Theoretical Interpretations of $J/\psi$ Suppression: A Summary*

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The strong “anomalous” $J/\psi$ suppression observed recently by the NA50 Collaboration at CERN SPS has attracted considerable attention. Is it the first signature of a long-awaited quark-gluon plasma, or just a peculiar combination of “conventional” effects acting together to produce the puzzling pattern observed experimentally? This talk is an attempt to summarize the theoretical explanations proposed during the last two years.

1. INTRODUCTION

The data on $J/\psi$ production in high energy nuclear collisions [1] have never been more puzzling, the debates on the origin of $J/\psi$ suppression have never been more heated, and the topic is rapidly attracting attention of physicists, including even those who have never been interested in it before. What is at the heart of the debate, and why is $J/\psi$ suppression so interesting?

$J/\psi$ is a peculiar object. Since it is made of heavy quark and antiquark, its size is small enough to make perturbation theory meaningful, and the description of $J/\psi$ properties and decays was among the first successful applications of perturbative QCD. It is not sufficiently small though to make non-perturbative effects totally negligible; however, they can be analyzed in a systematic way, providing a unique information about the strength of soft gluon fields in QCD vacuum [2]. The $J/\psi$ thus serves a special role of the “borderguard” [3] on the mysterious border of perturbative world of quarks and gluons and non-perturbative world of hadrons. When the structure of the vacuum is violently disturbed in a high energy nuclear collision and the soft and colorless hadronic world suffers the intrusion of abundantly produced colored gluons and quarks, these borderguards are among the first to suffer. What is even more important, $J/\psi$’s, unlike light hadrons, cannot be easily reproduced at later stages of the collision, and their disappearance is documented in the dilepton spectra. These considerations laid the basis for the proposal [4] to use $J/\psi$’s and other heavy quarkonium states for the diagnostics of hot and dense QCD matter.

Observed experimentally by the NA38 Collaboration in 1987, $J/\psi$ suppression therefore excited considerable interest, and immediately triggered debates as to the origin of the effect. It has become clear eventually that a “conventional” approach can explain all features of the $J/\psi$ suppression observed in nuclear collisions with light ion projectiles.

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However the controversy resumed when the new Pb-Pb results of the NA50 Collaboration \cite{1} have been revealed.

2. IS THE OBSERVED $J/\psi$ SUPPRESSION ANOMALOUS?

Before we start discussing various theoretical explanations of the observed phenomenon, let us recall briefly what is actually observed and why it is so surprising. The entire set of the $J/\psi$ production data from $pA$ and $AB$ \cite{5} collisions available before the advent of the Pb beam at CERN SPS has been found \cite{6} to be consistent with the nuclear absorption model \cite{7}. However the fact that $\psi'/J/\psi$ ratio in $pA$ collisions does not depend on the atomic number $A$ (see \cite{8} for a comprehensive compilation of the available data) shows that one cannot interpret the observed nuclear attenuation as the result of the absorption of physical $J/\psi$ and $\psi'$ states in nuclear matter: $\psi'$ is known to have a radius about twice larger than that of $J/\psi$ and is expected to be absorbed with a much larger cross section. Another argument against the naive picture of $J/\psi$ absorption in nuclear matter stems from the magnitude of the extracted cross section, which appears to be approximately two times larger than the $J/\psi$ absorption cross section extracted from the data on $J/\psi$ photoproduction on nuclear targets at small energies \cite{3} and from the VMD analyses of photoproduction on protons. It seems quite safe therefore to state that the gross features of the data on $J/\psi$ production on nuclear targets available before the new Pb-Pb results are consistent with pre-resonance absorption. (This concerns the integrated cross sections, which are determined mainly by the central region; we leave aside for the moment the interesting question of $x_F$, or rapidity, dependence of the $J/\psi$ suppression).

