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J/Ψ Suppression in Nuclear Collisions: a Unique Signal of Quark-Gluon-Plasma (QGP)

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ABSTRACT

J/Ψ suppression has long been proposed as a diagnostic tool to probe the formation of quark-gluon plasma (QGP) in relativistic heavy-ion collisions. Over the last thirty years, many theoretical and experimental efforts have been made to understand the dynamics of J/Ψ production in nuclear collisions. An abundance of results are now available from high energy experiments from Super Proton Synchrotron (SPS), elativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) that provide a comprehensive picture of the evolution of the medium produced in these energetic collisions. In this article, an overview of our current understanding on different aspects of J/Ψ production in nuclear collisions will be discussed.

INTRODUCTION

Collisions between heavy nuclei at relativistic energies are believed to produce hot and dense strongly interacting matter in the laboratory, whose properties are governed by Quantum Chromodynamics (QCD). At extremely high temperatures and/or densities, the quasi-free quarks and gluons form a deconfined state of matter under local thermal equilibrium, popularly known as quark-gluon plasma (QGP). The transient nature of the plasma renders its identification difficult in the laboratory. Over past three decades, substantial studies have been performed to search for unambiguous and experimentally viable probes to indicate the onset of color deconfinement in nuclear collisions. In this respect, J/Ψ suppression in heavy-ion collisions is believed to be a prominent signature to indicate the formation of the partonic medium. The bound states of a heavy quark (*Q*) and its anti-quark (*Q-bar*) are collectively called *quarkonium* states, where *Q* can be either a charm (*c*) quark, forming *charmonium* states, or a bottom (*b*) quark, leading to *bottomonium* states. The first discovered and, to date, the most extensively studied *quarkonium* state is J/Ψ, the bound state of *c* and *c*. In 1974 it was found simultaneously at Brookhaven National Laboratory (BNL) in proton-nucleus collisions and at the Stanford Linear Accelerator Center (SLAC) in electron-positron annihilation. In the long history of particle physics, this particle holds a unique place, bearing two names, given to it by the two teams, J by BNL and Ψ by SLAC. The excited states of the *cc* system including Ψ′ and χ were discovered at SLAC. Later, the even more massive *bb-bar* bound states of the *bottomonium* family were also discovered.

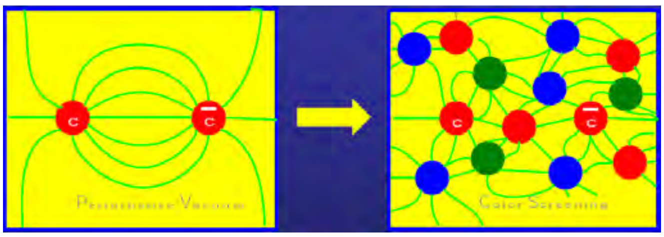

Fig. 1: Cartoon showing the disintegration of *cc-bar* bound states due to Debye screening inside QGP.

While the discovery of J/Ψ helped to confirm the basic validity of the quark model, its absence in nuclear collisions was predicted as clear evidence to confirm the existence of QGP. In 1986, Matsui and Satz argued [1] that if nuclear collisions lead to QGP production, Debye screening of the huge number of colored partons (quarks and gluons) that make up plasma causes the binding between *c* and *c-bar* to become weaker, ultimately leading to the disintegration of the pair and J/Ψ disappears, i.e., it is suppressed. The process is schematically illustrated in Fig. 1. The same picture holds true for other *quarkonium* states as well.

DYNAMICS OF J/Ψ PRODUCTION IN NUCLEAR COLLISIONS

In order to use the J/Ψ meson, which itself is produced in a collision, as a potential probe for deconfinement transition, one needs to have a clear understanding of its production in a vacuum and how the production is affected in the presence of the hadronic medium. We first briefly discuss J/Ψ production in elementary proton-proton (p+p) collisions and then in proton-nucleus (p+A) collisions where the production is affected by the presence of the normal nuclear medium. Finally, we describe J/Ψ production in heavy-ion collisions.

