J/ψ Suppression

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I discuss the current theoretical interpretations of the anomalous J/ψ suppression and their comparison to the most recent experimental data.

1. Introduction

The behavior of J/ψ mesons in a hot strongly interacting medium was proposed as a test for its confinement status [1]: it was argued that the J/ψ, due to its small size and strong binding energy, can not break up as a consequence of interactions with normal hadrons, while in a deconfined medium, the color screening dissolves the $c\bar{c}$ bond.

After this proposal, the study of the charmonium suppression in heavy ion collisions has aroused a lot of interest. With a careful and extensive analysis of the experimental data for different interacting systems (from proton-proton to proton-nucleus and nucleus-nucleus) it has been possible to observe a *normal* suppression of the J/ψ meson, presumably due to the absorption of the preresonant $c\bar{c}$ state in the nuclear medium, in all interactions up to S-U collisions and peripheral Pb-Pb. The experimental data, for proton-nucleus (p-A) collisions, can be accurately described by a simple probabilistic formula for the J/ψ survival probability [2]:

$$S_{pA} \equiv \frac{\sigma^{\psi}_{pA}}{A\sigma^{\psi}_{pN}} = \int d^2b \int_{-\infty}^{\infty} dz\, \rho_A(b,z) \exp\left\{-(A-1)\int_z^{\infty} dz'\, \rho_A(b,z')\sigma_{abs}\right\}\,, \tag{1}$$

where σ_{abs} is the effective cross-section for the absorption of the J/ψ in nuclear matter: the experimental data fit gives $\sigma_{abs} = 4.18 \pm 0.35$ mb [3]; ρ_A is the nuclear profile function, with parameters tabulated in [4].

The obvious generalization of eq.(1) to the nucleus-nucleus (A-B) case [2] gives an excellent description of the J/ψ suppression in S-U as well as in peripheral Pb-Pb collisions.

In central Pb-Pb collisions, i.e. with impact parameter $b < 8 - 8.5$ fm, a stronger suppression is observed [3]: this *anomalous* suppression is the candidate as a signal of deconfined matter production at SPS. Recent NA60 data in In-In collisions confirmed the departure from the normal absorption in central collisions, with a pattern very similar to the one observed in Pb-Pb[5]. Surprisingly, also the first data from PHENIX (RHIC) show a suppression of the J/ψ meson comparable with what observed at SPS energies[6,7], while the common expectation pointed to a much stronger one.

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The aim of this contribution is to give a critical overview of different theoretical interpretations of the anomalous suppression, comparing them to the most recent experimental data. In Section 3, I will present a popular model which explains the NA38/NA50 data without assuming the deconfinement transition. Sections 4 and 5 present two different models of J/ψ suppression in a deconfined medium: thermal dissociation and parton percolation. In Section 6, I will discuss the regeneration model: a recent approach which assumes that the observed J/ψ's can be produced not only in the initial interactions but also in a subsequent stage of the system evolution. This second contribution is expected to be marginal at SPS, but very important at RHIC and LHC energies. Finally, in Section 7, I will draw some conclusions of what we learned in these first ten years of J/ψ suppression and what we need from future experiments.

2. General remarks

It is known from proton-nucleon and pion-nucleon [8] (and, more recently, from electron-proton [9]) interactions that a large fraction (about 30%-40%) of the observed J/ψ's are the decay products of higher excited states of $c\bar{c}$ pairs (ψ', χ). Since the life-time of these quarkonium states is much larger than the typical life-time of the medium which is produced in the nucleus-nucleus collisions, they decay in the vacuum. Therefore this medium (either hadronic gas or quark-gluon plasma) sees not only the ground state quarkonium, but also the different excited states, which have different properties (size, binding energies) and different behavior: a smaller binding energy (and, consequently, a larger radius) requires a lower dissolution temperature, in the case of a deconfined medium; on the other hand, for the case of a hadronic system, a weakly bound quarkonium state has a large break-up cross-section for interactions with the other particles.

