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J/Ψ Suppression as an Evidence for Quark-Gluon Matter

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Abstract

The J/ψ suppression was originally proposed as a signature of the quark-gluon plasma. Strong suppression of J/ψ production was indeed observed recently by the NA50 Collaboration at CERN SPS. Is it the first signature of a long-awaited quark-gluon matter, or just a peculiar combination of "conventional" effects acting together to produce the puzzling pattern observed experimentally? In this lecture, I am trying to summarize the existing theoretical explanations.

1 Introduction

The 1974 discovery of J/Ψ opened the door to the exciting new world of heavy quarkonia. From the very beginning it had been recognized that the J/ψ , with its unusually small width and large mass, was different from other hadrons. The large mass was soon understood to be the consequence of the existence of a new massive quark flavor, and the small width – the consequence of asymptotic freedom, making the coupling, and therefore, the annihilation probability, small at the scale of the charm quark mass. The understanding of J/ψ properties was therefore crucial for establishing QCD as the standard model of strong interactions.

The small size of heavy quarkonia and the asymptotic freedom dictate that quarkonium interactions with the rest of hadronic world should be rather weak. This leads to the following experimentally confirmed consequences: 1) the cross sections of heavy quarkonium interactions are small; 2) the decay widths of heavy quarkonia are small on a typical hadronic scale; 3) no bound states of heavy quarkonia and light hadrons were observed so far. This latter means that, unlike in the interactions of light hadrons among themselves, no s-channel resonances are present in quarkonium scattering on light hadrons; extrapolating the common wisdom accumulated in the physics of light hadrons to the interactions involving heavy quarkonia is therefore hard to justify.

Both experimental observations and theoretical arguments point therefore to the fact that the world of heavy quarkonia is only weakly coupled to the world of light hadrons – color fields inside light hadrons as seen by heavy quarkonia appear to be soft and weak. However this situation can change when the external color fields become strong, as is expected, for example, in ultra-relativistic heavy ion collisions. The onset of Debye screening in a high-density quark-gluon matter will prevent the very formation of bound states – this is the basis of the idea by Matsui and Satz [1] to use heavy quarkonium states for the diagnostics of excited QCD matter. Moreover, sufficiently strong external color fields can easily dissociate heavy quarkonium states. This "gluo-effect" dissociation process was considered by Shuryak [2]. Later it was found [3, 4] that the role of dissociation processes is negligible in the hadron gas, and becomes very important in the quark-gluon matter – this result confirms the usefulness of the J/ψ as a useful and unique probe.

Observed experimentally by the NA38 Collaboration in 1987, J/ψ 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/ψ suppression observed in nuclear collisions with light ion projectiles. However the controversy resumed when the new Pb-Pb results of the NA50 Collaboration [5] have been revealed.

2 Quarkonium Production in Hadron Collisions

The perturbative approach to quarkonium production [6] is based on the assumption that the production process is localized at distances $\sim m_Q^{-1}$, much shorter than the size of quarkonium $r \sim [\alpha_s(r^{-1})m_Q]^{-1}$. This approach is justified if all gluons involved in the production carry a high momentum $q \sim m_Q$. However, the hadroproduction of vector states, for example, requires at least three gluons, of which only two must be hard to create the $\bar{Q}Q$ pair. At small P_T (the domain that dominates the integrated quarkonium production cross sections), the third gluon can be very soft, and is emitted (or absorbed) at distances of the order of quarkonium size. This is clearly inconsistent with the factorized form of the amplitude, and may "explain" the failure of perturbative approach in describing the integrated cross sections of quarkonium production at fixed target energies. At collider energies, the perturbative approach fails even at high P_T, since the non-perturbative contribution to the gluon fragmentation becomes important [7]. A consistent solution of this problem emerges if one assigns the soft gluon to the quarkonium wave function introducing the notion of $|\bar{Q}Qg...\rangle$ higher Fock states [8]. The simplest example of such system is provided by the $|[\bar{Q}Q]_8 g\rangle$ state. It is interesting to observe that this component of the J/ψ wave function emerges naturally also in a completely different approach – since the vacuum of QCD has a complicated structure [9] with $\langle g^2G^2\rangle \neq 0$, it induces a significant admixture of the $|[\bar{Q}Q]_8 g\rangle$ component in the wave function of quarkonium [10].