In hadronic collisions, J/Ψ production is considered as a factorizable two-stage process. The first stage is the production of *cc-bar* pairs. Because of the large mass of the charm quarks ($m_c \sim 1{:}5$ GeV/c^2), this stage can be accurately described by perturbative QCD (pQCD). In the second stage, the initially produced colored *cc-bar* pairs form the color-neutral physical bound states. This stage is non-perturbative in nature and still not amenable to fundamental theoretical calculations. Different models have been proposed for inclusive J/Ψ production. Another important feature of J/Ψ production in elementary collisions is that of the measured J/Ψ rates; only around 60% is directly produced as a J/Ψ state, while 30% comes from χ(1P) and 10 % from Ψ(2S) decay. These excited states have narrow decay widths. In nuclear collisions, the presence of any medium would thus affect these excited states themselves and not their decay products. In experiments, J/Ψ production cross-sections in p+p collisions have been measured over a wide range of energies, starting from the threshold up to the highest LHC energies. Let us now consider nuclear collisions: proton-nucleus (p+A) and nucleus-nucleus (A+A) collisions. In both cases, J/Ψ production is affected by the presence of the nuclear matter. However, in case of nucleus-nucleus collisions, a so-called secondary medium is highly likely to be additionally produced. In p+A collisions, usually no such secondary medium is anticipated and hence they provide a reliable tool to estimate J/Ψ production in a confined medium. In p+A collisions, nuclear effects can come into play in all of the evolutionary stages of J/Ψ production. A number of different phenomena have been identified so far and have been collectively termed as cold nuclear matter (CNM) effects. Due to CNM effects, J/Ψ production is depleted inside the nuclear medium as compared to hadronic collisions. The reduction in the production cross sections are usually quantified in terms of an effective absorption cross section, σ_{abs}, which represents the break-up cross section of the *cc-bar* pair in its pre-resonance or resonance state inside the target nucleus [2]. Measurements of the J/Ψ production cross section in p+A collisions were extensively performed by different experimental collaborations at SPS. It was initiated by the NA38 Collaboration, which collected the J/Ψ events for the first time in 1988, with a 450 GeV proton beam incident on various targets. Later, both NA50 and NA60 Collaborations reported the effective absorption cross section σ_{abs} with incident proton beams of energies 450, 400 and 158 GeV. σ_{abs} is found to depend on the collision energy and increases with decreasing energy of the incident proton beam. Moreover Ψ′ was found to be more suppressed compared to J/Ψ, due to its much smaller binding energy.

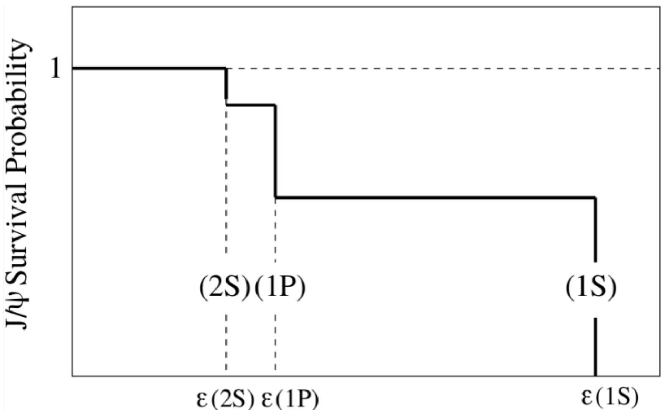

Fig. 2: Sequential J/Ψ suppression by color screening inside QGP. Different dissociation temperatures led to different dissociation energy densities for different charmonium states.

After discussing J/Ψ production in p+p and p+A collisions, we have now come to heavy-ion collisions. Here, one would look for suppressed production of J/Ψ mesons that are connected to the formation of QGP. However, the CNM effects will also be present at a higher degree due to the spectator nucleons present in both the target and projectile. If some *anomalous* suppression, in addition to the normal nuclear suppression, could be detected in the heavy-ion data, then that could be connected to the presence of a secondary medium eventually produced in the collisions. The two most important effects of a deconfined medium on J/Ψ production are sequential J/Ψ suppression and regeneration of J/Ψ.

