Quarkonium Production and Colour Deconfinement in Nuclear Collisions

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The suppression of quarkonium production in nucleus-nucleus collisions was originally proposed as a signal of colour deconfinement. Strong “anomalous” \( J/\psi \) suppression in Pb-Pb collisions has been reported at this Conference by the NA50 Collaboration. Is this suppression really anomalous? Can we conclude that the quark-gluon plasma is already discovered? What has to be done next? I address these questions basing on the current theoretical understanding of quarkonium production and new precise experimental information.

1. INTRODUCTION

The idea to use heavy quarkonia as a probe of excited QCD matter produced in relativistic heavy ion collisions was proposed a decade ago [1]. This suggestion was based on the concept of colour screening of static potential acting between the heavy quark and antiquark, which occurs in hot and/or dense quark-gluon matter. A year later, the \( J/\psi \) suppression in nucleus-nucleus collisions was observed experimentally [2]. Since that time, quarkonium suppression has always been a respectable prospective signal of deconfinement. However, the experimentally observed suppression has been consistent not only with the deconfinement scenario, but with a plenty of “conventional” explanations as well [3]. Moreover, the differences between various conventional approaches, invoking such different mechanisms as nuclear absorption, gluon shadowing, or comover absorption, but nevertheless all providing more or less reasonable description of the data, created a lively controversy. The problem thus was clearly awaiting a more detailed and systematic analysis, many essential inputs for which were missing. In fact, the lack of precision data on \( J/\psi \) and \( \psi' \) production in \( p-A \) collisions, poor theoretical understanding of \( J/\psi \) production and its interactions with light hadrons made this analysis virtually impossible.

Fortunately, the situation has started to change recently: new high precision data on quarkonium production (see [4]-[6] and references therein) have significantly advanced the theory [7], and the operator product expansion techniques have allowed a systematic calculation of quarkonium absorption cross sections [8]-[10] and dissociation rates in confined matter [10]-[14]. The dominance of higher Fock states in quarkonium production, revealed by the new Fermilab data [6] and naturally emerging theoretically, has inspired a new approach to nuclear attenuation of quarkonium production [15]. This approach, as I shall discuss in this talk, has enabled a quantitative understanding of quarkonium
suppression in both $p-A$ and $A-B$ collisions, giving a credit to the nuclear absorption model [16]. It has become clear that the existing $S-U$ data in fact do not exhibit any anomalous behaviour and are not consistent with a deconfinement scenario, which requires additional strong suppression. This is why the results on $J/\psi$ suppression in Pb-Pb collisions were so anxiously awaited – they were our last chance to see something unusual before the advent of future experiments at RHIC and LHC.

These results, presented by the NA50 Collaboration at this Conference [17], are striking. The data clearly show a strong $J/\psi$ suppression, going way beyond the expected. But is this suppression really anomalous? Have we finally reached the border of the long-awaited terra incognita of deconfined quark-gluon matter? In this talk, I shall attempt to address these questions.

2. QCD ATOMS IN EXTERNAL FIELDS

2.1. Quarkonium Interactions and the Operator Product Expansion

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

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

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 $S$ [8] and $P$ [14], [18] states in the leading order in $1/N^2$ ($N$ is the number of colours). The expectation values $\langle O_n \rangle$ of the operators composed of gluon fields can be expressed as Mellin transforms [19] of the gluon structure function of the light hadron, evaluated at the scale $Q^2 = \epsilon_0^2$,

$$\langle O_n \rangle = \int_1^1 dx x^{n-2} g(x,Q^2 = \epsilon_0^2).$$

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 $\lambda$ 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
Figure 2. $J/\psi$ photoproduction cross section; the curve is the theoretical prediction [20].