For a physical J/ψ state, this leads to the following generic decomposition:

$$|J/\psi\rangle = a_1\ |\bar{c}c\rangle\ +\ a_2\ |[\bar{c}c]_8 g\rangle\ +\ ... \qquad (1)$$

Similar decompositions hold for other quarkonium states; for χ states, for instance, the importance of higher Fock component is implied by the divergence of the perturbative annihilation amplitude in the soft gluon limit [8]. The magnitude of the $|[\bar{Q}Q]_8 g\rangle$ state admixture is reflected by the magnitude of relativistic corrections in the NRQCD approach [7] and by the size of power corrections in the QCD sum rule approach [9]. These corrections are generally not very large, making applicable the familiar concept of heavy quarkonium as of a non-relativistic system essentially composed of just $\bar{Q}Q$ state. However in certain processes – like production and annihilation of quarkonium – these components can play extremely important role. In fact, the leading order production of heavy vector quarkonium proceeds via the gluon fusion producing the $\bar{Q}Q$ pair in a color-octet state that later neutralizes its color emitting (or absorbing) an extra gluon. If this extra gluon is soft (as is the case in the small P_T domain), the production process can be visualized as proceeding via the higher Fock state $|[\bar{Q}Q]_8 g\rangle$.

Since the color Coulomb interaction between the heavy quarks in the color-octet state is repulsive and weak ($\sim 1/(N^2-1)$ with respect to the attraction in the color-singlet state, where N is the number of colors), the $|[\bar{Q}Q]_8 g\rangle$ state is separated from the basic $|\bar{Q}Q\rangle$ state by the mass gap of $\simeq \epsilon_0$, where ϵ_0 is quarkonium binding energy. This (virtual) state therefore has a proper lifetime of $\tau \simeq 1/\epsilon_0$. In the frame where quarkonium moves with momentum P, the superposition (1) will be coherent over a distance $z_c \simeq \tau P/2M_Q$. At high energies, this distance is sufficient for a produced $|[\bar{Q}Q]_8 g\rangle$ state to traverse the entire nuclear volume.

3 Quarkonium Interactions in Matter

In the Operator Product Expansion (OPE) approach [11, 3], the amplitude of heavy quarkonium interaction with light hadrons is represented in the form

$$F_{\Phi h} = i \int d^4x e^{iqx} \langle h|T\{J(x)J(0)\}|h\rangle = \sum_n c_n(Q, m_Q)\langle O_n\rangle, \tag{2}$$

where the set $\{O_n\}$ should include all local gauge-invariant operators expressible in terms of gluon fields; the matrix elements $\langle O_n\rangle$ are taken between the initial and final light-hadron states. The coefficients c_n are expected to be computable perturbatively and are process-independent.

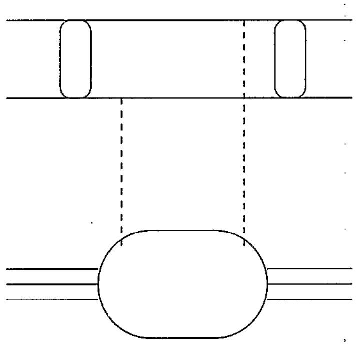

Figure 1. A sample diagram describing quarkonium interaction with a light hadron in the OPE scheme; dashed lines are the gluon propagators, ovals represent the quarkonium wave function, and the blob stands for the gluon structure function of the hadron.

The Wilson coefficients c_n were computed for S [11] and P [12], [13] states in the leading order in $1/N^2$ (N is the number of colors). The expectation values $\langle O_n \rangle$ of the operators composed of gluon fields can be expressed as Mellin transforms [14] of the gluon structure function of the light hadron, evaluated at the scale $Q^2 = \epsilon_0^2$,

$$\langle O_n \rangle = \int_0^1 dx \; x^{n-2} g(x, Q^2 = \epsilon_0^2). \tag{3}$$