Sequential J/Ψ suppression

Inside QGP, Debye color screening becomes operative and with increasing plasma temperature the binding potential weakens, leading to the dissociation of *cc-bar* bound states at some characteristic dissociation temperature, T_d. Different *charmonium* states, owing to different binding energies, correspond to different values of T_d. Color screening would thus produce a sequential suppression pattern with the excited states dissociated at a lower temperature than the ground state. As mentioned earlier, in hadronic collisions only 60% of the measured J/Ψ are directly produced and the rest comes from decay of the excited states. As a consequence, inside a QGP medium, J/Ψ exhibits a step-like suppression pattern, as illustrated schematically in Fig. 2, where the J/Ψ survival probability is set to unity if the production rate suffers only from CNM effects. However, in addition to plasma screening effects, another essentially important effect was found to be the collisional dissociation of J/Ψ due to hard partons, which leads to sizable inelastic reaction rates comparable to the fireball expansion rate. Debye screening, being a macroscopic effect, remains operative as the deconfined medium is in thermal equilibrium. On the other hand, collisional dissociation can also be operational in the pre-equilibrium phase as long as the medium is in deconfined stage.

Regeneration of J/Ψ

The normal and anomalous suppression mechanisms discussed above are applicable to the primordial J/Ψ mesons produced in initial hard nucleon-nucleon collisions. In case of heavy-ion collisions at SPS energy, the average number of *cc-bar* pairs produced per central Pb+Pb collisions is much less than one. Hence, if the initially produced charm quark pairs fail to form a *charmonium* state close to their creation point, it is highly improbable that they recombine at a later stage in the medium and form a resonant state. However, for nuclear collisions at collider energies like those available from RHIC and LHC, the physical scenario might be different. In a central Au+Au collision at the top RHIC energy, about 10 *cc-bar* pairs are produced, while at LHC energies the number is approximately 100. Theoretical estimations show that at LHC, the uncorrelated *c* and *c-bar* quarks from different pairs thus have significant probability to meet and form a *charmonium* bound state, either during evolution of the QGP phase or at hadronization of the plasma.

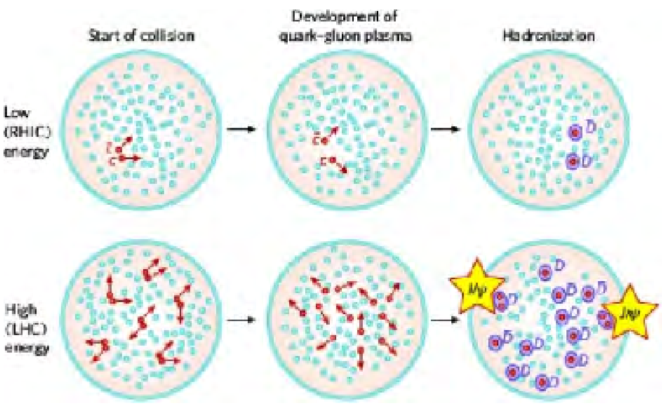

Fig. 3: Cartoon showing regeneration of J/Ψ mesons from exogamous *cc-bar* pairs at LHC energies. The figure is adopted from Ref.[3].

The resulting regeneration of J/Ψ arises as a novel mechanism for *charmonium* production in heavy-ion collisions at higher energies, as illustrated via the cartoon in Fig. 3. One common assumption of the theoretical models accounting for *charmonium* regeneration is that the initially produced J/Ψ mesons are entirely destroyed due to color screening in the deconfined medium. A wealth of data on J/Ψ production in heavy-ion collisions from different experiments have been collected for the last three decades.

