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J/Ψ production at RHIC

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Abstract. The study of J/Ψ production is expected to provide evidence for the production of the Quark-Gluon Plasma (QGP) in relativistic heavy ion collisions. Several models indicate that the production of a QGP will result in changes to the J/Ψ yield. At CERN, the NA50 experiment observed a strong suppression compared to expectations. At RHIC, the PHENIX experiment has measured J/Ψ production at 200 GeV, in pp and d+Au collisions to study cold nuclear effects, in Au+Au and Cu+Cu collisions to study hot and dense medium effects. Here the PHENIX results will be presented and compared to various theoretical models.

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The production of charmonium states in relativistic heavy ion collisions has been a subject of extreme interest along the past twenty years. As first predicted by Matsui and Satz [1], the suppression of charmonia production is expected to be an unambigous signature for the formation of a Quark Gluon Plasma (QGP). A first anomalous J/Ψ suppression, increasing with the centrality of the collision, has been observed by the NA50 experiment at CERN/SPS in Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV, leading to an intense theoretical work. Since 2001, the PHENIX experiment, one of the four experiments running at the Relativistic Heavy Ion Collider (RHIC) has measured the J/Ψ production in p+p, d+Au, Cu+Cu and Au+Au collisions at a center-of-mass energy per nucleon pair up to 200 GeV. The PHENIX experiment measures J/Ψ via its dilepton decay in two central arms (electron channel) covering the mid-rapidity region $|y| < 0.35$ and two forward arms (muon channel) covering forward and backward rapidity region $1.2 < |y| < 2.2$. Here we will review the results obtained by the PHENIX experiment and compare them to the CERN/SPS results, as well as to theoretical expectations. In order to study "anomalous" suppression induced by Hot and Dense Matter (HDM) effects, we will, in a first part, cover "normal" suppression, the Cold Nuclear Matter (CNM) effects induced by the fact that J/Ψ's are produced in nuclei. These effects are studied with p+p and d+Au results. In a second part, we will review the results obtained at RHIC in Cu+Cu and Au+Au interactions and compare them with SPS results. Finally, we will compare these results with theoretical expectations.

1 Cold nuclear effects

The p+p measurement defines the baseline to study nuclear effects for J/Ψ production. It is used to compute the nuclear modification factor R_{AB}:

$$R_{AB} = \frac{dN^{J\psi}_{AB}}{\langle N_{coll}\rangle \times dN^{J/\psi}_{pp}} \qquad (1)$$

where $dN^{J/\psi}_{AB}$ and $dN^{J/\psi}_{pp}$ are respectively the J/Ψ yield observed in A+B collisions and p+p collisions, and $\langle N_{coll}\rangle$ is the average number of nucleon-nucleon collisions (extracted from a Glauber model) occuring in a A+B collision. Any nuclear effect for J/Ψ production leads to a deviation of the R_{AB} ratio from unity. As already mentioned, nuclear effects can come either from Cold Nuclear Matter (CNM) or Hot and Dense Matter (HDM). While HDM effects are studied in A+B (Au+Au or Cu+Cu) collisions, CNM effects have been studied with d+Au collisions (where only CNM effects are expected to occur). Figure 1 shows R_{dAu} (the R_{AB} ratio for d+Au collisions) as a function of rapidity [2]. It exhibits modest CNM effects which can be fairly reproduced by models [4] incorporating weak gluon shadowing which induces a modification of the parton structure functions and weak nuclear absorption which comes from the fact that J/Ψ's are produced in nuclei and can thus interact with the surrounding nucleons [1]. Figure 2 shows the R_{dAu} ratio as a function of the centrality. Again, weak gluon shadowing and weak absorption cross-section seem to be at play. It's important

[1] This last effect is well established. At SPS energies, the absorption cross section has been measured to be 4.18 ± 0.35 mb [3], while at RHIC, its value seems to stand between 1 (the favored one) and 3 mb (the maximum absorption).