Therefore the final J/ψ survival probability, to be compared to the experimental data, has to be calculated as an average over the different components, each of them weighted with the corresponding fraction f_i of contribution to the observed J/ψ's in the final state:

$$S_{J/\psi} = f_{J/\psi} S^{dir}_{J/\psi} + f_\chi S^{dir}_\chi + f_{\psi'} S^{dir}_{\psi'} \qquad (2)$$

This fact has a very important consequence on the pattern of the J/ψ suppression as a function of the centrality and of the energy collisions and it must be considered for a careful comparison to experimental data.

3. Suppression by hadronic interactions

Before concluding that the anomalous suppression indicates the formation of deconfined matter, one should check that the same affect can not be reproduced in a normal hadronic scenario.

Many models of comover suppression have been proposed in the last years, the crucial parameter is the J/ψ-hadron inelastic cross-section $\sigma_{\psi h}$. The current theoretical estimates are quite vague, ranging from 0.1 to a few mb !

Since in S-U interactions the observed suppression is compatible with the normal one, the room for an additional suppression, due to inelastic interactions with secondary hadrons, is very small : this favors a very small $\sigma_{\psi h}$, since a large cross section would have sizable effects.

On the other hand, the anomalous suppression in central Pb-Pb is very strong and sets in quite abruptly : to obtain this effect a comover model must implement a mechanism which gives a very strong increase of the comover density in going from S-U to Pb-Pb[2]. The Dual-Parton Model (DPM) [11] is the most effective one in this respect. The number of secondary hadrons is the sum of two contributions, proportional to the number of participating nucleons and to the number of individual nucleon-nucleon collisions respectively:

$$N_{com}(b,s,y,\sqrt{s}) = C_1(y,\sqrt{s})N_{part}(b,s,\sqrt{s}) + C_2(y,\sqrt{s})N_{coll}(b,s,\sqrt{s}). \tag{3}$$

In the previous formula, b is the impact parameter, s is the 2-dimensional coordinate in the transverse plane, y is the rapidity and $\sqrt{s}$ is the incident energy in the center of mass system. The coefficients C_1 and C_2 are predicted in the DPM, as well as their rapidity and energy dependence. The inelastic cross-section $\sigma_{\psi h}$ is fitted to the experimental data and found to be 0.65 mb [12]. Predictions for RHIC energies are, of course, possible [13], with a correction taking into account shadowing effects (needed to reproduce the data on hadron multiplicity).

In ref. [12] a reasonable description of S-U and Pb-Pb data is shown. However the model fails in describing the In-In results obtained by the NA60 Collab. [5]: the suppression predicted by the DPM is much stronger than what is observed, signaling that the effect of the collision term in Eq.3 is too strong: one could try to reduce it by refitting the parameters, but then the agreement with Pb-Pb data would be lost. The same problem occurs at RHIC energies, where the experimental data are largely underestimated by the theoretical curve [13]. In my opinion, these data clearly disfavor the comover interactions as an explanation for the observed J/ψ suppression.

4. Thermal dissociation

In sufficiently hot deconfined matter, color screening dissolves the binding of the quark-antiquark pair, and a stronger binding energy requires a higher temperature to be dissolved. On a microscopic level, it was argued that only a hot medium provides sufficiently hard gluons to dissociate the quark-antiquark bound state, and this again implies a dissociation hierarchy as function of the binding energy. Another possible mechanism is the decay into open charm mesons due to in-medium modification of mesonic masses[14].

Implicit, in this approach, is the assumption that the medium probed by the quarkonium state is in thermal equilibrium. Lattice studies show that the transition between confined and deconfinement medium occurs at the critical temperature $T_c \simeq 150-200$ MeV.

The large values of the charm (and bottom) quark mass allows potential theory to describe quite accurately the quarkonium spectroscopy[15].