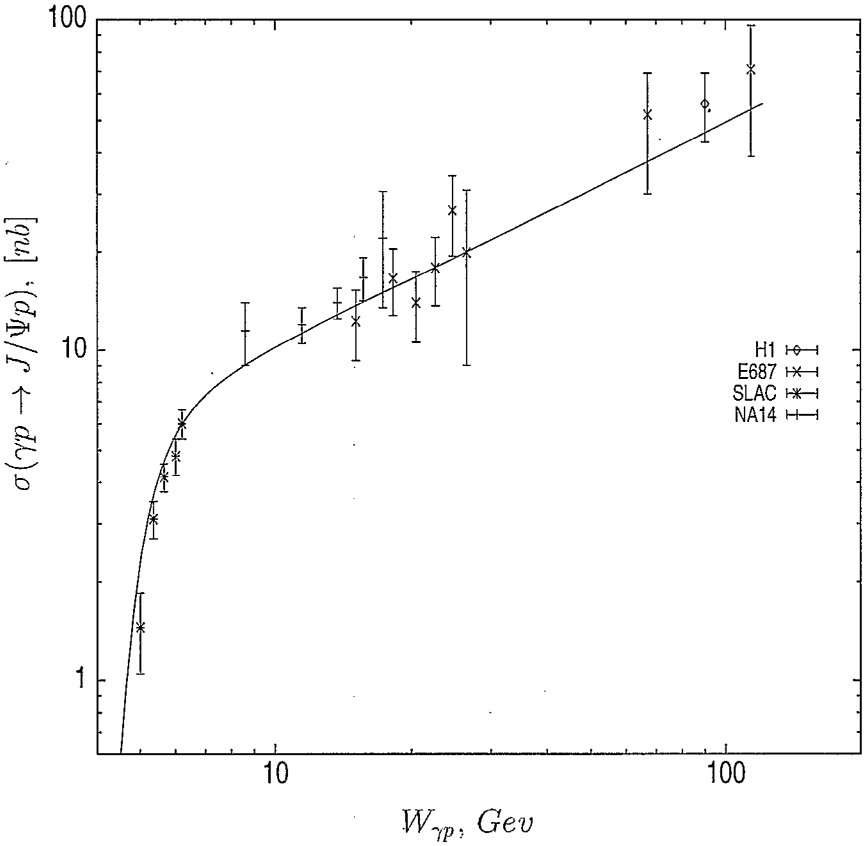

Figure 2. J/ψ photoproduction cross section; the curve is the theoretical prediction [15].

Since the total $\Phi - h$ cross section is proportional to the imaginary part of the amplitude $F_{\Phi h}$, the dispersion integral over the c.m.s. energy λ leads to the set of sum rules, relating the cross section to the gluon structure function of the light hadron. This relation, illustrated in Fig. 1, has a very important property: the magnitude and energy dependence of the quarkonium dissociation cross section at low energies is entirely determined by the behaviour of the gluon structure function at large $x \sim 1/\lambda$, whereas the cross section at high energy is governed by the small

x behaviour of the structure function. Since the gluon structure functions of light hadrons are suppressed at large x, the calculated cross section rises very slowly from the threshold. When the hadron momentum in the J/ψ rest frame is $P_h \simeq 5$ GeV, the cross section is more than an order of magnitude below its asymptotic value.

Recently, the calculation sketched above has been refined [15] by taking into account target mass corrections, the real part of the scattering amplitude restored by dispersion relations, and the use of modern gluon structure functions inferred from the analyses of HERA data. This allows to evaluate the cross section in the entire energy range accessible to present experiments; the results confirm the threshold behaviour of the absorption cross section established previously. Vector meson dominance relates the cross sections of J/ψ dissociation and photo-production; Fig. 2 shows the results compared to the available data. One can see that a strong threshold suppression of the J/ψ absorption cross section is actually required by the data.

4 Quarkonium production in nuclear collisions and the NA50 puzzle

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/ψ production data from pA and AB [16] collisions available before the advent of the Pb beam at CERN SPS has been found [17] to be consistent with the nuclear absorption model [18]. However the fact that $\psi'/J/\psi$ ratio in pA collisions does not depend on the atomic number A (see [19] 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/ψ and ψ' states in nuclear matter: ψ' is known to have a radius about twice larger than that of J/ψ and is expected to be absorbed with a much larger cross section. Another argument against the naïve picture of J/ψ absorption in nuclear matter stems from the magnitude of the extracted cross section, which appears to be approximately two times larger than the J/ψ absorption cross section extracted from the data on J/ψ photoproduction on nuclear targets at small energies [20] 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/ψ 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/ψ suppression).

