THE CALIBRATION OF QUARKONIUM PRODUCTION IN NUCLEAR COLLISIONS*

Helmut Satz

Fakultät für Physik, Universität Bielefeld
33501 Bielefeld, Germany
satz@physik.uni-bielefeld.de

Quarkonium production has been considered as a tool to study the medium formed in high energy nuclear collisions, assuming that the formation of a hot and dense environment modifies the production pattern observed in elementary collisions. The basic features measured there are the relative fractions of hidden to open heavy flavor and the relative fractions of the different hidden heavy flavor states. Hence the essential question is if and how these quantities are modified in nuclear collisions. We show how the relevant data must be calibrated, *i.e.*, what reference has to be used, in order to determine this in a model-independent way.

The original suggestion for charmonium production as a means to test the formation of a deconfined medium in high energy nuclear collisions was based on the idea that color screening in such a medium would prevent the binding of charm quarks to a color neutral J/ψ [1]. The J/ψ production process in elementary hadronic collisions (taking pp as example) begins with the formation of a $c\bar{c}$ pair; this pair can then either lead to open charm production (about 90%) or subsequently bind to form a charmonium state (about 10% for all charmonia). A schematic illustration (Fig. 1) shows the dominant high energy reaction through gluon fusion.

The initial $c\bar{c}$ production can be calculated in terms of the parton distribution functions f_{p} of the relevant hadrons and the pertubative partonic cross section. The full description of charmonium binding has so far resisted various theoretical attempts; on the other hand, the process is in good approximation independent of the incident hadronic collision energy [2, 3]. This is a consequence of the fact that the heavy quark propagator in the reaction
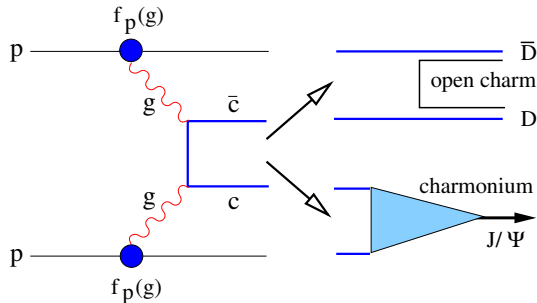

Fig. 1. Schematic view of J/ψ production in pp collisions.

$gg \to c\bar{c}$ strongly dampens the mass variation of the $c\bar{c}$ pair with incident energy. Thus the fractions of the produced $c\bar{c}$ system into hidden *versus* open charm as well as those for the different charmonium states are approximately constant; once determined at one energy, they remain the same also for different energies. As a result, the phenomenological color evaporation model [4–7] provides a good description of charmonium production through the form

$$\sigma_{hh \to J/\psi}(s) = g_{c\bar{c} \to J/\psi}\, \sigma_{hh \to c\bar{c}}(s)\,, \tag{1}$$

and, correspondingly, for the other charmonium states. Here, the constant $g_{c\bar{c} \to J/\psi}$ specifies what fraction of the total $c\bar{c}$ production cross section goes into J/ψ production; in pp collisions it is typically about 2%. The set of the different constants $g_{c\bar{c} \to i}$ for the different charmonium states i thus effectively characterizes charmonium production in the absence of a medium.

A further important aspect of quarkonium production in elementary collisions is that the observed $(1S)$ ground states J/ψ and Υ are in both cases partially produced through feed-down from higher excited states [8–11]. Of the observed J/ψ rates, only some 60% is a directly produced $J/\psi(1S)$ state; about 30% comes from $\chi_c(1P)$ and 10% from $\psi'(2S)$ decay. Because of the narrow width of the excited states, their decay occurs well outside any interaction region.