The authors of ref. [14] use the heavy-quark potential $V(T)$ calculated on the lattice[16] to obtain the quarkonium binding energy $M_Q(T)$ (i.e. the mass) and radius $r_Q(T)$, as

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[2] One should, of course, make sure that the comover density needed to reproduce the data is not unrealistically large: this problem, unfortunately, is usually neglected. The authors of ref. [10] use a different approach: they set a physically meaningful limit for the density and the temperature of the hadron gas and conclude that it is not possible to describe the data of the anomalous suppression in the hadronic scenario

a function of the temperature, by solving the Schrödinger equation. Below the critical temperature T_c one finds that the masses $M_Q(T)$ of the $c\bar{c}$ bound states are a decreasing function of the temperature: when the condition $M_Q(T) < V_\infty(T)$ for a given bound state is satisfied ($V_\infty(T)$ is the asymptotic limit of the potential for $r \to \infty$) the dissociation process $Q\bar{Q} \to Q\bar{q} + \bar{Q}q$ is energetically favored and that bound state dissolves.

Above the critical temperature T_c one compares the binding radius $r_Q(T)$ to the screening radius $1/\mu(T)$ (the distance at which the interquark interaction vanishes, according to the lattice results): again it is natural to assume that the bound state dissolves when $r_Q(T) > 1/\mu(T)$. With these ingredients the authors of ref. [14] find that χ and ψ' dissolve already below the critical temperature, while the J/ψ dissolves slightly above T_c. As a consequence, a characteristic sequential suppression pattern is found, with three steps for the onset of the suppression of the ψ', χ and directly produced J/ψ respectively. One has to assume a model to translate the temperature into some experimental variable related to the centrality of the collision, and to take into account fluctuations in the number of participants and collisions for a given impact parameter: the final result will be a smooth curve with two evident drops, one for the χ and the ψ' suppression (if they occur for peripheral collisions they can hardly be separated) and the second one for the J/ψ.

5. Parton percolation

Hadrons are made by partons. When two ore more hadrons overlap, their partons interact. In a normal hadron-hadron interaction, the overlapping phase is so short in time that the partons separate again into hadrons before reaching an equilibrium condition. On the other hand, in a nucleus-nucleus collision, the number of interacting hadrons is so high that their partons can interact several times, they therefore loose their "identity", so that they do not belong anymore to a particular hadron but form a big cluster of deconfined medium: the quark-gluon plasma (QGP).

The percolation theory is a mathematical tool which studies how simple objects form clusters; there are applications of the percolation idea in many physical problems and the deconfinement transition in strongly interacting matter is one of them. For instance, in ref. [17] hadrons interact by exchanging color strings. When many hadrons interact simultaneously in a small space-time region, these strings overlap and, when their density reaches a critical value, they percolate. The model of hadron interaction based on color string exchange (below the percolation threshold) is able to reproduce many features of experimental data (see references in [17]). This model therefore interpolate nicely from interactions in a normal hadronic medium and deconfined matter. A similar approach was followed in [18]: a model of string fusion and percolation is used to describe several experimental observables, including J/ψ suppression.

The work of references [19–21] is essentially focused on J/ψ suppression by parton percolation, inspired by lattice results where it was shown that the deconfined transition in SU(2) Gauge Theory can be described by percolation of Polyakov Loops[22].

Parton percolation is an essential prerequisite for QGP formation. It should be noted that thermal equilibrium is not required and this is main difference with respect to the approach described in section 4.

Cluster formation in percolation theory shows critical behavior : the cluster size diverges at the percolation onset determined by the critical density n_c of overlapping objects. In a finite system the percolation onset is defined as the point at which the grow of the cluster is more rapid [19].

The above considerations apply to a nucleus-nucleus collision if one makes the following assumptions : the overlapping objects, forming clusters, are colored partons and the two-dimensional space where they are distributed is the transverse plane projection of the overlapping region of the two incident nuclei. A parton cluster represents a region in which color charges can move freely: if it extends over the entire space, one has, by definition, color deconfinement.