A model which naturally accomodates the listed above features of the J/ψ production on nuclear targets [21] is motivated by the presence of the higher Fock states in the J/ψ wave function [8], revealed by the recent Tevatron results [22]. At small p_T, the J/ψ production is assumed to proceed through the formation of the color singlet pre-resonance $|\bar{c}cg\rangle$ state. Even though the proper formation time of the physical J/ψ and ψ' 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/ψ 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 [23].

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/ψ production data [17] (see Fig. 3, which shows the result of Glauber calculation with the central value of $\sigma_{abs} = 7.3$ mb)[1].

However around $E_T \simeq 50$ GeV (corresponding to the average impact parameter of $b \simeq 8 \pm 1$ fm) the J/ψ/DY ratio jumps down, and deviates significantly from the predictions of Glauber model. The ψ'/DY 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/ψ 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/ψ production data accumulated prior to the NA50 experiment. We now proceed to the discussion of various theoretical explanations of this effect.

5 What is the origin of the suppression?

5.1 Initial state interactions

Several authors [24] have considered the effect of nucleon energy loss in the initial state on the J/ψ production. Their idea can be briefly summarized as follows: in a nucleus-nucleus collision, the colliding nucleons loose energy before they produce J/ψ's. Since at SPS we are still in the energy range where the J/ψ production cross section is a steep function of the incident nucleon's momentum (see e.g. [25]), this initial state energy loss will lead to a strong suppression of the J/ψ production. The Glauber – like approaches do not consider the energy loss mechanism and are therefore misleading, significantly underestimating the J/ψ suppression expected from conventional mechanisms. At first glance, the argument looks correct, and

[1] The peripheral Pb-Pb data alone suggest a somewhat larger value of σ_{abs}, but it is consistent within the error bars with $\sigma_{abs} = 7.3 \pm 0.6$ mb extracted from the previous data.