The features we have here summarized for charm and charmonium production are readily extended to that of bottom and bottomonium. To simplify the discussion, we shall continue referring to the charmonium case, keeping in mind that all arguments apply as well to bottomonia. Given the patterns observed in elementary collisions, we want to see how they are modified in the presence of a medium, as provided by nuclear collisions. From the point of view of production dynamics, one way such modifications can arise is as *initial state effects*, which take place before the $c\bar{c}$ pair is produced. The main possibilities considered so far are nuclear modifications of the parton distribution functions (shadowing or antishadowing) and a possible energy

loss of the partons passing through the nuclear medium to produce the $c\bar{c}$. Once produced, the pair can encounter *final state effects*, either in the form of a phase space shift already of the $c\bar{c}$, *e.g.*, through an energy loss of the unbound charm quarks, or through effects on the nascent or fully formed charmonium state. Such effects may arise from the passage through the cold nuclear medium, or because of the presence of the medium newly produced in the nuclear collision. The latter is evidently what we have in mind when we want to use quarkonia to study quark–gluon plasma production. The difficulties encountered over the past years [12, 13] in arriving at a conclusive analysis of the relevant nuclear collision data on J/ψ production are largely due to the problem of parametrizing the different effects and then constructing a convincing model correctly incorporating all of them. We want to show here that today experimental means have become available which allow us to calibrate the measured results in a way which avoids these difficulties.

Before we turn to the problem of determining medium effects on quarkonium production, we recall the two main conceptual approaches on what may happen; the two can perhaps best be labeled *suppression* and *enhancement.* Color screening in a quark–gluon plasma will decrease the quarkonium binding, both in strength and in its spatial range, and this should for sufficiently energetic nucleus–nucleus collisions lead to quarkonium dissociation or melting. Since the larger and less tightly bound states will melt at lower temperature or energy density than the ground states, color screening will produce *sequential suppression* [14, 15]. We illustrate this for the J/ψ. After an initial threshold melting the ψ' and hence removing its feed-down component for J/ψ production, there will be a second threshold for χ_c melting and then finally a third, at which the direct $J/\psi(1s)$ is dissociated. The resulting pattern is illustrated in Fig. 2. We have here introduced something denoted as J/ψ survival probability. Theoretically, this is the chance of a J/ψ to
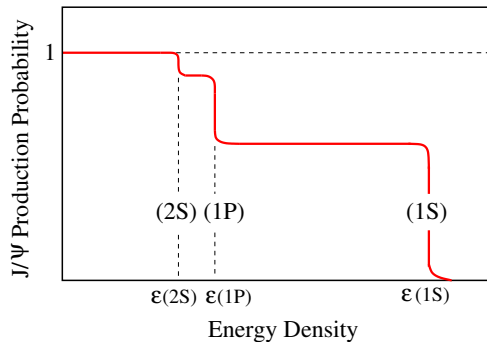

Fig. 2. Schematic view of sequential J/ψ suppression in a deconfined medium.

persist as a bound state in a deconfined medium. How to properly define this quantity as a useful observable in experimental studies is the subject of this paper.

The other alternative, J/ψ enhancement, assumes, in accord with color screening and the resulting suppression, that at sufficiently high energies there is an almost complete dissociation of the J/ψ's produced in primary nucleon–nucleon interactions. On the other hand, at such collision energies, these interactions lead to abundant $c\bar{c}$ production; the rate for this process grows faster than that for the production of light quarks, and if the $c\bar{c}$ pairs remain present in the evolution of the medium, the system will at the hadronisation point show an oversaturation of charm, compared to the predicted thermal abundance. If these charm quarks have become part of an equilibrated medium and as such undergo hadronisation in the form of statistical combination, then such secondary charmonium formation can convert more $c\bar{c}$ pairs into J/ψ's than the dynamical primary production mechanism, thus leading to an effective J/ψ enhancement [16–19], as shown in Fig. 3. We note that this scenario invokes a new and so far unknown binding dynamics to form charmonia; the outcome is assumed to be determined simply by the relative abundance of charm quarks [20].
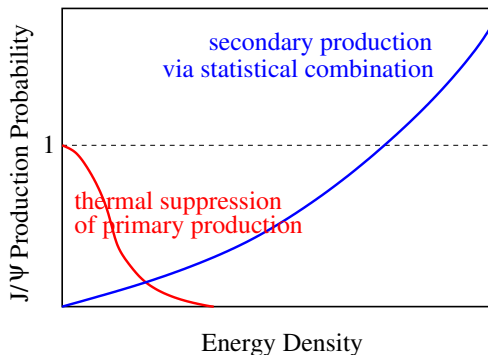

Fig. 3. Schematic view of secondary production through statistical combination.

