Abstract

Quarkonium has been proposed as a sensitive probe of quark-gluon plasma (QGP) more than thirty years ago. Since then, lots of experimental efforts have been devoted to study its production in heavy-ion collisions in order to search for QGP and study its properties and significant progresses have been made. In this paper, an overview of recent experimental results on charmonium and bottomonium production in heavy-ion collisions as well as in small systems are presented. Furthermore, the results on exotic particle X(3872) production in Pb+Pb and p+p collisions are also discussed.

Keywords: Quarkonium, Heavy Flavor, Relativistic Heavy-ion collisions, Quark-Gluon Plasma

1. Introduction

Quarkonium is a tightly bound state of a heavy (charm and bottom) quark and its anti-quark. Charmonium (bottomonium) is refer to the bound state of charm (bottom) quark and anti-quark pair. Table 1 shows the mass, binding energy and radius of various quarkonium states [1]. Although the production mechanism of quarkonium in elementary particle collisions such as p+p collisions is still not fully understood, it has been proposed as a unique probe of the deconfined hot and dense medium, so-called quark-gluon plasma (QGP), created in ultra-relativistic heavy-ion collisions by T. Matsui and H. Satz in 1986 [2]. If QGP is formed in heavy-ion collisions, the production yield of quarkonium is expected to significantly suppressed with respect to the yield in p+p collisions scaled by the number of binary nucleon-nucleon collision because the potential of the heavy quark and its anti-quark is modified by the deconfined medium and the quarkonium state is subject to be dissociated (or melted) when the temperature of the medium is high enough. The temperature required to dissociate a quarkonium state (dissociation temperature, \( T_d \)) depends on the binding energy or radius of the quarkonium state. More loosely bound state (lower binding energy or larger radius) has lower \( T_d \). In both charmonium and bottomonium sectors, \( T_d \) decreases with increasing quarkonium mass and the excited states have lower \( T_d \) than the 1S state. When put the charmonium and bottomonium states together as shown in Table [1] for comparison, one finds that \( T_d^{\Upsilon(1S)} \sim T_d^{\Upsilon(2S)} \sim T_d^{\Upsilon(3S)} \sim T_d^{\psi(2S)} \sim T_d^{\psi(3S)} \). The systematical measurements of quarkonium suppression can also help to constrain the temperature profile and the dynamic evolution of the fireball produced in ultra-relativistic heavy-ion collisions.
However, other effects need to be taken into account. First of all, in the deconfined medium, the (un)correlated heavy quark and anti-quark could (re)combine into a quarkonium state when they get close enough in phase space. The probability is proportional to the square of the total number of heavy quark and anti-quark pair produced in one collision. The production yield of quarkonium is expected to be enhanced in central heavy-ion collisions with respect to peripheral heavy-ion collisions and p+p collisions. Although the (re)combination effect is competing with the QGP melting effect, both of them requires deconfinement and can be used to search for QGP and study its properties. In addition to these two hot nuclear matter effects, quarkonium production in heavy-ion collisions is also affected by cold nuclear matter (CNM) effects, including modification of parton distribution function in nucleus (nPDF), breakup by hadrons, the scattering and/or energy loss of the parton evolved in quarkonium production etc. The CNM effects can be experimentally studied via the collisions of p or light nucleus and heavy nucleus. There are other effects need to be taken into account when interpret the experimental results. One important effect is the feed-down contribution of the quarkonium production. For example, the inclusive J/ψ consists of prompt J/ψ and non-prompt J/ψ, the latter is refer to the contribution from the decay of B-hadrons. While the former includes direct J/ψ and the feed-down from excited charmonium states. Since different quarkonium states has different component of a quarkonium state should also have different suppression. The composition of different prompt quarkonium states can be found at [3]. Another important effect is the contribution from jet fragmentation at intermediate and high $p_T$ range. The quarkonium from jet fragmentation could form outside of the fireball thus doesn’t affected by the QGP melting or (re)combination, but affected by “jet quenching”.

In the following sections, the selected latest experimental results obtained at RHIC and LHC will be presented and physics implications will be discussed.