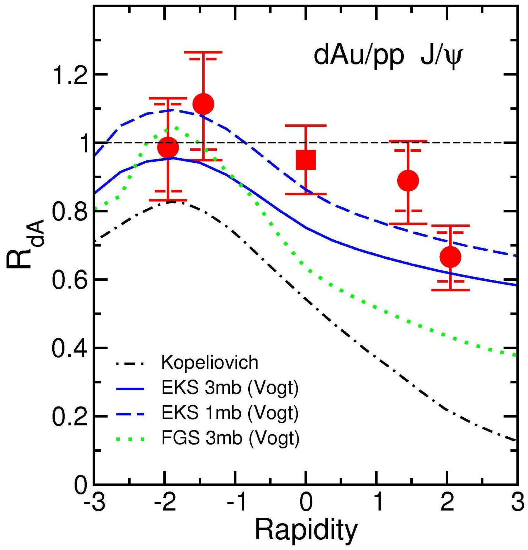

Fig. 1. Nuclear modification ratio for J/ψ production in d+Au collisions as function of rapidity. The lines correspond to several theoretical models [4][6]. Data are well reproduced by a model (EKS 1mb) involving weak gluon shadowing and small absorption cross-section (1 mb).

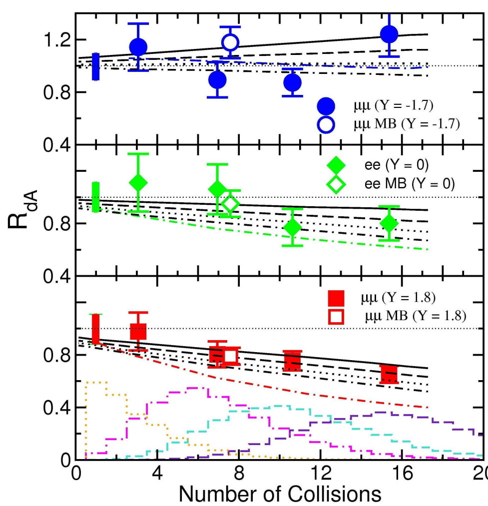

Fig. 2. Nuclear modification ratio for J/ψ production in d+Au collisions as a function of the centrality (given here by the number of collisions N_{coll}). Colored lines correspond to FGS parametrization [4]; black lines correspond to EKS parametrization [4] with several absorption cross-sections, from 0 (upper line) to 3 mb (lower line).

to note that CNM effects depend on the centrality of the collision. Consequently, one has to take these effects into account in order to estimate the Hot and Dense Matter effects.

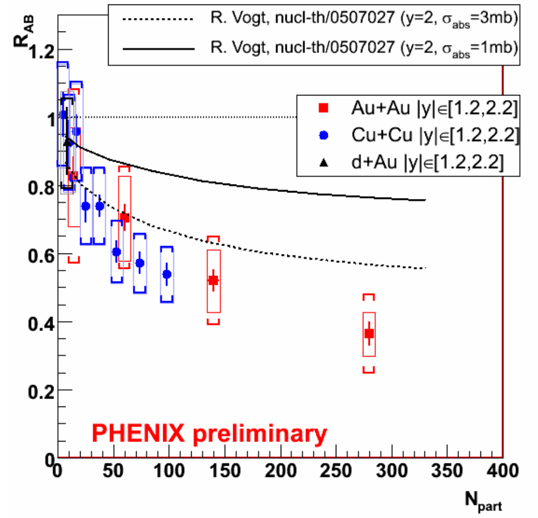

Fig. 3. Nuclear modification factor as a function of centrality (given here by the number of participants) for d+Au, Cu+Cu and Au+Au data at forward rapidity. The curves correspond to theoretical predictions [5] for Au+Au collisions, which include weak shadowing and small abosrption cross-section (1 mb, upper curve, and 3 mb, lower curve).