A model which naturally accommodates the listed above features of the $J/\psi$ production on nuclear targets \cite{10} is motivated by the presence of the higher Fock states in the $J/\psi$ wave function \cite{11}, revealed by the recent Tevatron results \cite{12}. At small $p_T$, the $J/\psi$ production is assumed to proceed through the formation of the color singlet pre-resonance $|\bar{c}c_{g}\rangle$ state. Even though the proper formation time of the physical $J/\psi$ and $\psi'$ states is estimated to be rather short, about 0.3 fm, the pre-resonance state can propagate through the entire volume of the nucleus already at SPS energies due to the Lorentz dilatation factor. The target independence of the $\psi'/J/\psi$ ratio in $pA$ collisions is natural in this picture. Furthermore, since the $\bar{c}c$ pair is produced at short distances $\sim 1/2m_c$, much smaller than the inverse transverse momentum of the collinear gluon, the color structure of this state is that of a color dipole formed by two octet charges - the gluon and the almost pointlike $(\bar{c}c)_8$. The interaction of such a dipole with external color fields is enhanced, compared to the usual triplet-antitriplet dipole structure of the $J/\psi$ by the color Casimir factor of $9/4$; one therefore expects an accordingly larger absorption cross section for this pre-resonance state. It should be noted however that a first-principle QCD calculation based on this picture, which would allow to promote the model to a consistent theoretical approach, is still lacking at present \cite{13}.

The new Pb-Pb data in the peripheral region of $E_T \leq 50$ GeV are consistent, within error bars and uncertainty in the value of the absorption cross section, with the pre-resonance absorption calculated in Glauber theory with the cross section of $\sigma_{abs} = 7.3 \pm 0.6$ mb, extracted from the previous $J/\psi$ production data \cite{6} (see Fig. 1, which shows the
result of Glauber calculation with the central value of $\sigma_{abs} = 7.3$ mb).

Figure 1. Left: the $J/\psi$/DY ratio in Pb-Pb collisions [1] versus the prediction of the pre-resonance absorption model [6] with $\sigma_{abs} = 7.3$ mb (the upper curve). Right: the same, normalized to the prediction of the pre-resonance absorption model. The lower curve is the result of the calculation based on the model of ref [45] (see text).

However around $E_T \approx 50$ GeV (corresponding to the average impact parameter of $b \approx 8 \pm 1$ fm) the $J/\psi$/DY ratio jumps down, and deviates significantly from the predictions of Glauber model. The $\psi'/\psi$ ratio at the same time does not seem to show any discontinuities. Remarkably, the integrated Drell-Yan production cross section was found to be consistent with the $A \cdot B$ scaling established previously.

To summarize, the $J/\psi$ suppression observed in Pb-Pb can indeed be considered “anomalous” – it is different from what was observed before in the entire set of the $J/\psi$ production data accumulated prior to the NA50 experiment. We now proceed to the discussion of various theoretical explanations of this effect.

### 3. INITIAL STATE INTERACTIONS

Several authors [14] have considered the effect of nucleon energy loss in the initial state on the $J/\psi$ production. Their idea can be briefly summarized as follows: in a nucleus-nucleus collision, the colliding nucleons lose energy before they produce $J/\psi$’s. Since at SPS we are still in the energy range where the $J/\psi$ production cross section is a steep

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2 The peripheral Pb-Pb data alone suggest a somewhat larger value of $\sigma_{abs}$, but it is consistent within the error bars with $\sigma_{abs} = 7.3 \pm 0.6$ mb extracted from the previous data.
function of the incident nucleon’s momentum (see e.g. [15]), this initial state energy loss will lead to a strong suppression of the $J/\psi$ production. The Glauber-like approaches do not consider the energy loss mechanism and are therefore misleading, significantly underestimating the $J/\psi$ suppression expected from conventional mechanisms. At first glance, the argument looks correct, and seems to be well supported experimentally—the effects of the nucleon energy loss in $pA$ and $AB$ collisions are well established [13]. The problem arises, however, when one recalls that the Drell-Yan pair production cross section, also measured in Pb-Pb collisions by the NA50, follows the $A \cdot B$ scaling law established previously in $pA$ and $SU$ data. Indeed, the high-mass ($M \geq 4$ GeV) Drell-Yan pair production cross section is also a steep function of the incident momentum at SPS energies (see e.g. [17]), and if the initial state nucleon energy loss effects are important, one inevitably arrives to the conclusion that Drell-Yan pairs should also be strongly suppressed—contrary to experimental observations. It looks therefore that we have a difficulty reconciling the two well established experimental facts—the existence of the nucleon energy loss in nuclear matter and the $A \cdot B$ scaling of the Drell-Yan pair production. Is this a paradox?