In high energy nuclear collision there is one additional difficulty: the partons are emitted by the interacting nucleons, therefore their distribution is not uniform in the transverse plane, but rather reflects the original distribution of the initial nucleons, with a higher concentration in the center than near the surface of the nucleus. It is possible that in a given collision, only the most central region of the produced medium is dense and hot enough to allow for the deconfinement transition. In this situation a local definition of percolation, as the one used in ref. [20], is more appropriated since the J/ψ meson is very small and therefore it is sensitive to the properties of a small spatial region. The percolation approach, therefore, has this evident advantage: it naturally allows the deconfined matter to be formed only in a limited part of the produced medium.

Having specified the objects which form clusters, the partons, one has to describe their distribution in space to apply the percolation idea to nuclear collisions. Since these partons are emitted by the incident nucleons as a consequence of the strong interactions during the first stages of the nuclear collision, it is reasonable to assume that their number and spatial distribution is determined by the participating nucleons from which they originate, as done in refs [20,21]. Therefore the density of partons is given by the product of the participating nucleon density $n_s(b,A)$ (which depends on the nucleus A and on the impact parameter of the collision) and the number of partons per nucleon $dN_q(x,Q^2)/dy$ (the parton distribution function, known from deep inelastic scattering experiments). The fraction x of the nucleon momentum carried by the parton is related to the incident energy $\sqrt{s}$ by $x = (k_T/\sqrt{s})$ (at midrapidity); k_T is the average transverse momentum of the parton and it is inversely proportional to its transverse size. With these ingredients, the authors of ref. [21] find that the critical cluster density is reached, in Pb-Pb collisions at SPS, at $b \simeq 8$ fm and the corresponding value of the average transverse momentum of the partons is $Q_c \simeq 0.7$ GeV. The scales of the charmonium states χ_c and ψ', given by the inverse of their radii calculated in potential theory, are about 0.6 and 0.5 GeV respectively: they are therefore dissociated at the onset of percolation. On the other hand, directly produced J/ψ's have smaller radii, therefore the average transverse momentum of the deconfined partons must be at least 0.9-1.0 GeV to resolve them, so only a denser medium, produced in more central collisions, can dissociate them.

The J/ψ survival probability in nuclear collisions is then obtained, from the above considerations, by assuming that about 40% of J/ψ's (those coming from χ_c and ψ' decays) produced inside the percolating cluster disappear at the onset of percolation; those formed outside the cluster, i.e. near the surface, are not affected. The remaining 60% of J/ψ's (the directly produced ones) survive until a cluster of hard enough partons is produced ($b \simeq 3-4$ fm). For a realistic comparison to the experimental data one has, of course, to take into account impact parameter fluctuations (see, for instance,[2]). The result is in good agreement with the experimental data provided by NA50 Collab.

The same model has be used to predict the survival probability as function of the centrality in In-In collisions at SPS. One finds, in this case, that the percolation onset is reached in semi-central collisions ($N_{part} \simeq 140$), but the threshold for the dissociation of directly produced J/ψ's is never reached. One therefore expects, in this model, to observe a suppression pattern with only one step. The recently presented NA60 data show that this is indeed the case: the suppression pattern has one step only and the amount of the decrease is in remarkable agreement with the prediction of the percolation model, but the onset is wrong. It seems therefore that this model implements an excellent geometrical description of the deconfined phase (the amount of the suppression reflects the fraction of space occupied by the deconfined system) but needs to be improved.

6. Suppression and Regeneration

In the previous models it was assumed that the J/ψ are produced exclusively upon the first, hard interactions of the colliding nucleons. Recently, the idea that the J/ψ could also be created at the hadronization transition, by combining the $c\bar{c}$ pairs present in the plasma [23] has been proposed. This phenomenon is possible if the J/ψ states survive above the transition temperature, as suggested by lattice and potential calculations [14, 24].

The authors of refs. [25–27] consider both mechanisms : the primordial J/ψ yield is subjected to nuclear absorption followed by dissociation in the QGP phase. A thermal contribution from statistical recombination of c and $\bar{c}$ quarks at the hadronization transition is added and also the J/ψ break-up due to interactions in the hadron gas is included. The agreement with the experimental data of J/ψ suppression in Pb-Pb collisions at SPS is excellent. The result also shows that the regeneration process gives a small contribution at SPS energies, while it is the dominant one at RHIC in central Au-Au collisions.