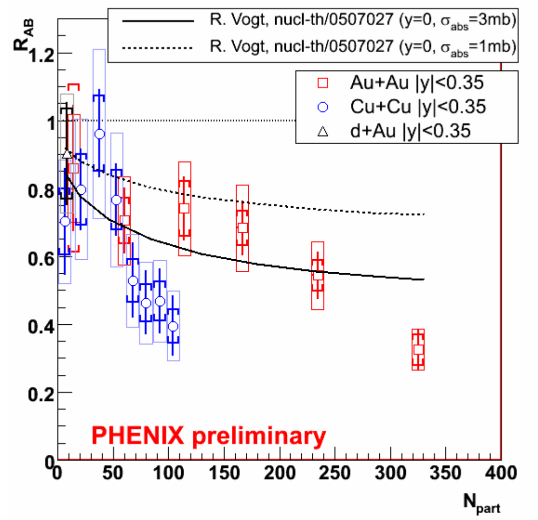

Fig. 4. Nuclear modification factor as a function of centrality (given here by the number of participants) for d+Au, Cu+Cu and Au+Au data at forward rapidity. The curves correspond to theoretical predictions [5] for Au+Au collisions, which include weak shadowing and small abosrption cross-section (upper curve : 1 mb, lower curve : 3 mb).

2 Cu+Cu and Au+Au results

In order to study HDM effects, we consider the results obtained with Au+Au collisions collected in 2004 (241 μb^{-1}) and Cu+Cu collisions collected in 2005 (3.06 nb^{-1}), both at $\sqrt{s_{NN}} = 200$ GeV. Figures 3 and 4 show the results obtained for d+Au, and the preliminary results for Cu+Cu and Au+Au data, both at forward and central rapidities [7]. The lines show theoretical predictions [5] in Au+Au

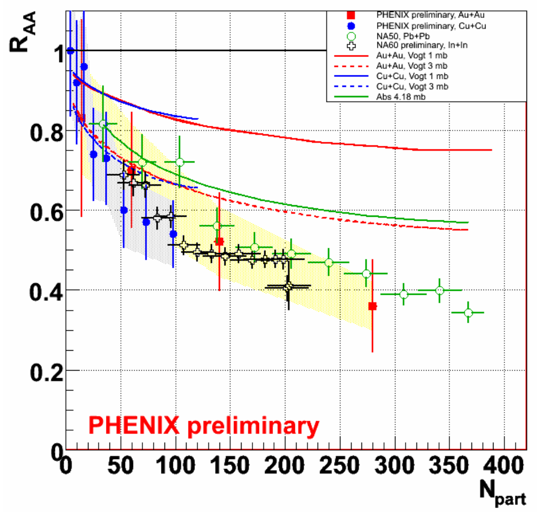

Fig. 5. Nuclear modification factor R_{AA} as a function of centrality (given here by the number of participants N_{part}) for NA50, NA60 and PHENIX data (at forward rapidity).

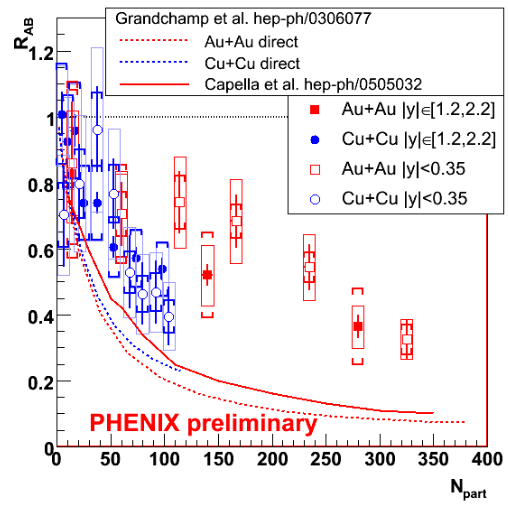

Fig. 6. Nuclear modification factor R_{AA} as a function of centrality (given here by the number of participants N_{part}) for Cu+Cu (blue circles) and Au+Au (red squares) PHENIX data at central (open symbols) and forward (closed symbols) rapidities. Lines are theoretical curves (see text).

collisions for cold nuclear effects. In both cases (at forward and backward rapidity), the J/Ψ suppression in most central Au+Au collisions goes significantly beyond the CNM effects. A factor of at least 2 is observed relative to expected CNM effects and a factor of 3 relative to binary scaled p+p results.

