma, above the critical temperature $T_c$ for deconfinement.

The mass and lifetime of the $B_c$ produced in $pp$ have been measured by the CDF and DØ collaborations at Tevatron by studying both its semileptonic $B_c \rightarrow J/\psi \ e^{-}\nu X$ and the hadronic $B_c \rightarrow J/\psi \ \pi$ decay channels [4, 5]. Being the heaviest of the $B$ family, the $B_c$ meson has not been observed until recently, in relatively clean experimental conditions. In 2012 the CMS collaboration observed these $B_c^+$ decays at the LHC a mass of $m_{B_c} = 6.272 \pm 0.003$ GeV for the $J/\Psi + \pi^+$ channel and of $m_{B_c} = 6.265 \pm 0.004$ GeV for the $J/\Psi + 3\pi$ channel [6].

In order to study the temperature evolution of the mass and energy eigenvalues of the $B_c$ mesons, we shall employ a non-relativistic potential model, which is justified by the large mass of the constituents quarks (see e.g. Refs. [7, 8]).
In Section 2 we shall shortly review our potential model approach, which is based on accurate fits of lattice data for the thermodynamical free energy. Then we report our estimates for the dissociation temperatures of the $B_c$ family. A short discussion of the $B_c$'s decay modes and our conclusions are contained in the last Section.

A REVIEW OF OUR POTENTIAL MODEL

The considerable mass of the $B_c$ meson allows us to apply to the $B_c$'s the same potential model at finite temperature we previously developed \cite{9,10} in order to study the $J/\psi$ and $\Upsilon$ states. The main points of our approach are the following ones: we suppose that the heavy meson bound states are formed in the initial stage of the heavy ion collision. These states then cross the deconfined plasma, which weakens their binding and in many cases leads to their dissociation. We chose to encode this behavior into an effective temperature-dependent potential, which can be extracted from a fit to lattice QCD calculations of the color singlet free energy $^1 F_1$. From an accurate series of fits on $F_1$ \cite{9},

$$ F_1(r,T) = \frac{-4}{3} \alpha(r,T) e^{M(T)r} + C(T) \tag{1} $$

the singlet internal energy was calculated as $U = -T^2 \partial (F/T)/\partial T$ and the effective heavy quark potential $V(r,T)$ was singled out from the medium contributions \cite{10,13}:

$$ V_1(r,T) = U_1(r,T) - U_1(r \to \infty, T). \tag{2} $$

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1 The potential model adopted here was fitted to lattice data obtained in the approximation of $N_f = 2$ light flavors \cite{11}. We are aware of more recent data \cite{12}, which have been qualitatively improved by increasing the number of lattice points for small $T$. This is however not too relevant for our case, since the present approach is valid only close to $T_c$ or above it.
In Eq. (1) the coupling $\alpha$ is fixed by the customary RGE, but employing a temperature dependent scale, with coefficients determined, at each temperature, by the above mentioned fitting procedure. For further details we refer the reader to Ref. [3].

We then solve the Schrödinger equation associated to the quarkonium states,

$$\left(-\frac{\hbar^2}{2\mu}\nabla^2 + V(r,T)\right)\psi(\vec{r},T) = \epsilon(T)\psi(\vec{r},T),$$

and obtain the temperature dependent energy eigenvalues, which allow us to follow the evolution of the bound state masses and to determine the dissociation temperatures, namely the temperature at which the binding vanishes.

By evaluating the quarkonium radial wave functions $R(r)$ in the origin, we are also able (via a non-relativistic QCD expansion) to construct the corresponding spectral functions $|\chi_{B_c}|^2$ [13, 15], which encode many physical properties of these states and allow a direct comparison with lattice QCD results [10, 14].

RESULTS AND DISCUSSION.

We present our results starting with the temperature dependence of the masses of the $B_c$ states. The fundamental state ($B_c$), the first radially excited state ($B'_c$) and the first P-wave state ($\chi_{B_c}$) have been considered. Our model does not distinguish between states with intrinsically different angular momentum, hence the $B_c$ and its hyperfine partner $B_c^*$ appear degenerate. In order to establish the model dependence on the effective masses chosen for the heavy quarks, we performed calculations using both $m_c = 1.4$ and 1.6 GeV for the charm quark and both $m_b = 4.3$ and 4.7 GeV for the beauty. Dynamical thermal masses, defined as the sum of the quark mass and the asymptotic value of the $Q\bar{Q}$ potential, are also introduced [10]. While the necessity of including such contributions may be questionable, we remark that the resulting variation in the meson masses is almost negligible, being always below 50 MeV for $T < T_c$ and below 20 MeV for $T > T_c$.