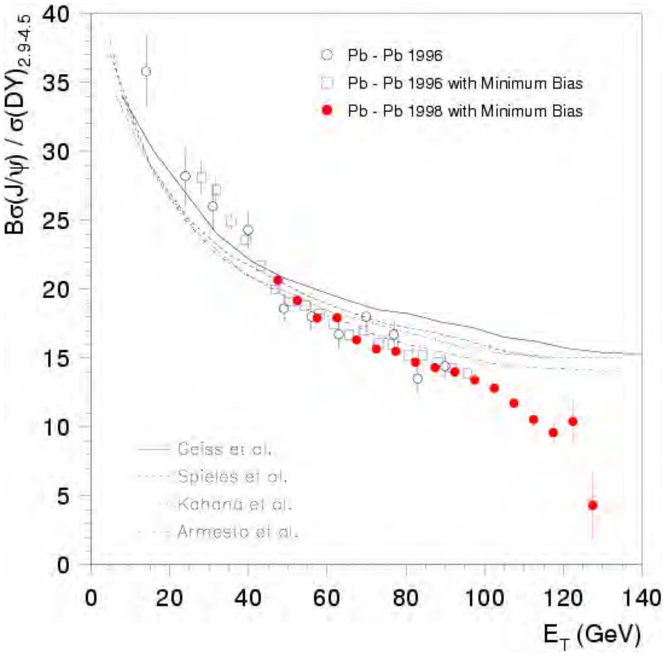

Fig. 4: Evidence for anomalous J/Ψ suppression in 158 A GeV Pb+Pb collisions, measured by the NA50 Collaboration at SPS. The figure is adopted from Ref.[4]

The first significant measurement of anomalous J/Ψ suppression in heavy-ion collisions was first observed by the NA50 Collaboration in Pb+Pb Collisions, at a beam energy of 158 A GeV [4], as shown in Fig. 4. However the theoretical origin of the additional suppression is still unsolved and debated, as the data have been found to be explained by a variety of models, with or without incorporation of the deconfinement scenario.

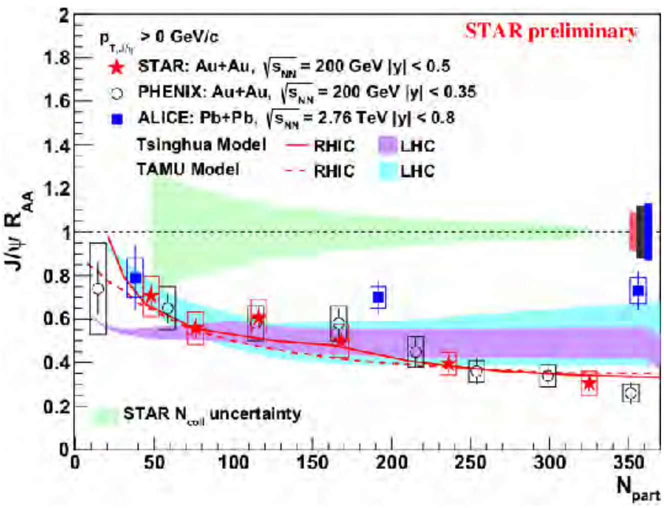

Fig. 5: Inclusive J/Ψ R_{AA} at mid-rapidity as a function of collision centrality measured by STAR and PHENIX at RHIC and ALICE at LHC and their comparison to theoretical models. The figure is adopted from Ref. [5].