The answer has been known for quite a long time [18], [19]: quantum mechanics implies that at high energies, soft processes develop over large longitudinal distances. Consider, for example, a proton with momentum $P$ which undergoes an inelastic diffractive interaction inside the nuclear target, transforming itself into a cluster of particles of invariant mass $M_\ast$. Let us consider the amplitude of this process in the momentum representation:

$$M(q_L) = \int dz \ e^{iq_Lz} \ M(z),$$

where $q_L$ is the longitudinal momentum transfer (we have suppressed the transverse coordinate integration). Energy conservation implies that

$$q_L = \sqrt{E^2 - M_p^2} - \sqrt{E^2 - M_\ast^2} \simeq \frac{M_\ast^2 - M_p^2}{2P},$$

where $M_p$ is the mass of the proton. Because of the presence of oscillating exponential in (1), the most important contribution to $M(q_L)$ will come from the region where $q_Lz \leq 1$, i.e. from the region with the longitudinal size of

$$z \simeq \frac{2P}{M_\ast^2 - M^2} = \frac{P}{(M_\ast + M)/2} \cdot \frac{1}{M_\ast - M}. \quad (3)$$

It is clear from (3) that inelastic interactions of the incident nucleon, responsible for its energy loss, at high energies develop over large longitudinal distances which grow proportionally to the initial momentum. The result (3) in a time-dependent picture can be interpreted as the product of proper formation time $\tau \simeq (M_\ast - M_p)^{-1}$ of the proton, given by the uncertainty relation, and the Lorentz factor $P/M$, where $M = (M_\ast + M_p)/2$ is the average mass of the wave packet consisting of a proton and the excited state with invariant mass $M_\ast$. (It is worth to note that we were able to deduce the existence of formation zone (3) starting from the mere assumption that the process is described by

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3The $A \cdot B$ scaling of the cross section implies that all individual nucleon–nucleon collisions are equally effective in producing Drell-Yan pairs.
an amplitude (1), rather than a probability.) The data on the invariant mass distributions in the inelastic proton interactions show that in most collisions the invariant mass $M_*$ is not large [20]; typically $M_* \leq 4$ GeV. The formula (1) implies therefore that already at SPS energies a typical inelastic collision develops over a distance comparable to, or larger than, the size of the nucleus. This means that the nucleons traversing the nucleus have not lost their energy yet; all of their incident momentum can still be utilised for a hard process, which is much better localized in the longitudinal direction. Quantum mechanics therefore provides a natural explanation of the apparent “paradox”, and forces us to discard the nucleon energy loss explanation of $J/\psi$ suppression.

A different approach [21] considers initial state interactions on the parton level. In this way, formation time effects are implicitly taken into account: at high energies, because of the Lorentz factor, the time during which the nucleon traverses the nucleus is shorter than it takes for a signal to propagate through the nucleon’s transverse size. This implies that different parton configurations of the nucleon will interact incoherently; one can therefore distinguish between the interactions of (anti)quarks and gluons from the incident nucleon. Because of the larger color charge, the gluons are expected to interact stronger than quarks inside the nucleus. Since the Drell-Yan pairs are produced (in the leading order in $\alpha_s$) by the quark-antiquark fusion, and the heavy quarks by the gluon-gluon fusion, one can try to reconcile the absence of initial state effects in Drell-Yan pair production with strong suppression observed for the $J/\psi$ even though the Drell-Yan data still do impose an important constraint on the model.

Besides $J/\psi$ suppression, this mechanism should also cause suppression of the open charm production in $pA$ and $AB$ collisions. Even though the current data do not seem to show such suppression, I certainly agree with the authors of ref [21] that more data, particularly on correlated $\bar{D}D$ production, are needed to clarify the issue. Nevertheless, before such data become available, let me present a theoretical argument\footnote{The arguments below are based on the discussion with Yu. Dokshitzer.} in favor of universality of quark and gluon depletion in nuclear matter at small $x$ (high energies and central region), which implies that the initial-state gluon absorption (or energy loss) is unlikely to be the mechanism responsible for the observed $J/\psi$ suppression. Indeed, the virtuality ordering in the QCD DGLAP [22] evolution means that at small $x$, the heavy quarks and Drell-Yan pairs are generated \textit{at the very end} of the parton ladder; the evolution at the preceding stages of the parton cascade is identical in both cases. Moreover, the gluons fusing to form a heavy quark pair, or quarks and antiquarks annihilating into a Drell-Yan pair, have a large virtuality and, at small $x$, small momentum – therefore, they almost do not propagate inside the nucleus! To see how it works numerically, let us consider a nucleus–nucleus collision at $P = 200$ GeV of incident momentum. In the lab frame, the partons producing a heavy quark (or a Drell-Yan) pair of invariant mass $Q$ propagate the distance