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 $J/\psi$ 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 [20] 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 $J/\psi$ dissociation and photo-production; Fig. 2 shows the results compared to the available data. One can see that a strong threshold suppression of the $J/\psi$ absorption cross section is actually required by the data.
2.2. Quarkonium Interactions with Pions

It can be shown that spontaneously broken chiral and scale symmetries of QCD imply decoupling of low-energy pions from heavy quarkonium \[14\]. The proof is based on the application of low-energy QCD theorems \[21\] (see \[22\] for a recent review and introduction) to the amplitude of quarkonium interactions with light hadrons \[23\]. Qualitatively, the origin of the decoupling can be explained in the following way. At low energies, the amplitude of quarkonium interaction is proportional to the gluon field operator dominating the trace of the energy-momentum tensor of QCD. The appearance of this operator in the trace of the energy–momentum tensor is a reflection of the broken scale invariance of QCD, so the coupling is determined by the scale dimension of the hadron field. Chiral symmetry, however, implies zero scale dimension for the Goldstone boson fields – otherwise scale transformations would break chiral invariance.

2.3. Quarkonium Production in Hadron Collisions

The perturbative approach to quarkonium production \[24\],\[25\] 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 \[7\]. These arguments help to understand the phenomenological success of the colour evaporation model in explaining the data (see \[26\] for a recent study).

A consistent solution of this problem emerges if one assigns the soft gluon to the quarkonium wave function introducing the notion of \([\bar{Q}Qg...]\) higher Fock states \[7\]. In fact, such states appear naturally in the OPE scheme described above. Consider, for example, the amplitude of quarkonium interaction with an external gluon field (see Figs. 1 and 3): it includes the transformation of the colour-singlet quarkonium into a colour-octet \([\bar{Q}Q]\) state. The overall colour neutrality is of course preserved and ensured by the coloured gluon cloud surrounding the \([\bar{Q}Q]\) state. The simplest example of such system is provided by the \([\bar{Q}Qg]\) state. Since the vacuum of QCD has a complicated structure \[27\] with \(<g^2G^2> \neq 0\), it induces a significant admixture of the \([\bar{Q}Qg]\) component in the wave function of quarkonium \[28\] – see Fig. 3a. For a physical \(J/\psi\) state, this leads to the following generic decomposition:

\[
|J/\psi\rangle = a_1 |\bar{c}c\rangle + a_2 [|\bar{c}c]_8 g\rangle + \ldots \tag{3}
\]

Similar decompositions hold for other quarkonium states; for \(\chi\) states, for instance, the importance of higher Fock component is implied by the divergence of the perturbative annihilation amplitude in the soft gluon limit \[29\]. The magnitude of the \([\bar{Q}Qg]\) state
admixture is reflected by the magnitude of relativistic corrections in the NRQCD approach \cite{29} and by the size of power corrections in the QCD sum rule approach \cite{27}. 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\footnote{Another example is provided by the scattering of quarkonium states at very high energies \cite{30}.}. In fact, the leading order production of heavy vector quarkonium proceeds via the gluon fusion producing the $\bar{Q}Q$ pair in a colour-octet state that later neutralizes its colour 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 $|\bar{Q}Q|_{s\bar{g}}\rangle$ (see Fig. 3b).

Since the colour Coulomb interaction between the heavy quarks in the colour-octet state is repulsive and weak ($\sim 1/(N^2 - 1)$ with respect to the attraction in the colour-singlet state, where $N$ is the number of colours), the $|\bar{Q}Q|_{s\bar{g}}\rangle$ state is separated from the basic $|\bar{Q}Q\rangle$ state by the mass gap of $\approx \epsilon_0$, where $\epsilon_0$ 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 (3) will be coherent over a distance $z_c \simeq \tau P/2M_Q$. At high energies, this distance is sufficient for a produced $|\bar{Q}Q|_{s\bar{g}}\rangle$ state to traverse the entire nuclear volume.