Subsequently, the NA60 Collaboration has also measured J/Ψ suppression in 158 A GeV In+In collisions. Data were found to be compatible with cold nuclear matter suppression without leaving any room for the anomalous suppression mechanism to be operative. No measurement exists, to date, on J/Ψ production in heavy-ion collisions below the top SPS energy. The primary reason for this is the extremely small charm production cross sections at lower collision energies. This, in turn, demands accelerators with very high beam intensities and detectors enabled with unprecedented high rate capabilities. On the higher energy side, J/Ψ production has been extensively measured at center-of-mass energy 200 GeV Au+Au collisions by the STAR and PHENIX Collaborations at RHIC and at center-of-mass energy 2:76 TeV Pb+Pb collisions by ALICE, CMS and ATLAS Collaborations at LHC. The observed suppressions are quantified in terms of the nuclear modification factor, R_{AA}, defined as the ratio of J/Ψ production in A+A collisions to that in p+p collisions, normalized to the number of binary nucleon-nucleon collisions, N_{coll}, from the colliding nuclei. The measurements are in line with the fact that J/Ψ undergoes significantly weaker suppression at LHC compared to at RHIC. This can be attributed to the larger relative contribution from regeneration of the exogamous charm quark pairs at the LHC. Theoretical models incorporating plasma screening, regeneration and CNM effects can describe data at both RHIC and LHC reasonably well, as depicted in Fig. 5. The J/Ψ measurements at RHIC have also been extended to lower beam energies by both the PHENIX and STAR Collaborations, through the RHIC beam energy scan program. In most central collisions, the mid-rapidity J/ΨR_{AA} exhibits nearly a flat trend from SPS to the top RHIC energy and then increases towards LHC. This feature can also be reproduced by theoretical models considering regeneration. The recent results at LHC pushed the J/Ψ measurements to a higher collision energy. The suppression is found to be lesser at 5.02 TeV than at 2.76 TeV, as evident from Fig. 6. This confirms a higher degree of regeneration of J/Ψ mesons with increasing energy of the collision.

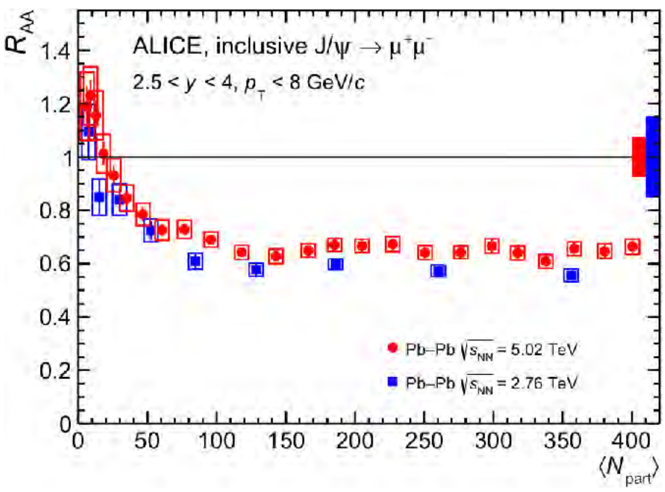

Fig. 6: Inclusive J/Ψ R_{AA} at a mid-rapidity as a function of collision centrality measured by STAR and PHENIX at RHIC and ALICE at LHC and their comparison to theoretical models. The figure is adopted from Ref. [6].

SUMMARY & CONCLUSION

In conclusion, the J/Ψ meson, which was discovered almost half a century ago, still continues to be a topic of active interest in nuclear physics. With the available measurements on J/Ψ production at SPS, RHIC and LHC, a comprehensive understanding of the multifaceted aspects of production dynamics is gradually emerging. In the low p_T regime, J/Ψ has significantly less suppression at LHC energy than at RHIC energy due to the larger relative contribution from the regeneration process. At high p_T, J/Ψ production is less sensitive to the regeneration effect, and the observed suppression is seen to increase with increasing collision energy, which can be attributed to the higher temperature of the plasma. Looking toward the future, the Compressed Baryonic Matter (CBM) experiment at the Facility for Antiproton and Ion Research (FAIR) [7], in Darmstadt, Germany has planned to perform pioneering measurements on J/Ψ production in nuclear collisions, in the beam energy range 10 - 40 A GeV. Due to very low charm production cross sections, the regeneration effects are anticipated to be negligibly small at FAIR, which would provide the possibility to observe the exact traces of primordial suppression. A close to 10 A GeV beam sub-threshold production mechanism will come into play. Altogether, these measurements will open up a new window in this classical topic in the coming years.

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