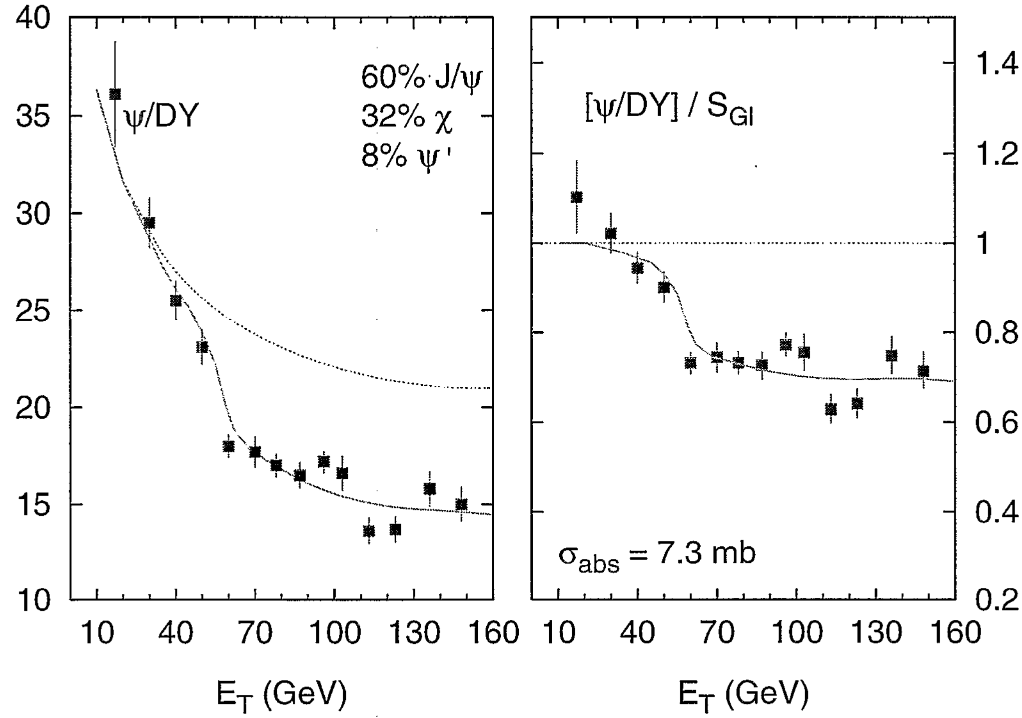

Figure 3. Left: the $J/\psi/\mathrm{DY}$ ratio in Pb-Pb collisions [5] versus the prediction of the pre-resonance absorption model [17] with $\sigma_{abs} = 7.3$ mb (the upper curve). Right: the same, normalized to the prediction of the pre-resonance absorption model. The lower curve is the result of the calculation based on the model of ref [50] (see text).

seems to be well supported experimentally – the effects of the nucleon energy loss in pA and AB collisions are well established [26]. 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. (The $A \cdot B$ scaling of the cross section implies that *all* individual nucleon–nucleon collisions are equally effective in producing Drell-Yan pairs.) 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. [27]), 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 [28], [29]: 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_*. Let us consider the amplitude of this process in the momentum representation:

$$M(q_L) = \int dz\ e^{iq_L z}\ M(z), \tag{4}$$

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

$$q_L = \sqrt{E^2 - M_p^2} - \sqrt{E^2 - M_*^2} \simeq \frac{M_*^2 - M_p^2}{2P}, \tag{5}$$

where M_p is the mass of the proton. Because of the presence of oscillating exponential in (4), the most important contribution to $M(q_L)$ will come from the region where $q_L z \leq 1$, i.e. from the region with the longitudinal size of

$$z \simeq \frac{2P}{M_*^2 - M^2} = \frac{P}{(M_* + M)/2} \cdot \frac{1}{M_* - M}. \tag{6}$$

It is clear from (6) 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 (6) in a time-dependent picture can be interpreted as the product of proper formation time $\tau \simeq (M_* - M_p)^{-1}$ of the proton, given by the uncertainty relation, and the Lorentz factor $P/\bar{M}$, where $\bar{M} = (M_* + M_p)/2$ is the average mass of the wave packet consisting of a proton and the excited state with invariant mass M_*. (It is worth to note that we were able to deduce the existence of formation zone (6) starting from the mere assumption that the process is described by an *amplitude* (4), 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 [30]; typically $M_* \leq 4$ GeV. The formula (6) 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/ψ suppression.

A different approach [31] 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 stonger than quarks inside the nucleus. Since the Drell-Yan pairs are produced (in the leading order in α_s) by the quark-antiquark fusion, and the heavy quarks by the gluon-gluon fusion, one can try to reconcile the absense of initial state effects in Drell-Yan pair production with strong suppression observed for the J/ψ even though the Drell-Yan data still do impose an important constraint on the model.

Besides J/ψ 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 [31] 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[2] 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/ψ suppression. Indeed, the virtuality ordering in the QCD DGLAP [32] evolution means that at small x, the heavy quarks and Drell-Yan pairs are generated *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

$$z \simeq \frac{Px}{Q}\ \frac{1}{Q}, \tag{7}$$

where x is the fraction of the incident nucleon's momentum carried by the parton before it splits into a $\bar{Q}Q$ or a Drell-Yan pair; the formula (7) 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 (7), 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/ψ 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

[2]The arguments below are based on the discussion with Yu. Dokshitzer.

any discontinuities in J/ψ/DY ratio arising from these effects. However initial state interactions are clearly interesting in their own right and should be studied in detail.

5.2 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 [16] 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" [33] (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/ψ and ψ' states are formed. Since the ψ' 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 [34], [35], [17] that this scenario of ψ' suppression in S-U collisions is indeed plausible. On the other hand, the J/ψ suppression in S-U collisions is fully described by the pre-resonance nuclear absorption [17], without any sign of an additional absorption in the final state. This observation lends support to the short-distance QCD calculations [11], [36], [3] that predict a very small value of J/ψ dissociation cross section in its interactions with light hadrons at low energies.

Can one describe the J/ψ suppression observed in Pb-Pb collisions in the hadronic comover scenario? If one considers the J/ψ 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 [37], [35], [17]; for cascade calculations, see [38]. However, once the parameters of the calculation are fixed, one should be able to understand the J/ψ 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[3]. At first glance, this scaling looks trivial, but it is not; a naïve superposition of individual nucleon–nucleon collisions would 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 (6) 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 discissed 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" [39]) 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.