Figure 5 shows a comparison of the results obtained at $\sqrt{s_{NN}} = 200$ GeV at RHIC with the results obtained at lower energies ($\sqrt{s_{NN}} \sim 20$ GeV) at CERN by the NA50 [3] and NA60 [8] experiments. On the experimental point view, without taking into account any CNM effect, the results obtained at both energies are similar. At CERN, the CNM effects are well reproduced with a 4.18 mb absorption cross-section (without including any gluon shadowing effect). At RHIC, depending on the amount of nuclear absorption one considers, the suppression pattern due to CNM effect is similar (if taking 3 mb absorption cross-section) or smaller by a factor of ∼1.3 (if taking 1 mb absorption cross-section), when comparing with SPS results. Depending of the amount of nuclear absorption one takes to reproduce RHIC data, one can conclude that the net additionnal suppression, coming from HDM effects, is either the same at SPS and RHIC, or larger at RHIC. This ambiguity points out the necessity to take additionnal d+Au data at RHIC to improve our knowledge of CNM effects observed at RHIC.

3 Comparison with models

Several models have been proposed to accomodate the results obtained both at SPS and RHIC. In the first subsection, we will cover the models which have been used to fit SPS data and their extensions to RHIC data. Then, we will show the regeneration models and finally we will present the expectations from a sequential suppression model.

3.1 Suppression models

Figure 6 shows Au+Au and Cu+Cu PHENIX results (at both rapidities) and their comparison with some theoretical curves which have been fitted on NA50 data and extrapolated to RHIC energy [9][10]. These models clearly overestimate the J/Ψ suppression observed at RHIC, suggesting that new mechanisms could be at work, J/Ψ regeneration, for instance.

3.2 Regeneration

The regeneration process is based on the idea that in a medium such as a Quark Gluon Plasma, if several c and $\bar{c}$ quarks are produced, then, a c quark from one initial $c\bar{c}$ pair can interact with a $\bar{c}$ quark from a different initial $c\bar{c}$ pair to form a J/Ψ, thus leading to an increase of the net J/Ψ production cross-section. The number of J/Ψ formed via such interactions is expected to be proportional to the number of $c\bar{c}$ combinations, which is roughly proportional to the square of the number of $c\bar{c}$ pair [9][11].
At CERN energies, this process doesn't occur since around 0.1 $c\bar{c}$ pairs are produced, on average, in each collision. On the other hand, at RHIC energies, the amount of $c\bar{c}$ pairs produced in a collision is larger than ten [12].
Figure 7 shows Au+Au and Cu+Cu PHENIX results (at both rapidities) and their comparison with several theoretical curves which include regeneration process. The lower decreasing dashed curves correspond to a direct suppression without regeneration (as in figure 6), the increasing dashed curve corresponds to the regeneration mechanism, and the full curves show the combination of direct suppression and regeneration. Even though the more central Au+Au points are not well reproduced by these curves,

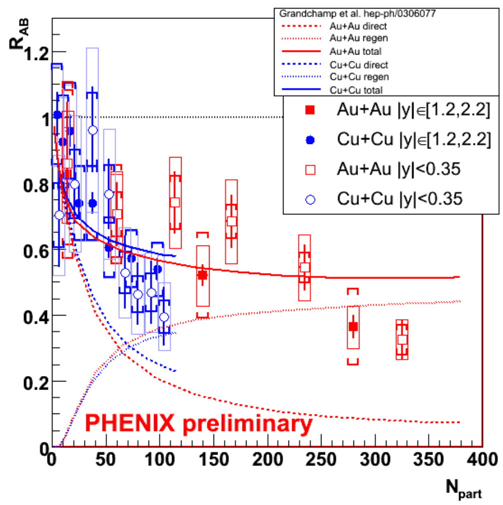

Fig. 7. Nuclear modification factor R_{AA} as a function of centrality (given here by the number of participants N_{part}) for Cu+Cu (blue circles) and Au+Au (red squares) PHENIX data at central (open symbols) and forward (closed symbols) rapidities. Lines are theoretical curves (see text).