2. Quarkonium production in $p$+$A$ collisions and small systems

![Fig. 1. J/ψ nuclear modification factor as a function of Rapidity in $p$+Al, $p$+Au and $^3$He+Au collisions at $\sqrt{s_{NN}}=200$ GeV](image)

PHENIX Collaboration measured the inclusive J/ψ nuclear modification factor as a function of rapidity at forward ($p^3$He-going direction) and backward (Al/Au-going direction) rapidity range in $p$+Al, $p$+Au and $^3$He+Au collisions at $\sqrt{s_{NN}}=200$ GeV as shown in Fig. [image]. The theoretical calculations with nPDF along and with nPDF and nuclear absorption are also shown for comparison. At forward rapidity ($p^3$He-going direction), significant suppression is observed for inclusive J/ψ for Au target but consistent with no suppression for Al target. The theoretical calculations incorporating nPDF (EPPS16, nCTEP15) with and
without nuclear absorption describe the data reasonably well. At backward rapidity (Al/Au-going direction), the nuclear modification factor is systematically larger than unity with Al target but exhibits obvious suppression with Au target. The theoretical calculations with nPDF only predict enhancement at backward rapidity, do not agree with the data for Au target. With the nuclear absorption from global fit to world data added, the theoretical calculations can describe the rapidity dependence of the inclusive \( J/\psi \) suppression in \( p+Al \), \( p+Au \) and \( ^3He+Au \) collisions at RHIC reasonably well. It is also found that the suppression in \( 0\%-20\% \ ^3He+Au \) collisions is very similar as in \( p+Au \), suggesting that there is little final state effect on \( J/\psi \) production in \( p+Au \) and \( ^3He+Au \) collisions.

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**Fig. 2.** Left: Inclusive \( \Upsilon(1S) \) nuclear modification factor as a function of rapidity in \( p+Pb \) collisions at \( \sqrt{s_{NN}} = 8.16 \) TeV [5]. Middle: The cross section ratio of \( \Upsilon(1S) \) and \( J/\psi \) from \( b \) decays in \( p+p \) and \( p+Pb \) collisions [6]. Right: The nuclear modification factor of \( \Upsilon(1S, 2S, 3S) \) as a function of rapidity in \( p+Pb \) collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV [7].

ALICE Collaboration measured the inclusive \( \Upsilon(1S) \) nuclear modification factor as a function of rapidity at forward and backward rapidity range in \( p+Pb \) collisions at \( \sqrt{s_{NN}} = 8.16 \) TeV and compared to LHCb measurements as shown in the left panel of Fig. 2 [5][6]. At forward rapidity, strong suppression is observed and can be described by theoretical calculations with various nPDF only or energy loss only or nPDF + energy loss or nPDF + breakup by comovers etc. At backward rapidity, the data is systematically lower than unity and the theoretical calculations. LHCb also measured the cross section ratio of inclusive \( \Upsilon(1S) \) and \( J/\psi \) from \( b \) decays as a function of rapidity in \( p+p \) collisions at \( \sqrt{s} = 8 \) TeV and \( p+Pb \) collisions at \( \sqrt{s_{NN}} = 8.16 \) TeV as shown in the middle panel of Fig. 2 [6]. At backward rapidity, the ratios in \( p+p \) and \( p+Pb \) are consistent with each other. While at forward rapidity (p-going direction), a small suppression of the ratio is visible in \( p+Pb \) collisions with respect to \( p+p \) collisions. This indicates different suppression mechanism for bottomonium and open beauty. But the rapidity smearing effect in \( b \) to \( J/\psi \) decays should also be addressed. The right panel of Fig. 2 shows the nuclear modification factor of \( 1S, 2S \) and \( 3S \) state of \( \Upsilon \) in \( p+Pb \) collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV measured by the CMS Collaboration [7]. The sequential suppression is observed and is more pronounced in backward rapidity (Pb-going direction). The nPDF effect on \( 1S, 2S \) and \( 3S \) states should be similar and result in \( \sim \) 1 nuclear modification factor at backward rapidity. The sequential suppression at backward indicates there is significant final state effects such as breakup by co-movers or possible hot nuclear medium effects.

### 3. Quarkonium production in heavy-ion collisions

#### 3.1. Charmonium

STAR Collaboration recently published the centrality and \( p_T \) dependence of the inclusive \( J/\psi \) production in wide \( p_T \) range in \( Au+Au \) collisions at \( \sqrt{s_{NN}} = 200 \) GeV [8]. The left panel of Fig. 3 shows the inclusive \( J/\psi \) nuclear modification factor as a function of \( N_{\text{part}} \) in \( Au+Au \) collision at \( \sqrt{s_{NN}} = 200 \) GeV at low-\( p_T \), \( (p_T > 0.15 \) GeV/c\) and high-\( p_T \), \( (p_T > 5 \) GeV/c\) region. The suppression for both low-\( p_T \) and high-\( p_T \) \( J/\psi \) increases towards central collisions and exhibits significant suppression in central collisions (a factor of ~ 3).