What will be the effect of the nuclear medium on the propagation of such a state? To answer this question, let us first note that the produced $|\bar{Q}Q|_{s\bar{g}}\rangle$ pair is initially almost pointlike, with the transverse size of $r_{\perp QQ} \approx 1/2m_Q$ (see Fig. 3b). The produced $|\bar{Q}Q|_{s\bar{g}}\rangle$ state can be thus considered as a colour dipole formed by an almost pointlike colour-octet $\bar{Q}Q$ state and a collinear gluon. The transverse size of the $|\bar{Q}Q|_{s\bar{g}}\rangle$ state can be estimated \cite{15} from the characteristic virtualities of the diagram of Fig.3b as $r_{\perp} \simeq (2m_c\Lambda_{QCD})^{-1/2} \approx 0.20 - 0.25$ fm. An interaction inside nuclear matter will most likely prevent this state from binding, at later stage, to the quarkonium – the colour octet $\bar{c}c$, with its collinear gluon stripped off, will preferably produce open charm mesons\footnote{Note that the $J/\psi$ production cross section represents only a tiny part, of the order of 1\%, of the total charm production – this means that the probability to pick up a collinear gluon for the colour-octet $\bar{Q}Q$ state is in general very small.}.
Let us try to estimate the break-up cross section of such $|\bar{Q}Q\rangle_{8g}$ state in its interaction with nucleons $|\bar{Q}Q\rangle$. The transverse size of the $|\bar{c}c\rangle_{8g}$ state estimated above is roughly the same as the size of $J/\psi$. The $|\bar{c}c\rangle_{8g}$ state however is not bound, so, contrary to the case of $J/\psi$, we do not expect any threshold suppression of the break-up cross section. We can therefore estimate the $|\bar{c}c\rangle_{8g}$ break-up cross section rescaling the value of the $J/\psi$ break-up cross section at high energy (where the threshold suppression does not affect the cross section) by the colour factor $9/4$, arising from the difference between the couplings of colour dipoles formed by the triplet and octet charges. At the energy range relevant for the fixed target experiments, the $J/\psi$ break-up cross section evaluated in the formalism of section 2.1 is $\sigma_{J/\psi N} \simeq 2.5 - 3$ mb. We therefore get $\sigma_{(\bar{c}c)N} \simeq 6 - 7$ mb as an estimate of the $|\bar{c}c\rangle_{8g}$ absorption cross section. The analogous estimate for bottomonium states yields $\sigma_{(\bar{b}b)N} \simeq 1.5 - 2$ mb. These estimates are admittedly rough; they show, however, that the nuclear attenuation of quarkonium production is in general quite strong and, in the first approximation, is universal for various quarkonium states.

3. QUARKONIUM AS A PROBE OF DECONFINED MATTER

We have shown in the previous section that the absorption cross sections of tightly bound quarkonium states at low energies are very small due to the softness of gluon fields confined inside light hadrons; this protects $J/\psi$ in a thermal hadron gas at all meaningful temperatures ($T \leq 0.3$ GeV) [10]-[14]. On the other hand, the distribution of gluons in a deconfined medium is directly thermal, so that the deconfined gluons are hard, with the average momentum of $\langle p_g \rangle_{deconf} = 3T$. An immediate consequence of deconfinement is thus a considerable hardening of the gluon momentum distribution [10] [11]. Hard deconfined gluons can easily break up the $J/\psi$; the cross section of this “gluo-effect” is given by

$$\sigma_{gJ/\psi}(k) = \frac{2\pi}{3} \left(\frac{32}{3}\right)^2 \left(\frac{m_c}{\epsilon_0}\right)^{1/2} \frac{1}{m_c^2} \frac{(k/\epsilon_0 - 1)^{3/2}}{(k/\epsilon_0)^5},$$

where $k$ is the momentum of the gluon incident on a stationary quarkonium with binding energy $\epsilon_0$. We thus see qualitatively how a deconfinement test can be carried out. If we put a $J/\psi$ into matter at a temperature $T = 0.2$ GeV, then the $J/\psi$ will survive if the matter is confined, and will disappear if the matter is deconfined, since in the latter case the gluons will be hard enough to break it up.

The latter part of this statement is in accordance with the original prediction that the formation of a QGP should lead to a $J/\psi$ suppression [1][31]. There it was argued that in a QGP, colour screening would prevent any resonance binding between the perturbatively produced $c$ and $\bar{c}$, allowing the heavy quarks to separate. At the hadronization point of the medium, they would then be too far apart to bind to a $J/\psi$ and would therefore form a $D$ and a $\bar{D}$. Our picture complements this argument by the conclusion that additional suppression of physical $J/\psi$ in dense matter will occur if and only if there is deconfinement.