![Fig. 2: Mass as a function of temperature of the first](image1)

![Fig. 3: Mass as a function of temperature of the lowest](image2)

The results for the masses of the pseudoscalar ground state $B_c$, for the radial excitation $B'_c$ and for the P-wave state $\chi_{B_c}$ as a function of $T/T_c$ are shown in figures 1, 2 and 3 respectively. The values obtained from lattice QCD predictions $m_{B_c} = 6304 \pm 20$ MeV [18] and a study with zero temperature potential models gives $m_{B_c} = 6258 \pm 3$ MeV [14], the latter being closer to the most recent measurement [8]. These numbers are quoted for reference only, but cannot be directly compared with the mass values obtained at finite temperatures: in particular the present approach cannot be extended to temperatures much below the critical one.

Table I shows the dissociation temperatures (defined as the value where the binding energy vanishes) obtained for the various states, in units of the critical temperature $T_c = 202$ MeV (we use here the same value of $T_c$ employed in Refs. [9] and [11] for $n = 2$ flavors).

We also report in Figs. 4 and 5 the variation with the temperature of the radial wave function (or of its first derivative for the P wave state) evaluated in the origin for the $B_c$ and $\chi_{B_c}$ states respectively. The values obtained by zero temperature potential models [13] are $|R(0)|^2 = 1.68$ for the S-wave and $|R'(0)|^2 = 0.20$ for the P-wave state.
The values of $R(0)$ and $R'(0)$ are then used to build the spectral functions at different temperatures. Indeed, we recall that the spectral function for a generic meson channel $\sigma_M(\omega, T)$ can be written as \[8\]

\[
\sigma_M(\omega, T) = \sum_n |\langle 0 | j_M | n \rangle|^2 \delta(\omega - E_n) = \sum_n F_{M,\lambda}^2(\omega - E_n) + \theta(\omega - s_0)F_{M,\epsilon}^2,
\]

where, for instance, $F_{PS}^2 = \frac{N_c}{2\pi} |R(0)|^2$ for the pseudo-scalar state and $F_S^2 = \frac{9N_c}{2\pi m_b} |R'(0)|^2$ for the P-wave scalar state \[15\].

In order to achieve a better comparison with lattice and perturbative QCD results, we add, respectively, a finite width to the bound state peaks ($\Gamma = 100$ MeV ) and a multiplicative factor which restores the correct asymptotic $\propto \omega^2$ behavior of the continuum part of the spectral functions.

Figures 6 and 7 show the evolution of the S wave spectral function with the temperature. As one can see, the fundamental bound state peak survives above critical temperature (up to $\sim 2 T_c$), while the excited state dissociates around $T_c$. We also report in Fig. 8 the shape of the P-wave spectral function. The fundamental P-wave state dissociates at $T \sim T_c$.

### Decays

The $B_c$ lifetime is considerably longer than the one of the other heavy quarkonia, due to the lack of direct annihilation decay channels. Usually the $B_c$ decays are divided into three classes, the first two involving the decay of one quark with the other acting as a spectator and a third one involving annihilation. It has already been pointed out that an accurate study of the $B_c$ decays would allow better estimates of some CKM matrix elements, as well as of some leptonic decay constants. We would like however to underline the importance of this meson as an additional probe for the dynamics of deconfinement in a hot hadronic environment. At present, as already mentioned in the Introduction, a few hundreds decays of the $B_c$ into $J/\Psi + \pi$ ’s has been observed by CMS; this is also the best decay channel for the $B_c$ detection in the ALICE experiment: the beauty decay would bring to a final state with a $J/\Psi$ and a single pion, with a branching ratio estimated around $\sim 2\%$ \[19\].

In conclusion we have investigated the survival above the critical temperature of a few special quarkonium states, the ones of the $B_c$ family, with the main purpose of drawing the attention of the on-going experiments at LHC on these intriguing heavy quarkonia. As already pointed out for the $J/\Psi$ and $Y$ families, they can survive above the
FIG. 6: The $b\bar{c}$ S-wave channel spectral function divided by $\omega^2$ as a function of $\omega$ at $T = 0.8 T_c$ and at $T = 0.95 T_c$ by $\omega^2$ as a function of $\omega$ at $T = 1.2, 1.3$ and $1.4 T_c$.

temperature for deconfinement of the medium and give important information on the properties of the hot medium itself.

FIG. 7: The $b\bar{c}$ S-wave channel spectral function divided by $\omega^2$ as a function of $\omega$ at $T = 0.9 T_c$.

FIG. 8: The $b\bar{c}$ P-wave channel spectral function divided by $\omega^2$ as a function of $\omega$ at $T = 0.9 T_c$.

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Electronic address: piotr.czerski@ifj.edu.pl

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