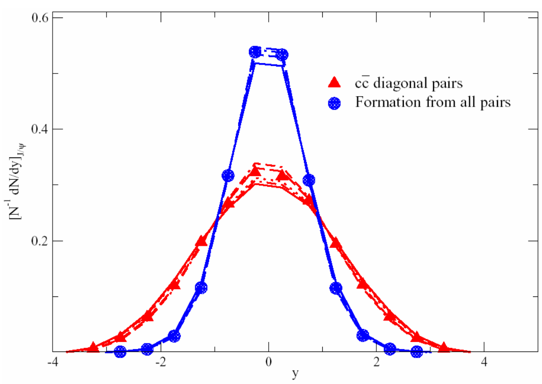

Fig. 8. Predicted rapidity spectra, within the regeneration framework [11], of J/Ψ in Au+Au reactions at 200 GeV.

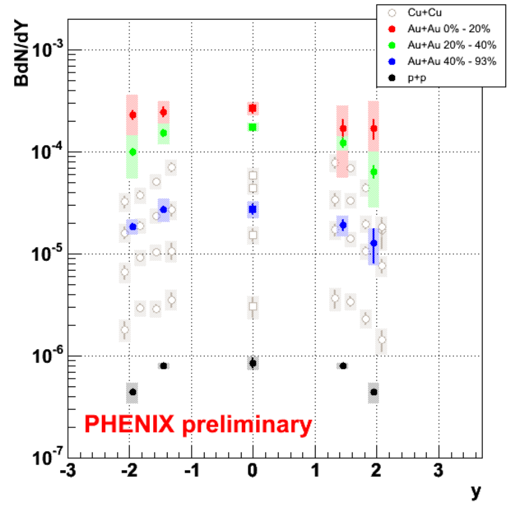

Fig. 9. Measured rapidity spectra for p+p (black points), Cu+Cu (gray points) and Au+Au (colored points). For Cu+Cu and Au+Au, data are displayed for several centrality bins (0% - 2% being the most central one).

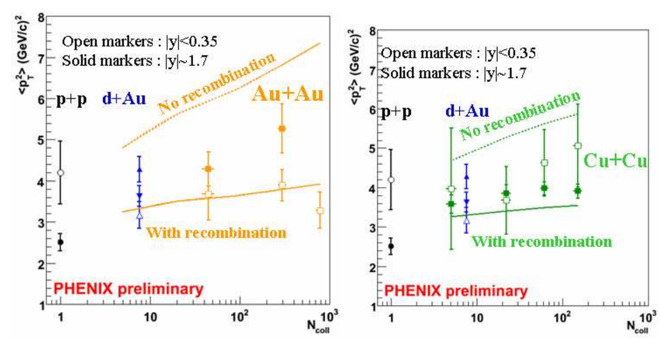

Fig. 10. Mean J/Ψ squared transverse momentum as a function of the number of binary collisions N_{coll}. Left plot shows p+p, d+Au and Au+Au data; right plot shows p+p, d+Au and Cu+Cu data. Lines correspond to theoretical curves with and without regeneration [11].

the agreement is much better than without any regeneration, advocating in favour of a regeneration mechanism interplay at RHIC energies.

Based on scenarios involving regeneration, predictions have been made, both for the J/Ψ rapidity and p_T distributions [11]. Figure 8 shows the predicted rapidity spectra of J/Ψ in Au+Au interactions at 200 GeV. The solid triangles correspond to initial J/Ψ production via diagonal $c\bar{c}$ pairs as it occurs in p+p interactions. Circles correspond to J/Ψ in-medium formation involving regeneration mechanism. As one can see, the spectrum involving regeneration is narrower than the one corresponding to a "standard" J/Ψ production.