For low-\( p_T \), \( J/\psi \), the suppression is due to the interplay of CNM effects, QGP melting and (re)combination effects. While for high-\( p_T \), \( J/\psi \), the (re)combination effect is negligible. The nuclear modification factor
measured in $d+Au$ and $p+Au$ collisions is found to be consistent unity at $p_T$ above 5 GeV/$c$, suggesting that CNM effect is also not important at high-$p_T$ \cite{9,10}. The observed significant suppression of high-$p_T$ $J/\psi$ provide strong evidence for the QGP melting of charmonium.

ALICE Collaboration recently released the results of inclusive $J/\psi$ nuclear modification factor using the Pb+Pb collisions data at $\sqrt{s_{NN}} = 5.02$ TeV taken in 2018 \cite{11}. The new data are found to be consistent with the previous results using data taken in 2015, but the precision is significantly improved. The middle panel of Fig. 3 shows the centrality dependence of the inclusive $J/\psi$ nuclear modification factor at mid-rapidity. Unlike the decreasing trend observed at RHIC energy, the nuclear modification factor at LHC decreases from peripheral collisions to semi-peripheral collisions then increases and saturates at around unity in semi-central and central collisions. The nuclear modification factor in central collisions at LHC is much larger than at RHIC energy for low-$p_T$ $J/\psi$. The $p_T$ dependence of the nuclear modification factor is also very different at RHIC and LHC. At RHIC, the $p_T$ dependence is rather flat, but there is clear decreasing trend with increasing $p_T$ at LHC as shown in the right panel of Fig. 3. These results provide strong evidence of significant contribution of (re)combination for low-$p_T$ $J/\psi$ at LHC energy. The right panel of Fig. 3 compares the $p_T$ dependence of the inclusive $J/\psi$ nuclear modification factor in various rapidity windows. In all of the presented rapidity windows, the nuclear modification factor shows decreasing trend. At low $p_T$, the nuclear modification factor decreases with increasing rapidity. This is also consistent with the expectation of (re)combination dominance in the low-$p_T$ $J/\psi$ production as the charm quark production cross section decreases with increasing rapidity. At high $p_T$ region, the rapidity dependence is not so straightforward. The Statistical Hadronization Model and Transport Models can describe the centrality dependence of the inclusive $J/\psi$ nuclear modification factor within uncertainties. But the uncertainties of the theoretical calculations are larger than data, suggesting that more precise measurements on total charm cross section and CNM effects are needed to provide better constraint.

The (re)combination effect can also be investigated via the measurements of quarkonium elliptic flow $v_2$. The experiments at both RHIC and LHC found $v_2$ of open charm mesons follow the number-of-constituent-quark (NCQ) scaling as the light flavors, suggesting that charm quarks are thermalized and gain flow via the interaction with the hot, dense medium. Quarkonium produced via the heavy quark (re)combination should inherit the flow of the heavy quarks. ALICE Collaboration measured the inclusive $J/\psi$ $v_2$ as a function of $p_T$ at forward rapidity as shown in the left panel of Fig. 4 and mid-rapidity (not shown, worse statistics) in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV \cite{11}. Significant positive $v_2$ is observed. The data at low-$p_T$ can be described by transport model calculations, indicating that charm quark are thermalized and (re)combination is the dominant contribution at low-$p_T$ range. At $p_T$ above 4 GeV/$c$, the data is systematically higher than the model calculations even with the non-prompt $J/\psi$ contribution being taken into account. Other effect such as contribution from jet fragmentation probably need to be considered. Based on the measurements of $J/\psi$ production in a jet in $p+p$ collisions at 8 TeV, the CMS Collaboration concluded that “jet fragmentation is the dominate source of prompt $J/\psi$ mesons with $E_{T,J/\psi} > 15$ GeV and |$y_{J/\psi}$| < 1” \cite{12}. It is of great interest to push the measurement to lower $E$ or $p_T$.

The ALICE Collaboration reported the first measurement of $J/\psi$ polarization in Pb+Pb collisions \cite{11}. The measurement of $J/\psi$ polarization in heavy-ion collisions is a novel probe of the quarkonium production mechanism in QGP. $J/\psi$ polarization in heavy-ion collisions can be modified with respect to $p+p$ collisions...
Fig. 4. Inclusive $J/\psi$ elliptic flow $v_2$ (left) and polarization parameters (right) as a function of $p_T$ in Pb+Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV measured by the ALICE Collaboration [11]. Theoretical calculations on $v_2$ in Pb+Pb collisions and measurements of polarization in $p+p$ collisions are also shown for comparison.

by various effects: 1) Quarkonium produced via (re)combination should be different from that of primordial $J/\psi$; 2) Since different quarkonium states have different polarization, sequential evolution of quarkonium polarization is expected due to sequential suppression; 3) Modification by possible strong electromagnetic field; 4) The screening of non-perturbative effects in quarkonium production in QGP may result in increase of quarkonium polarization [13]; and so on. With current precision, the ALICE results in Pb+Pb collisions are consistent with no polarization and $p+p$ results. The precision is expected to be significantly improved with LHC Run-3 data.