We now come to our central question: how to calibrate the J/ψ survival? Since we are interested in using quarkonium production as a tool to study the medium produced in nuclear collisions, our primary concern is not if such collisions produce more or fewer $c\bar{c}$ pairs than proton–proton collisions, but rather if the presence of the medium modifies the fraction of produced $c\bar{c}$ pairs going into charmonium formation. In other words, the crucial quantity is the amount of charmonium production relative to that of open charm [21]. To illustrate: in pp collisions, about 2% of the total $c\bar{c}$ production goes into J/ψ's. If in high energy nuclear collisions the to-

tal $c\bar{c}$ production rate were reduced by a factor two, but we still have 2% of these going into J/ψ's, then evidently AA collisions do not modify J/ψ binding. This is, of course, strictly true only for fully integrated rates, which is difficult to check; we return to the issue of phase space variations shortly. But we note here already that in the example just given, the number of J/ψ's produced in AA collisions would be half of that obtained by scaling the results from pp interactions. That is, however, not an indication of any J/ψ suppression; it is just the consequence of having fewer $c\bar{c}$ pairs to start with — the formation probability of charmonia has remained the same as in pp collisions, 2 in nuclear collisions.

To achieve that, we recall: both sequential suppression and statistical enhancement state that the total number of $c\bar{c}$ pairs produced in nuclear collisions is distributed among hidden and open charm differently than it is in proton–proton collisions. The essential observable is thus the ratio of charmonium states to open charm in nuclear collisions, compared to that in pp interactions. Sequential suppression predicts it to decrease with centrality and eventually vanish, statistical enhancement has it increasing with centrality, in many studies beyond the pp value. Hence, the relevant observable is the fraction of charmonia to open charm, or more generally, that of quarkonia to the relevant open heavy flavor production [21–23]. In this quantity, if measured over the entire phase space, the effects of possible initial state nuclear modifications — shadowing/antishadowing, parton energy loss — cancel out, so that whatever changes it shows relative to the pp pattern is due to final state effects.

It should be noted here that in actual applications, it will most likely not be necessary (nor generally possible) to measure the total open charm production rate. The relative abundances of the different open charm states produced in high energy collisions are, so far, found to be in good agreement with the predictions of the statistical hadronisation model [24, 25], with a universal hadronisation temperature of some 150–170 MeV. For open charm production, this model assumes an initial dynamical (perturbative) $c\bar{c}$ production; subsequently, at the hadronisation point, the charm quarks thus produced form open charm hadrons according to their statistical abundances. The relative production rates are thus totally determined in terms of the mass of the open charm state and the universal hadronisation temperature. Such a description is found to hold very well for open charm production in high energy interactions from e^+e^- annihilation through pp and pA collisions; studies of the AA behavior are underway. However, the model does not work for charmonium production, neither in elementary (e^+e^-, pp) nor in nuclear interactions, since the binding mechanism forming charmonia is evidently of dynamical and not of statistical origin. In nuclear collisions, there are in addition medium effects on the binding.

As a consequence, we expect that the *relative abundances* of the different open charm states will not depend on the collision energy and remain essentially the same for elementary and nuclear collisions. Analogous to Eq. (1), the production rate $N(hh \to D_i)$ for a specific open charm state D_i is then a constant fraction of the total open charm rate $N(hh \to c\bar{c})$

$$N(hh \to D_i) \simeq \bar{g}_{c\bar{c} \to D_i} N(hh \to c\bar{c}). \tag{2}$$

The crucial observable, the rate of $(J/\psi)/$open charm, can thus in good approximation be taken as the rate of $(J/\psi)/D_i$ for a specific D-meson state. This will, of course, greatly facilitate the analyis.