$$z \simeq \frac{P_x}{Q} \frac{1}{Q},$$

where $x$ is the fraction of the incident nucleon’s momentum carried by the parton before it splits into a $Q\bar{Q}$ or a Drell-Yan pair; the formula (4) is, as usual, the product of the Lorentz factor and the proper formation time $1/Q$. In the central rapidity region of...
$y^* \simeq 0$ one has a simple kinematical relation $x \simeq Q/\sqrt{s} \simeq Q/(2M_pP)^{1/2}$. The value of $Q \simeq 3$ GeV leads to $x \simeq 0.15$; this is the region of $x$ where the sea partons begin to dominate over the valence quarks in the nucleon’s wave function. Substituting this value of $x$ into (4), we find that the final partons of DGLAP ladder propagate inside the nucleus the distance of less than 1 fm. Since, as was stated above, the preceding part of the evolution is independent of the final stage, we do not expect any difference in the nuclear attenuation of quark– and gluon–induced hard processes. In particular, the $J/\psi$ and Drell-Yan suppressions due to the initial state effects have to be the same. The situation will change, however, if we move out of the central region, since either $x_p$ or $x_t$ will then become large, involving the valence partons in the production process.

To conclude this Section, let us note that independently of any dynamical details of initial state interactions, their effects are expected to increase gradually when the atomic number of the colliding nuclei grows. Therefore one certainly does not expect any discontinuities in $J/\psi$/DY ratio arising from these effects. However initial state interactions are clearly interesting in their own right and should be studied in detail.

4. INTERACTION WITH HADRONIC SECONDARIES

The large number of hadronic secondaries in a typical nucleus-nucleus collisions naturally implies the possibility of final state interactions, absent in a $pp$ collision. In fact, one can even prove that final state interactions are important for charmonium production – the $\psi'/J/\psi$ ratio in S-U collisions is known [1] to drop by a factor of two in comparison to its value in $pp$ and $pA$ reactions. The additional suppression in this case can be explained by the interaction with hadronic secondaries, or “comovers” [23] (an alternative, more exotic, explanation will be discussed below). Indeed, the final state interactions occur at a later stage of the collision, when the $J/\psi$ and $\psi'$ states are formed. Since the $\psi'$ state has a rather large size and a tiny binding energy of $\simeq 50$ MeV, it can be easily destroyed by the interactions with hadrons. Calculations show [24], [25], [6] that this scenario of $\psi'$ suppression in S-U collisions is indeed plausible. On the other hand, the $J/\psi$ suppression in S-U collisions is fully described by the pre-resonance nuclear absorption [6], without any sign of an additional absorption in the final state. This observation lends support to the short-distance QCD calculations [26], [27], [28] that predict a very small value of $J/\psi$ dissociation cross section in its interactions with light hadrons at low energies.

Can one describe the $J/\psi$ suppression observed in Pb-Pb collisions in the hadronic comover scenario? If one considers the $J/\psi$ dissociation cross section in its interactions with hadronic secondaries as a free adjustable parameter, then the calculations show that the magnitude of the observed suppression can be explained [29], [25], [6]; for cascade calculations, see [30]. However, once the parameters of the calculation are fixed, one should be able to understand the $J/\psi$ suppression (or more precisely, the absence of it) in S-U collisions as well. This appears to be very difficult. Indeed, the atomic number dependence of total multiplicity produced in AB collisions at SPS energies is known to scale reasonably well with the number of participants[4]. At first glance, this scaling looks trivial, but it is not; a naïve superposition of individual nucleon–nucleon collisions would

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5 This concerns only the total multiplicity; the yield of strange particles, for example, does not follow this simple scaling, but this is almost irrelevant for the $J/\psi$ suppression.
result in the scaling with the number of collisions instead. The physics at work here can be understood if we again recall the existence of formation zone in high energy soft processes. If the length of the formation zone is larger than the size of the nucleus, the formation of hadronic secondaries (accompanied by the energy loss discussed above) will take place only after the nuclei have already passed through each other; the multiplicity of produced hadrons in this case will be proportional to the number of inelastically excited (“wounded”) nucleons, and not to the number of collisions. The density of produced secondaries in this picture is proportional to the density of wounded nucleons in the transverse plane, which can be computed using the Glauber theory. To address the $J/\psi$ suppression, one has also to take into account the fact that the $J/\psi$ distribution in the transverse plane is determined by the nuclear overlap function ($J/\psi$ production is a hard process with short formation length – see (4)). This leads to an effective increase of the average density of hadronic secondaries which is “seen” by $J/\psi$’s. Calculations based on this approach show that the average density of secondaries which interact with $J/\psi$’s increases only by $\simeq 10\%$ from S-U to Pb-Pb system. This implies a difficulty in reconciling the absence of additional $J/\psi$ suppression in S-U collisions with a strong suppression observed in Pb-Pb. One can still try to adjust the parameters of this model to interpolate between S-U and Pb-Pb, but the fit appears unacceptably poor.