7. Discussion and Conclusions

The recently presented experimental data allows us to make a few considerations. First, they show that comover models can not describe simultaneously the S-U, Pb-Pb and In-In data at SPS energies. Even at RHIC energy they fail because they predict a suppression much stronger of what is observed. Actually, every model proposed so far which does not include the statistical regeneration fails in the comparison to PHENIX data. It would be tempting, therefore, to conclude that RHIC data show evidence of the regeneration mechanism at work. However, this conclusion is, in my opinion, premature. First of all, it is difficult to understand, even in the regeneration scenario, how can the J/ψ suppression both in Au-Au and Cu-Cu at different energies ($\sqrt{s_{NN}} = 62$ and 200 GeV) be equal: perhaps a different explanation should be invoked.

A closer look to the newest NA50 and NA60 data shows that the J/ψ suppression, and more precisely the ratio of the number of measured J/ψ's to the expected ones (considering also the normal suppression) is always larger than 0.6. It was only in the previous data analysis that a few experimental points descended below this value for very central collisions, suggesting the presence a ‘second drop’ due to the suppression of directly produced J/ψ's.

The newest SPS data show no evidence of direct J/ψ suppression : the experimental data could be explained, with Eq.2, by assuming $S^{dir}_{J/\psi} = 1$. This is confirmed by the agreement of the result of the percolation model with the NA60 data in central In-In collisions : in this model only ψ' and χ are suppressed, because the J/ψ onset is out of reach in this system. The fact that the suppression in central In-In is about 0.8 instead of 0.6 (as it should be if one removes totally the ψ' and χ components) is due to finite size effects: the deconfinement sets in only in the central, hottest region and only the ψ' and χ formed inside are affected.

This observation is corroborated by recent lattice calculations[24], where the dissociation temperature for the J/ψ in the QGP is found to be very high, about $1.6 - 2T_c$. Similar results have been found in recent potential model calculations, as shown in refs. [28,29]. The practical consequence of this fact is that the energy density required to break up the directly produced J/ψ's can be as high as 30 GeV/fm^3, definitely out of reach at SPS and even in central Au-Au collisions at RHIC ! If this is the case, we should be able to see the suppression of the direct J/ψ component only at LHC.

In this way it is easy to understand why the suppression observed at RHIC is quantitatively similar to the one seen at SPS: since the ψ' and χ components are already totally removed (except for finite size effects) at SPS, they can not be *more* suppressed at RHIC. J/ψ's are unaffected both at SPS and at RHIC. Obviously, more precise data from RHIC experiments are necessary to confirm this scenario.

The reason why all theoretical models not including regeneration effects underestimate the data is simply that all of them assume that the direct J/ψ component can be suppressed: partially at SPS and more intensely at RHIC.

It seems, therefore, that RHIC data can be explained without invoking the regeneration of J/ψ's. Of course, one should check this idea, by looking, for instance, to other observables related to the J/ψ, like flow, rapidity and p_T distribution. The regeneration model has already provided quantitative predictions in this respect[30,31].

Finally, I would like to present a few comments about the deconfinement models in general. It is very common to assume that all charmonium states inside the QGP bubble are inexorably and instantaneously suppressed. This is, of course, an extreme hypothesis: even in a deconfined phase, some time is required to break up a J/ψ (or ψ' or χ) meson, at least the time needed for the c and $\bar{c}$ to fly apart from each other. If the QGP lifetime is shorter of this time or if the $c\bar{c}$ is produced near the QGP surface with a transverse momentum enough to escape before being affected, then the corresponding charmonium state has a chance to survive even in the deconfined medium ! These effects are reasonably very important in small system (like In-In) or in peripheral collisions, right at the onset of the deconfinement. It was reasonable, so far, to neglect these corrections to keep under control the number of free parameters of the theory, but the level of accuracy reached now by the latest data forces us to seriously think about this necessary step forward in future developments.

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