3.2. Bottomonium

Due to much lower production cross section of $b\bar{b}$ than $c\bar{c}$, bottomonium is expected to be less affected by (re)combination effect compared to charmonium thus provide a better probe of QGP melting. Recently, the measurements of $\Upsilon(1S, 2S, 3S)$ suppression in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are available (ATLAS [14] and CMS [15]) at mid-rapidity and ALICE [11] at forward rapidity). Significant suppression of $\Upsilon(1S)$ is observed and the rapidity dependence seems to be more flat than that at 2.76 TeV. The sequential suppression in the bottomonium sector observed at 2.76 TeV is also confirmed with the data at 5.02 TeV with improved precision.

Fig. 5. $\Upsilon(1S)\ v_2$ at forward rapidity (left) and mid-rapidity (right) in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV measured by ALICE [16] and CMS [17], respectively.

Lots of attention was drawn by the first measurements of $\Upsilon(1S)\ v_2$ in heavy-ion collisions done by the ALICE [16] and CMS [17] Collaborations. Figure 5 shows the data and the comparison to inclusive $J/\psi$ and theoretical calculations. The $v_2$ of $\Upsilon(1S)$ is lower than that of inclusive $J/\psi$ and consistent with
zero and theoretical calculations within large uncertainties on the \( \Upsilon(1S) \) measurements. For the physics interpretation of the data, there are several questions need to be understood: 1) Does bottom quark flow? The non-zero \( v_2 \) of \( b \)-hadrons are observed, but it doesn’t mean \( b \)-quarks have flow; 2) What is the fraction of (re)combination for \( \Upsilon(1S) \). On the experimental side, it is important to improve the precision and push the measurement to higher \( p_T \) due to the large mass of bottom quark [18].

3.3. Comparison of \( J/\psi \) and \( \Upsilon \)

![Fig. 6](image)

With high-quality quarkonium data in heavy-ion collisions, it is possible to do comparison between the charmonium sector and bottomonium sector to better understand physics behind the measurements. In the charmonium sector, I focus on the high \( p_T \) region in order to avoid the contribution from (re)combination. The left panel of Fig. 6 shows the nuclear modification factor of \( \Upsilon(1S) \) and prompt \( J/\psi \) as a function of \( p_T \) in Pb+Pb collisions at \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \) [14]. The suppression of high-\( p_T \) \( J/\psi \) due to QGP melting is expected to be stronger than \( \Upsilon(1S) \) because the radius of \( \Upsilon(1S) \) is much smaller than \( J/\psi \). However, the nuclear modification factor of \( \Upsilon(1S) \) is measured to be surprisingly similar as prompt \( J/\psi \) and lower than non-prompt \( J/\psi \) at high \( p_T \). Removing possible (re)combination may result in even stronger suppression of \( \Upsilon(1S) \). The right panel of Fig. 6 shows the nuclear modification factor of \( \Upsilon(1S) \) and prompt \( J/\psi \) in \( p+\text{Pb} \) collisions at \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \) [19]. At \( p_T > 14 \text{ GeV/c} \), the suppression of \( \Upsilon(1S) \) and prompt \( J/\psi \) are consistent within uncertainties, suggesting that the CNM effects are similar for \( \Upsilon(1S) \) and prompt \( J/\psi \) at high \( p_T \), thus can not explain the similarity of the suppression of \( \Upsilon \) and high-\( p_T \) prompt \( J/\psi \) in heavy-ion collisions. How about the feed-down contribution? According to Ref. [3], the composition of high-\( p_T \) prompt \( J/\psi \) is about 65% of direct production and 35% contribution from decay of excited charmonium states. While for high-\( p_T \), \( \Upsilon(1S) \), the composition is about 45% of direct production and 55% contribution from decay of \( \Upsilon(2S) \) and \( \chi_b \). Because \( \Upsilon(2S) \), \( \chi_b \) and \( J/\psi \) has similar radius as shown in Tab. [1] the comparison of prompt high-\( p_T \), \( J/\psi \) and \( \Upsilon(1S) \) is more like the comparison of direct \( \Upsilon(1S) \) and excited charmonium states (such as \( \psi(2S) \) and \( \chi_c \)). The similarity of high-\( p_T \) \( J/\psi \) and \( \Upsilon(1S) \) suppression may indicate that there are other effects such as jet fragmentation, formation time effect playing role in the quarkonium production at high \( p_T \).