To overcome this problem of the hadronic model, one has to assume that the density of hadronic secondaries increases faster than the density of wounded nucleons from S-U to Pb-Pb. A calculation of this kind was performed in Ref.\[32\]; basing on the dual parton model, the authors assume that the density of hadronic secondaries contains two terms: a component proportional to the number of wounded nucleons and a component proportional to the number of collisions. The relative strength of the two components is an adjustable parameter of the model. Using this revised version of the earlier approach \[25\], the authors find a better fit to the experimental $J/\psi$ survival probability. It remains to be seen, however, whether the model in its present version is consistent with the minimum bias and Drell-Yan–associated transverse energy spectra in both S-U and Pb-Pb collisions, as well as with the correlation of energy deposited in the transverse ($E_T$) and forward ($E_{ZDC}$) directions, measured for Pb-Pb.

Irrespectively of any details of specific models based on final state hadronic interactions, none of them predicts a discontinuity in the $J/\psi/DY$ ratio – the predicted suppression is always a smooth function of atomic number and centrality of the collision.

5. INTERACTION WITH PARTONIC SECONDARIES

Hard partons produced in the nucleus-nucleus collision should be very effective in breaking up charmonium states. The gluon–$J/\psi$ inelastic scattering (a “gluo-effect”; the magnitude of the corresponding cross section was first estimated in ref \[33\]), is expected to have an energy dependence which is very different from the energy dependence of $J/\psi$–hadron inelastic scattering; this leads to very distinct absorption rates of $J/\psi$ in partonic and hadronic systems, and again points to the possibility to use $J/\psi$ and other tightly bound quarkonium states as effective probes of the state of QCD matter \[28\],\[34\]. Unlike the original coherent mechanism of Debye screening \[4\], the gluo-effect mechanism is incoherent, and requires only the presence of sufficiently hard (deconfined) gluons at...
the stage when the physical \( J/\psi \) states are already formed. The relative importance of the two mechanisms is difficult to estimate at present; one needs to know in detail, in particular, the density dependence of the \( J/\psi \) binding energy.

At high energies, the nucleus-nucleus collisions are expected to produce a large number of semi-hard partons \[^{[35]}\]. These partons can then interact among themselves and with the produced \( J/\psi \)'s. The \( J/\psi \) survival probability at RHIC and LHC energies in this picture was considered in ref \[^{[36]}\]. The density of semi-hard partons is usually assumed to be proportional to the number of individual nucleon-nucleon collisions, since their proper formation time \( \sim 1/P_T \) is rather short. The \( J/\psi \) survival probability therefore is a steep function of the atomic number of the colliding nuclei and centrality of the collision.

The authors of ref \[^{[37]}\] considered an interesting possibility that semi-hard processes dominate the production of secondaries already at SPS energies. In this case the partonic density achieved in Pb-Pb collisions is much higher than in the S-U system; this allows therefore for a much stronger \( J/\psi \) suppression in the former case. It would be interesting to check this conjecture against the available SPS data on the minimum bias and Drell-Yan associated transverse energy production, as well as on the centrality dependence of multiplicity.

Incoherent partonic effects, as well as all other effects considered so far, cannot however produce a discontinuity in the \( J/\psi \) survival probability, unless one assumes that something dramatic happens to \( J/\psi \) only after the “critical density” is achieved. This brings us to the next, and most speculative, part of this overview.

6. ...DECONFINEMENT?