Figure 9 shows the rapidity distributions measured by the PHENIX experiment for p+p, Cu+Cu and Au+Au interactions. Cu+Cu and Au+Au results are plotted for several bins of centrality (0% - 20% being the most central one). According to the data, the rapidity distributions are mostly flat for all the systems and all centrality bins. One can then draw the conclusion that no modification in the rapidity shape is observed when comparing p+p to Cu+Cu and Au+Au data, which is in contradiction with the regeneration mechanism expectations.

Figure 10 shows $< p_T^2 >$, the mean J/Ψ squared transverse momentum, for various systems and centrality intervals (given here by the number of binary collisions N_{coll}). The observed broadening of the p_T spectra as a function of the number of collisions is usually attributed to the so-called Cronin effect, the initial state elastic scattering of the projectile parton in the nuclear target before the J/Ψ is produced. In Figure 10 the lines show the prediction made in the regeneration framework. Dashed lines correspond to the expected $< p_T^2 >$ distribution in case of no regeneration (usual Cronin effect); solid lines correspond to the expected $< p_T^2 >$ distribution in the scenario where full regeneration is at work. According to these plots, the "no recombination" (no regeneration) scenario doesn't fit the data. On the other hand the "with recombination"

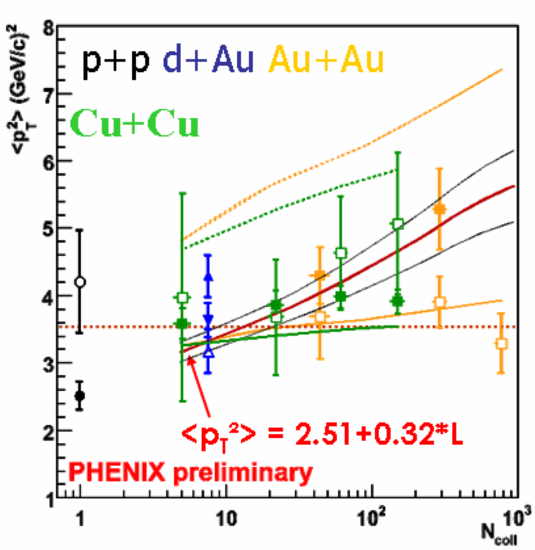

Fig. 11. Mean J/Ψ squared transverse momentum as a function of the number of binary collisions N_{coll} for p+p, d+Au, Cu+Cu and Au+Au data. Yellow and green lines are the same as in figure 10. Red line is a parametrization of Cronin effect derive from d+Au data [13]; the dotted lines on each side show the associated errors.

(regeneration) scenario exhibits a better agreement. According to this figure, the fit could well reproduce the data if one considers that both process are involved at the same time.
Within the PHENIX framework a recent phenomenological parametrization of the Cronin effect was done based on p+p and d+Au data [13]. The parametrization is made as a function of L the length of nuclear matter seen by the J/Ψ in the collision system :

$$\langle p_T^2 \rangle_{AA} = \langle p_T^2 \rangle_{pp} + \rho\sigma(\delta p_T^2) \times L = 2.51 + 0.32 \times L \quad (2)$$

where $\langle p_T^2 \rangle_{pp}$ is the mean squared transverse momentum measured in p+p interactions, ρ is the nuclear matter density, σ is the elastic parton-nucleon scattering cross-section, δp_T^2 is the average p_T quick accounting for one projectile parton scattering, and L is the lenght of nuclear matter seen by the J/Ψ [2]. The L values, corresponding to various N_{coll} values, are determined using a Glauber model. The value of $\rho\sigma(\delta p_T^2)$ given in equation 2 has been obtained by fitting p+p and d+Au data [3].
Figure 11 shows the results of this "Cronin" fit extrapolated to large N_{coll} values. One can see that, this phenomenological fit can fairly reproduce the Au+Au and Cu+Cu $\langle p_T^2 \rangle$ behavior at forward rapidity. At midrapidity, a better p+p baseline is needed to interpret the apparent flat $\langle p_T^2 \rangle$ pattern observed in Au+Au collisions.

[2] which is equivalent to the lenght of nuclear matter seen by the projectile parton since, on average, the J/Ψ is produced in the middle of the interaction region.