Since \( J/\psi \) and \( \Upsilon(2S) \) has similar radius, the suppression of high-\( p_T \) \( J/\psi \) and \( \Upsilon(2S) \) should be similar. However, the suppression of high-\( p_T \) \( J/\psi \) is found to be much less than \( \Upsilon(2S) \) at both RHIC and LHC as shown in the left two panels of Fig. 7. This could not be explained by feed-down effect and possible (re)combination effect. Different CNM effect could be the reason for the different suppression measured in Pb+Pb collisions. As shown in the right panel of Fig. 7 the nuclear modification factor of \( \Upsilon(2S) \) is much smaller than that of \( J/\psi \) at high-\( p_T \) in \( p+\text{Pb} \) collisions. Then the question is why the CNM effects of these two quarkonium states (with similar binding energy) are so different? Is it because of different nPDF? Nevertheless, it is important to consider CNM effects when interpret \( \Upsilon(2S) \) suppression measured in heavy-ion collisions, at least at LHC energies.
3.4. X(3872)

X(3872) is the first exotic hadron discovered by the Belle Collaboration in 2003 in the $J/\psi\pi^+\pi^-$ mass spectrum from $B$ decay [20]. The quantum numbers are measured to be incompatible with expected charmonium states [21]. Its mass is larger than the sum of charm quark and anti-charm quark and consistent with the sum of $D^0$ and $D^{\ast0}$ masses. The internal structure of X(3872) is under debate, the possible candidates are tetraquark state or $D^0\bar{D}^{\ast0}$ molecule state or mixed molecule-charmonium state. The tetraquark state and molecule state has very different binding energy. The radius of tetraquark is similar as that of charmonium state which is less than 1 fm. While for molecule state, the binding energy is very small result in radius as large as several fm. Similar as quarkonium, the yield of X(3872) in dense QCD environment may shed light on the binding energy (internal structure).

The left panel of Fig. 8 shows the ratio of high-$p_T$ ($p_T > 5$ GeV/c) X(3872) (renamed to $\chi_{c1}(3872)$ by PDG) over $\psi(2S)$ as a function of event activity in $p+p$ collisions at $\sqrt{s} = 8$ TeV [22]. It is found that for non-prompt production, the ratio has no significant change with event activity. While for prompt production, there is increasing suppression of X(3872) relative to $\psi(2S)$ with increasing event activity. This is consistent with the interpretation of X(3872) as a large, weekly bound state. The CMS Collaboration measured the ratio of 1.1 ± 0.51(stat.) ± 0.53(syst.) for high-$p_T$ prompt X(3872) and $\psi(2S)$ in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV as shown in the right panel of Fig. 8 [23]. The central value is about a factor of 10 larger than that in $p+p$ collisions, but the data is also consistent with $p+p$ results within 1.5$\sigma$. Better precision is needed to extract the internal structure of the X(3872) particle.
4. Conclusions

In this paper, recent quarkonium(-like) measurements in $p+p$, $p$ or light nucleus + $A$, and $A+A$ collisions at both RHIC and LHC are presented. In $p$ or light nucleus + $A$ collisions, nPDF is important to explain the results, but additional effects are needed. At RHIC energy, nuclear absorption at backward rapidity is needed to bring down the nuclear modification factor of $J/\psi$. At LHC, nuclear absorption should be negligible due to small crossing time. However, final-state effects (such as breakup by comovers, possible hot medium effects) is needed especially at the Pb-going direction. In heavy-ion collisions, the quarkonium production at low and intermediate $p_T$ fits the interplay of QGP melting, (re)combination and CNM effects.

The (re)combination plays significant role in charmonium production at low and intermediate $p_T$, at LHC. For $\Upsilon(2S)$ production in $p+Pb$ collisions at LHC, CNM effects may play important role. At high-$p_T$ region, $J/\psi$ may have sizable contribution from jet fragmentation.

Some new observables such as $J/\psi$ polarization in heavy-ion collisions, $\Upsilon$ $v_2$ in heavy-ion collisions and $X(3872)$ production yield in high multiplicity $p+p$ collisions and $Pb+Pb$ collisions are also presented. But better precision is needed to draw firm physics conclusion.

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