The difficulties of conventional approaches outlined above have inspired several authors, extending the earlier model of \[^{[12]}\], to assume that once the density of produced particles exceeds some critical value, the formation of a “deconfined phase” \[^{[39]}\], \[^{[40]}\] or “string percolation” \[^{[41]}\] takes place. In practical terms, the survival probability of \( J/\psi \) is assumed to be equal to zero if it is produced in the region where the density of produced particles exceeds some “critical” value. Since no anomalous \( J/\psi \) absorption was observed in S-U collisions, this critical density has to exceed the maximal density achievable in this system. The ways in which different authors evaluate the density of produced particles vary somewhat, but all of them agree that the magnitude of \( J/\psi \) suppression observed in central Pb-Pb collisions can be reproduced in this picture.

However even this approach, aimed at introducing the most sharp discontinuity in the \( J/\psi \) survival probability, appears to be incapable of reproducing the jump in the \( J/\psi/DY \) ratio observed experimentally. The reason is easy to understand: because of the fluctuations in the number of produced secondaries, each value of the measured transverse energy \( E_T \) actually corresponds to a rather broad range of the collision impact parameters; for the Pb-Pb system one typically finds an uncertainty of 1 – 3 fm’s. This effect leads to a gradual increase of \( J/\psi \) suppression as a function of the measured \( E_T \). We see that even this dramatic assumption does not lead to the explanation of the observed sharp discontinuity of the \( J/\psi/DY \) ratio, and this is very puzzling.

An interesting alternative realization of the deconfinement scenario was presented by E. Shuryak at this Conference \[^{[43]}\]; in their approach, the produced deconfined phase reaches
its “softest point” at some centrality in Pb-Pb collisions. This leads to a very long lifetime of the produced plasma, which can therefore effectively dissociate the produced $J/\psi$’s. (In this picture, one has to consider explicitly the finite dissociation rate of $J/\psi$ in deconfined matter; an estimate for this quantity can be found in ref [44].) A distinctive feature of this approach is that the $J/\psi$ absorption is maximal at some value of centrality, corresponding to the “softest point” of the equation of state of the produced deconfined phase; once the centrality increases further, the $J/\psi$ survival probability increases again. However, also in this approach, the sharp discontinuity is difficult to explain, and we are still left with the “jump puzzle”.

An attempt to interpret the presence of discontinuity in the $J/\psi/DY$ ratio was undertaken in ref [45]. The authors were motivated by the idea that the formed deconfined phase should occupy some minimal volume; it does not make sense to consider a droplet of a new thermodynamical phase of a size, say, less than 1 fm. In the nucleation theory, this size appears as a critical size of the bubble of a new phase in a first order phase transition. This minimal critical size then enters as an additional (to the critical density) parameter of the model. It was found that this assumption makes the description of the $J/\psi/DY$ discontinuity possible (see Fig. 1)\footnote{The discontinuity appears as a result of dissociation of $\chi$ states at the deconfinement point; $\chi$’s contribute $\simeq 40\%$ to the $J/\psi$ production.}; however the model as it stands at present is rather ad hoc. One may also worry about the consistency of the approach: indeed, the formation of equilibrated superheated hadron phase, which then undergoes a first order transition to the deconfined phase looks unlikely in a nucleus-nucleus collision. We have to keep in mind, however, the peculiarity of the theory we are dealing with – the ground state of QCD, filled with strong color fields, is, in a way, itself a statistical system. A large energy density of QCD vacuum, reflected by the phenomenological value of the gluon condensate \footnote{The discontinuity appears as a result of dissociation of $\chi$ states at the deconfinement point; $\chi$’s contribute $\simeq 40\%$ to the $J/\psi$ production.}, makes it a rather robust structure. However when the vacuum is disturbed by the multiple production of partons in a finite volume, its structure may change \footnote{The discontinuity appears as a result of dissociation of $\chi$ states at the deconfinement point; $\chi$’s contribute $\simeq 40\%$ to the $J/\psi$ production.}, and this is the process that we are aiming to induce. A simple, and explicitly solvable, example is given by the Friedberg–Lee model \footnote{The discontinuity appears as a result of dissociation of $\chi$ states at the deconfinement point; $\chi$’s contribute $\simeq 40\%$ to the $J/\psi$ production.}, describing the interaction of quarks with an effective $\sigma$ field

$$\mathcal{L} = \bar{\psi} \left( i \hat{\partial} - g\sigma \right) \psi - U(\sigma);$$

(5)

The effective potential of this model on the tree level is the sum of $U(\sigma)$ (the $\sigma$ self-coupling potential, sought to represent effectively the self–interactions of gluon fields), and the term $g\sigma \bar{\psi} \psi$, linear in the scalar quark density. Writing the $\sigma$ self–interaction as a polynomial, one finds

$$U_{\text{eff}}(\sigma) = a\sigma^2 + b\sigma^3 + c\sigma^4 + g \sigma \bar{\psi} \psi;$$