The dissociation of $J/\psi$ (or $\Upsilon$) in both pictures is a consequence of the interaction with strong gluon fields present in deconfined matter. There is, however, a difference between the two mechanisms: the static screening picture takes into account the effect of deconfined
fields on the binding potential acting between the heavy quarks, but neglects the energy-momentum transfer between the \(J/\psi\) and the heat bath. The dynamical “gluo-effect” picture of quarkonium suppression, on the other hand, emphasizes the role of the energy-momentum transfer from deconfined gluons to the \(J/\psi\), but neglects the screening of the binding potential. Both pictures are expected to describe the physics of \(J/\psi\) suppression in their respective domains of applicability; they should emerge as two limits in one unified microscopic approach, that still has to be developed. The parameter that is relevant in this problem is \(X(T) \equiv \Delta E(T)/T\), where the binding energy of quarkonium \(\Delta E\) depends on the temperature of the system \(T\) because of the Debye screening. In the weak coupling limit of \(X \ll 1\), the binding energy is negligible compared to the temperature, and the quarkonium will simply fall apart with the rate \(R = 4/L(T/\pi M_Q)^{1/2}\) (\(L\) is quarkonium size), which is the classical high temperature limit of thermal activation rate \([12]\). In the strong coupling limit of \(X \gg 1\), on the other hand, the system is tightly bound, and the binding energy threshold has to be overcome by the absorption of hard gluons from the heat bath. The rate of dissociation in this case should be computed from the thermal average of the gluon-quarkonium cross section \([4]\). The actual value of \(X\) at different temperatures depends, of course, on the detailed dynamics of screening; lattice calculations can be of significant help here, fixing the temperature dependence of quarkonium mass.

It is important to note that the dynamical “gluo-effect” approach to \(J/\psi\) suppression does not require a thermal equilibrium of the gluon fields, so that it will remain applicable even in deconfined pre-equilibrium stages. Quarkonium interactions in an equilibrating parton gas were considered in ref. \([32]\).

4. PHENOMENOLOGY OF QUARKONIUM PRODUCTION IN NUCLEAR COLLISIONS

4.1. \(p - A\) collisions

According to our discussion in section 2.3, in the presently accessible kinematic region of \(J/\psi\) production by \(p - A\) collisions \((x_F \geq 0)\), the target nucleus sees only the passage of the pre-resonance state; physical charmonium states are formed outside the nucleus. The size of the pre-resonance state is determined by the charmed quark mass and confinement scale and is therefore the same for \(J/\psi\) and \(\psi'\). The nuclear attenuation of \(J/\psi\) and \(\psi'\) production in \(p - A\) collisions should thus be universal. Indeed, the \(J/\psi\) and \(\psi'\) production in \(pA\) collisions shows to the same \(A\)-dependence. Fitting the available data on the \(\psi'/(J/\psi)\) ratio \([4]\) to the form \(A^\alpha\) leads to

\[
\alpha = 0.0 \pm 0.02, \quad 95\% \, C.L.;
\]

this rules out variations of more than 10% between \(pp\) and \(pU\) collisions. The suppression of \(J/\psi\) production in \(p - A\) collisions should thus be understood as pre-resonance absorption in normal nuclear matter. This accounts naturally for the equal suppression observed for the two states, which would be impossible for physical resonances of such different sizes.