[3] Note that due to the very poor statistic of the p+p sample at midrapidity, the fit has been performed on forward rapidity data.

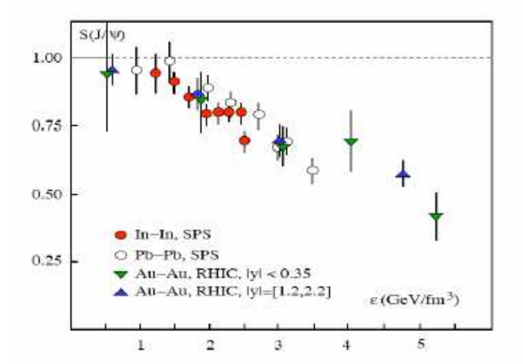

Fig. 12. J/Ψ suppression as a function of the energy density [14] for In+In (NA60), Pb+Pb (NA50) and Au+Au (PHENIX) data.

As a summary of this section, one can conclude that the addition of the regeneration process in the J/Ψ production mechanisms is of good help to interpret the nuclear modification factor observed at RHIC. But its predictions for rapidity distribution behaviours are in contradiction with the data, and the predictions for $\langle p_T^2 \rangle$ distributions are not needed to interpret the $\langle p_T^2 \rangle$ behavior observed in the data.

3.3 Sequential suppression

Recently, a new approach has been proposed [14] to interpret the results observed at RHIC based on recent lattice QCD calculations. According to this new approach, the J/Ψ melting temperature in a QGP could be higher than initially predicted, leading to the fact that the suppression of direct[4] J/Ψ could be out of range at RHIC energies. Only the production of J/Ψ coming from χ_c and Ψ' decays could be suppressed (since their binding energy is smaller than the J/Ψ one). This "hierarchy" in the suppression mechanism should lead to a sequential suppression pattern. In [14], the authors define the J/Ψ survival probability $S_{J/\Psi}$ as follows :

$$S_{J/\Psi} = 0.6 S_{\Psi} + 0.4 S_x \quad (3)$$

where S_{Ψ} is the survival probability for direct J/Ψ and S_x is the survival probability of J/Ψ coming from χ_c [5] and Ψ' [6] decays. Since direct J/Ψ are expected to not be suppressed even at RHIC energies, one expects that at both SPS and RHIC energies, one should observe a decrease of $S_{J/\Psi}$ as a function of the energy density involved in the reaction, until the reach of a plateau at $S_{J/\Psi} = 0.6$.
Figure 12 shows $S_{J/\Psi}$ as a function of the energy density as described in [14] for both RHIC and SPS data. As expected by the authors, $S_{J/\Psi}$ is decreasing until an energy density of ~ 3 GeV/fm^3. Wether data reach a plateau or not is debatable since the highest energy density point is

[4] prompt J/Ψ which are not coming from χ_c and Ψ' decays.

[5] 30% of the total amount of produced J/Ψ.

[6] 10% of the total amount of produced J/Ψ.

below the 60% expected in this scenario. More data are needed, especially in Au+Au collisions at RHIC, to obtain a clearer picture.

4 Conclusion

The results obtained at RHIC on J/Ψ production by the PHENIX experiment have lead to an intense theoretical work on both Cold Nuclear Matter effects and Hot and Dense Matter effects. The J/Ψ suppression pattern observed in A+A collisions is of the same order of magnitude as the one already observed at CERN. It seems to exceed the suppression expected for Cold Nuclear Matter effects, suggesting an additionnal anomalous suppression. This anomalous suppression seems weaker than one expected in the past by extrapolating models which fit SPS data at lower energy. New models such as regeneration models or sequential suppression model better agree with the data, but several questions are still open and will need more data to be fully answered. At RHIC, new sets of p+p data have already been taken in 2005 and 2006 (providing more than 10 times more statistics than got in 2003) and are currently under analysis. In the near future, new Au+Au and d+Au data at $\sqrt{s_{NN}} = 200$ GeV are expected to be stored at RHIC.

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