(6)

At vanishing quark density, the effective potential \footnote{The discontinuity appears as a result of dissociation of $\chi$ states at the deconfinement point; $\chi$’s contribute $\simeq 40\%$ to the $J/\psi$ production.}, with properly chosen parameters, possesses two minima: a global one at $\sigma = \sigma_0$, mimicking the presence of the gluon condensate in QCD vacuum, and another local minimum at $\sigma = 0$, corresponding to the vacuum of perturbation theory. When the density of quarks $\bar{\psi} \psi$ is small, the system stays at the true minimum; the quarks acquire large dynamical “mass” $g\sigma_0$ and are almost excluded from the physical spectrum. However once the density of quarks in a finite
volume becomes large, the presence of the last term in (6) makes the minimum at \( \sigma = \sigma_0 \) unstable, and it can decay to the new true vacuum with \( \sigma = 0 \); the decay proceeds via a formation of a finite size bubble of a new phase \([15]\). This schematic model illustrates the physical phenomena which might occur in a nucleus-nucleus collision when the density of produced partons exceeds some threshold value. Whether this decay of QCD vacuum can occur in nucleus-nucleus collisions, and whether it is responsible for the observed discontinuity of \( J/\psi \) survival probability remains an intriguing question, which still has to be answered.

At the same time the behavior of \( \psi' \) does not show any unusual behavior – the measured \( \psi' \) survival probability is a smooth function of \( E_T \). Is it consistent with the existence of a threshold phenomenon? The answer is the following: \( \psi' \)'s have a large radius and a small binding energy and are easily dissociated by hadronic secondaries; their density is the highest in the central region of the transverse plane, where the number of colliding nucleons is the largest. Calculations show that in this region almost all of the \( \psi' \)'s are absorbed. Introducing additional suppression, for example, by the formation of a bubble of deconfined phase, therefore does not affect the overall survival probability – the only observed \( \psi' \)'s are produced in the peripheral region of the transverse plane. In other words, the \( \psi' \) suppression in Pb-Pb and S-U collisions can be caused both by interactions with hadronic secondaries and by deconfinement, and there is no easy way to distinguish between the two effects.

To summarize this Section: the deconfinement scenario can accommodate the observed features of “anomalous” \( J/\psi \) suppression, but only at the expense of introducing some model–dependent assumptions. A detailed, consistent and convincing approach based on the deconfinement scenario still has to be developed. However this is the only picture known at present that is capable of explaining the observed stunning features of the data, and it has to be seriously examined and explored.

7. WHAT ELSE DO WE NEED TO KNOW?

One has to admit that the problems that the theorists are facing in the physics of relativistic heavy ion collisions are too difficult for them to solve. To prove this, let me remind you that none of the theorists predicted the onset of anomalous \( J/\psi \) suppression in Pb-Pb collisions, let alone the centrality at which it should begin. The advocates of deconfinement scenario, who made a generic prediction that the anomalous \( J/\psi \) suppression should show up once the density is “high enough”, at least have an excuse – for them, this is the phenomenon that was never observed before, and the behavior of QCD matter in these conditions is largely unknown. However, also the theorists advocating conventional explanations could not anticipate the onset of a stronger \( J/\psi \) suppression; in this case, since conventional mechanisms, by definition, are supposed to be well–known, one should have been able to make a prediction. The fact that none of these predictions were made before the experimental discovery of anomalous \( J/\psi \) suppression, tells us once again that the field of relativistic heavy ion collisions is, and most likely will remain to be, experiment–driven, and we will have to rely on the experimental results to make any progress.

What data do we need to clarify the origin of the anomalous \( J/\psi \) suppression? The most
important thing now is to establish firmly (or to discard) the presence of discontinuity in the $J/\psi/DY$ ratio. A further increase in statistics, especially for the high mass Drell–Yan events, would be beneficial for this. We should also verify that a decrease of the energy of the Pb beam and/or the use of a lighter target lead to the disappearance of the anomalous suppression. This would prove the threshold nature of the phenomenon responsible for the observed effect. We would then know for sure that the collective behavior in QCD matter has been discovered, and we have many years ahead of trying to understand it.

I would like to thank the Organizers of this Conference for their kind invitation to this most stimulating meeting.

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