\(^5\)This section is based on the work \([33]\).
We shall now determine the pre-resonance absorption cross section from the NA38/51 $p - A$ data at incident proton beam energies of 200 and 450 GeV [4]. In Glauber theory, the survival probability for a $J/\psi$ produced in a $p - A$ collision is given by

$$S_{pA}^{Gl} = \frac{\sigma_{pA \to \psi}}{A \sigma_{pN \to \psi}} = \int d^2b \ dz \rho_A(b, z) \exp \left\{ -(A - 1) \int_z^\infty dz' \rho_A(b, z') \sigma_{abs} \right\}. \quad (6)$$

Here $\rho_A$ is the nuclear density distribution, for which we take the standard three-parameter Woods-Saxon form with parameters as tabulated in Ref. [34]; it is normalized to unity, with $\int d^2b dz \rho_A(b, z) = 1$. The suppression is thus fully determined by the absorption cross section $\sigma_{abs}$ in nuclear matter. From the NA38/51 data we obtain the best fit for $\sigma_{abs} = 6.3 \pm 0.6 \text{ mb}, \ 95\% \ C.L.;$ (7)

the corresponding survival probabilities are plotted in Fig. 4. The agreement is seen to be excellent in all cases. The value (6) is consistent with the theoretical estimates of section 2.3, which suggest for the absorption cross section of the $\bar{c}c - g$ on nucleons $\sigma_{abs} \simeq 6 - 7 \text{ mb}$ [15].

![Figure 4. $J/\psi$ suppression in $pA$ collisions; the NA38/50 data (black points) are compared to the Glauber theory calculations (grey points) with $\sigma_{abs} = 6.3 \pm 0.6 \text{ mb}$.](image)

We have carried out the same analysis for the 800 GeV E772 data (see [4] for a review); here the cross section is slightly larger: $\sigma_{abs} = 7.4 \pm 0.7 \text{ mb}$, but within errors compatible with the value (6) obtained from the NA38/51 data. A slow increase of the absorption cross section with energy can be attributed to the growth of the gluon structure function towards smaller $x$ (the same effect is responsible for the increase of the $J/\psi$ absorption cross section in the relevant energy range, see Fig. 2).

We thus conclude that $J/\psi$ and $\psi'$ production in $pA$ collisions is quantitatively well described by absorption of a pre-resonance charmonium state in nuclear matter, with the absorption cross section for both states in the energy range of SPS experiments given by Eq. (6). We now extend this description to nuclear collisions.
4.2. S-U Collisions

In nucleus-nucleus collisions, charmonium production can be measured as function of the centrality of the collision, and hence we have to calculate the \( J/\psi \) survival probability at fixed impact parameter \( b \). It is given by

\[
\frac{dS_{\text{Gl}}^{AB}(b)}{d^2b} = \frac{1}{AB} \frac{1}{\sigma_{\text{NN}} \rightarrow \psi} \left[ \frac{d\sigma_{AB \rightarrow \psi}}{d^2b} \right] = \int d^2s dz' \rho_A(\vec{s}, z) \rho_B(\vec{b} - \vec{s}, z') S_A(z, \vec{s}) S_B(z', \vec{s}),
\]

where \( S_A(z, \vec{s}) = \exp \left\{ -(A - 1) \int_0^\infty dz_A \rho_A(\vec{s}, z_A) \sigma_{\text{abs}} \right\} \), and analogously for \( S_B(z', \vec{s}) \). Here \( \vec{s} \) specifies the position of the production point in a plane orthogonal to the collision axis, while \( z \) and \( z' \) give the position of this point within nucleus \( A \) and within nucleus \( B \), respectively. The nuclear density distributions \( \rho_A \) and \( \rho_B \) are defined as above. To obtain normalized survival probability at fixed impact parameter \( b \), we have to divide \[dS_{\text{Gl}}^{AB}/d^2b\] by \[dS_{\text{Gl}}^{AB}(b; \sigma_{\text{abs}} = 0)/d^2b\].

Experimentally, the centrality of the collision is determined by a calorimetric measurement of the associated transverse energy \( E_T \); we thus have to establish and test a correspondence between impact parameter \( b \) and transverse energy \( E_T \). This correlation can be expressed in terms of the number of “wounded” nucleons \[35 \]. Each wounded nucleon contributes on the average an amount \( q \) to the overall transverse energy produced in the collision, so we have the relation

\[
\bar{E}_T(b) = q \bar{N}_w(b)
\]

between the average number \( \bar{N}_w \) of nucleons wounded in a collision at fixed impact parameter \( b \) and the associated average transverse energy \( \bar{E}_T \) produced in that collision. In the analysis of specific experimental results, the proportionality factor \( q \) depends on the details of the detector, in particular on the rapidity and transverse momentum range in which the produced secondaries are measured.