The final state effect of interest to us is that caused by the newly produced medium. We, therefore, have to check to what extent the nascent or fully formed J/ψ is already dissociated by the cold nuclear matter of the target or the projectile. This can be done by studying the ratio hidden to open charm in high energy pA collisions. It is, in fact, known that in such interactions there exist reductions of J/ψ production beyond the scaled pp results, but the origin of these is not unambiguously clarified. They could arise largely from initial state effects; but if there is a stronger suppression of ψ' than of J/ψ at energies for which the state is formed inside the nuclear medium, this would indicate that there the interaction depends on its physical size. The different fates of the different quarkonium states in *cold* nuclear matter are due to their different sizes, in a *hot* medium due to the different binding energies. Thus dissociation by color screening should start with a threshold, while the break-up in nuclear matter is presumably continuous. Measurements of charmonia relative to open charm in pA up to highest energies (RHIC, LHC) are therefore of great importance.
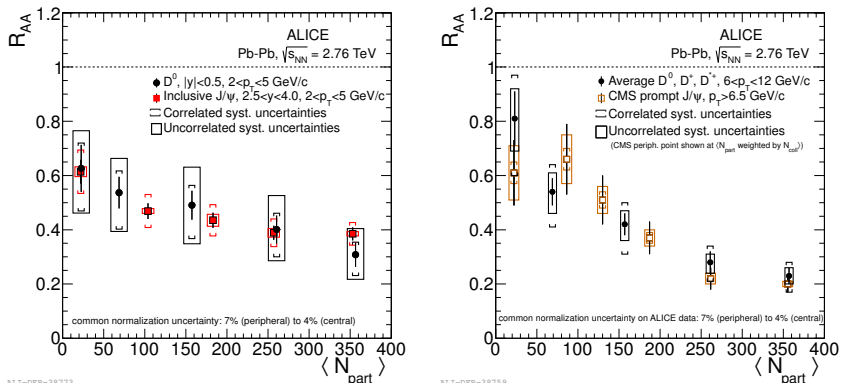

Fig. 4. LHC data from ALICE and CMS [27–29], comparing J/ψ production to open charm production at intermediate (left) and high (right) transverse momenta.

First applications of the in-medium charmonium study based on the relative survival of charmonia *versus* open charm were started last year, using the LHC data from ALICE and CMS [26–29]. In Fig. 4 (left), we show mid-rapidity ALICE data for J/ψ production at intermediate transverse momenta, compared to open charm production in a similar kinematic region. In Fig. 4 (right), the comparison is extended to larger transverse momenta, using CMS data for J/ψ production. In both cases, J/ψ production relative to pp results, scaled by the number of collisions, decreases with increasing centrality, as seen by the corresponding R_{AA} values.

This decrease has at times been considered as suppressed J/ψ production. However, that is incorrect: the corresponding R_{AA} for open charm production, as determined through D measurements, shows within errors the same behavior. In other words, the reduction of the J/ψ is in complete agreement with that of open charm; there is neither suppression nor enhancement, the fraction of the produced $c\bar{c}$ pairs going into J/ψ production has remained in the AA collisions considered here the same as in the corresponding pp interactions

$$R_{AA}(J/\psi) = \frac{N_{AA}(J/\psi)}{n_{\rm c} N_{pp}(J/\psi)} = \frac{N_{AA}(c\bar{c})}{n_{\rm c} N_{pp}(c\bar{c})} = R_{AA}(c\bar{c}), \qquad (3)$$

with $n_{\rm c}$ denoting the scaling factor for the number of collisions at the corresponding centrality. We, therefore, have

$$\frac{N_{AA}(J/\psi)}{N_{AA}(c\bar{c})} = \frac{N_{pp}(J/\psi)}{N_{pp}(c\bar{c})} = g_{c\bar{c}\to J/\psi} \qquad (4)$$

at all centralities, in the kinematic regime indicated. If we divide the J/ψ rates by the open charm rates in the same kinematic region (large $P_{\rm T}$), this ratio becomes centrality independent, and if we normalize it to the corresponding value from pp collisions, it becomes unity. The correct and model-independent J/ψ survival probability for experimental study is thus

$$S_{J/\psi} = \left(\frac{N_{AA}(J/\psi)}{N_{AA}(c\bar{c})}\right) \Big/ \left(\frac{N_{pp}(J/\psi)}{N_{pp}(c\bar{c})}\right) = \frac{1}{g_{c\bar{c}\to J/\psi}} \left(\frac{N_{AA}(J/\psi)}{N_{AA}(c\bar{c})}\right). \qquad (5)$$

In the kinematic regime considered so far, it is indeed unity, there is neither suppression nor enhancement.