[3]This concerns only the *total* multiplicity; the yield of strange particles, for example, does not follow this simple scaling.

To address the J/ψ suppression, one has also to take into account the fact that the J/ψ distribution in the transverse plane is determined by the nuclear overlap function (J/ψ production is a hard process with short formation length – see (7)). This leads to an effective increase of the average density of hadronic secondaries which is "seen" by J/ψ's. Calculations based on this approach show that the average density of secondaries which interact with J/ψ's increases only by $\simeq 10\%$ from S-U to Pb-Pb system [17]. This implies a difficulty in reconciling the absence of additional J/ψ 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.[40]; 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 [35], the authors find a better fit to the experimental J/ψ 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 hadonic 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.

5.3 Interaction with partonic secondaries

Hard partons produced in the nucleus-nucleus collision should be very effective in breaking up charmonium states. The gluon–J/ψ inelastic scattering (a "gluo-effect"; the magnitude of the corresponding cross section was first estimated in ref [2]), is expected to have an energy dependence which is very different from the energy dependence of J/ψ –hadron inelastic scattering; this leads to very distinct absorption rates of J/ψ in partonic and hadronic systems, and again points to the possibility to use J/ψ and other tightly bound quarkonium states as effective probes of the state of QCD matter [3],[4]. Unlike the original coherent mechanism of Debye screening [1], the gluo-effect mechanism is incoherent, and requires only the presence of sufficiently hard (deconfined) gluons at the stage when the physical J/ψ 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/ψ binding energy.

At high energies, the nucleus-nucleus collisions are expected to produce a large number of semi–hard partons [41]. These partons can then interact among themselves and with the produced J/ψ's. The J/ψ survival probability at RHIC and LHC energies in this picture was considered in ref [42]. 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/ψ survival probability therefore is a steep function of the atomic number of the colliding nucei and centrality of the collision.

The authors of ref [43] 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/ψ 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/ψ survival probability, unless one assumes that something dramatic happens to J/ψ *only* after the "critical density" is achieved. This brings us to the next, and most speculative, part of this overview.

5.4 ...Quark–gluon matter?

The difficulties of conventional approaches outlined above have inspired several authors, extending the earlier model of [44], to assume that once the density of produced particles exceeds some critical value, the formation of a "deconfined phase" [45], [46] or "string percolation" [47] takes place. In practical terms, the survival probability of J/ψ 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/ψ 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/ψ 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/ψ 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/ψ 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 proposed in ref [48]; in this 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/ψ's.

(In this picture, one has to consider explicitly the finite dissociation rate of J/ψ in deconfined matter; an estimate for this quantity can be found in ref [49]). A distinctive feature of this approach is that the J/ψ 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/ψ 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 [50]. 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. 3). The discontinuity appears as a result of dissociation of χ states at the deconfinement point; χ's contribute $\simeq 40\%$ to the J/ψ production. ; however the model as it stands at present is rather *ad hoc.* (The discontinuity appears as a result of dissociation of χ states at the deconfinement point; χ's contribute $\simeq 40\%$ to the J/ψ production.) 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 [9], 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, and this is the process that we are aiming to induce.

At the same time the behavior of ψ' does not show any unusual behavior – the measured ψ' survival probability is a smooth function of E_T. Is it consistent with the existence of a threshold phenomenon? The answer is the following: ψ''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 ψ''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 ψ''s are produced in the peripheral region of the transverse plane. In other words, the ψ' 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/ψ 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.

6 Summary

One has to admit that the problems that the theorists are facing in the physics of relativistic heavy ion collisions are often too difficult for them to solve. To prove this, let me remind you that none of the theorists *predicted* the onset of anomalous J/ψ 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/ψ suppression should appear 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/ψ 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/ψ 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/ψ 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.

To summarize, the physics of heavy quarkonium continues to develop at a fast pace. We expect new results from the NA50 Collaboration which would hopefully allow us to decypher the message contained in the observed J/ψ suppression. Moreover, we have every reason to believe that the start of RHIC experiments in the near future will mark the beginning of the new exciting era in this field.

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