At the LHC, corresponding data for low $P_{\rm T}$ open charm production is not yet available. At RHIC, however, it is provided by the PHENIX and STAR collaborations [30–34], and the relevant comparisons of J/ψ *versus* open charm production are shown in Fig. 5. At high $P_{\rm T}$, we have a similar behavior as at the LHC, no change of J/ψ production relative to open

charm. At low P_T, however, the $R_{AA}(c\bar{c})$ of open charm is within errors unity over the whole centrality range; in contrast, $R_{AA}(J/\psi)$ decreases strongly and thus here gives the correct J/ψ survival probability. We see that now with increasing centrality, a smaller and smaller fraction of $c\bar{c}$ pairs go into J/ψ production, with a suppression of up to 75% for the most central collisions. The J/ψ production finally surviving could conceivably be largely due to corona interactions [35].
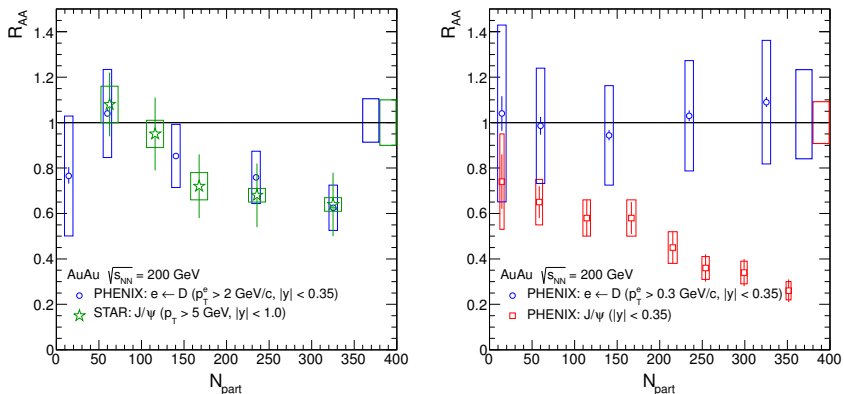

Fig. 5. RHIC data from PHENIX and STAR [31–34], comparing J/ψ production to open charm production at high (left) and low (right) transverse momenta.

In this context, it seems of interest to note that a decrease of the open charm production rates between central and forward rapidity is observed in both pA and AA collisions relative to pp collisions, at Fermilab (pA) and at RHIC (Cu–Cu). We note in particular in the Fermilab data based on 800 GeV pA collisions (see Fig. 6) that at forward rapidity there is a
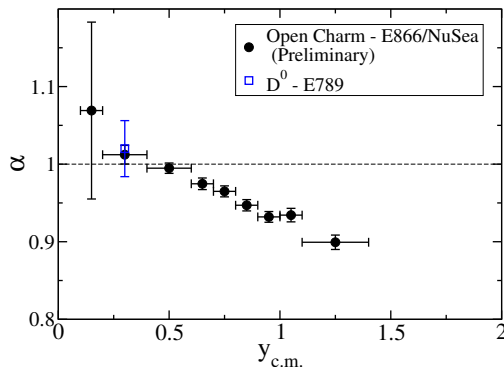

Fig. 6. The rapidity dependence of open charm production in pA collisions at 800 GeV, parametrized in the form $\sigma_{pA} = A^{\alpha}\sigma_{pp}$ [36].

suppression of open charm production, relative to scaled *pp* rates [36], while at midrapidity there is not. A similar effect is observed in Cu–Cu collisions with $\sqrt{s}$ = 200 GeV at RHIC [37]. If this is passed on to charmonium production, one expects for RHIC and LHC data a smaller $R_{AA}(J/\psi)$ at forward than at mid-rapidity, simply because there are fewer $c\bar{c}$ pairs there to form charmonia, no matter how. Such an effect was indeed observed at RHIC and has often been considered a puzzle [38].

The aim of this work was to show how quarkonium production has to be calibrated in order to obtain experiment-based, model-independent information on suppression or enhancement due to the hot medium formed in nuclear collisions. The cited data are given for illustration, to make the point. In a more complete study, the transverse momentum range of J/ψ and open charm should be correlated more precisely. The crucial question now remains, of course, how the open charm rates for low P_{T} production at the LHC will behave. That kinematic region is responsible for the bulk of $c\bar{c}$ production, and the issue to be decided is if nuclear collisions do or do not lead to an overall reduction. At RHIC, that is not the case, as Fig. 5 (right) shows.

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