The average number of wounded nucleons in an \( AB \) collision at impact parameter \( b \) is given by

\[
\bar{N}_w^{AB}(b) \equiv \int d^2s n_w^{AB}(b, s) = A \int d^2s T_A(\vec{s}) \left\{ 1 - \left[ 1 - \sigma_N T_B(\vec{s} - \vec{b}) \right]^B \right\} + B \int d^2s T_B(\vec{s} - \vec{b}) \left\{ 1 - \left[ 1 - \sigma_N T_A(\vec{s}) \right]^A \right\}.
\]

Here \( \sigma_N \approx 30 \text{ mb} \) denotes the inelastic production cross section, and \( T_A(\vec{s}) = \int dz \rho_A(z, \vec{s}) \) the nuclear profile function; the \( \vec{s} \)-integration runs again over a plane orthogonal to the collision axis. The distribution (10) is normalized in the following way:

\[
\bar{N}_w^{AB} = \frac{1}{\sigma_{AB}} \int d^2b \bar{N}_w^{AB}(b) = \frac{1}{\sigma_{AB}} (A\sigma_B + B\sigma_A).
\]

Since there are fluctuations in the number of wounded nucleons and in the transverse energy of the secondaries that each wounded nucleon produces, there will be corresponding fluctuations in the relation between \( E_T \) and \( b \). We assume the dispersion \( D \) in the produced transverse energy to be proportional to \( \sqrt{\bar{N}_w} \), \( D^2 = a\bar{E}_T(b) \), with a universal physical parameter \( a \) to be determined from \( pA \) or \( AB \) collisions. We choose the \( E_T - b \) correlation
function $P_{AB}(E_T, b)$ as a conventional (see, e.g., [34]) Gaussian distribution around the central value ($E_T$) with dispersion $D$; it is normalized at fixed $b$: $\int dE_T P_{AB}(E_T, b) = 1$.

We have checked [33] that both minimum bias [37] and Drell-Yan associated [2, 17] transverse energy spectra are very well reproduced in the approach outlined above. With the relation between the measured transverse energy $E_T$ and the impact parameter $b$ of the collision thus determined, we can now calculate the $E_T$ dependence of the charmonium survival probability in nuclear matter.

We begin with $J/\psi$ production. The experimentally determined quantity is the ratio $(d\sigma_{J/\psi}^{AB}/dE_T)/(d\sigma_{DY}^{AB})$ of $J/\psi$ to Drell-Yan production, measured in the mass interval $2.9 \leq M_{\mu\mu} \leq 5.5$ GeV. From this we obtain the survival probability at fixed $E_T$

$$S_{exp}^{J/\psi}(E_T) = \frac{\sigma_{DY}^{AB}}{\sigma_{J/\psi}^{AB}} \left[ \frac{d\sigma_{J/\psi}^{AB}/dE_T}{d\sigma_{DY}^{AB}/dE_T} \right]$$

(12)

by normalizing the measured ratio at fixed $E_T$ by the measured integrated cross sections. The quantity (12) can be directly computed in the Glauber theory formalism outlined above. Using the value of the pre-resonance absorption cross section (7), determined from the analysis of $p-A$ data, we have found a good agreement with the $E_T$-integrated $O-Cu$, $O-U$ and $S-U$ data and with $E_T$ distributions measured in $S-U$ collisions, as we shall shortly show.

For $\psi'$ production, the situation changes. The data for the integrated and the differential survival probabilities are considerably lower than what nuclear absorption predicts, and the additional suppression moreover increases with increasing $E_T$. We therefore need to include the effect of additional $\psi'$ suppression on $J/\psi$ production. The branching ratio for the reaction $\psi' \rightarrow J/\psi$ is 0.57; therefore the $\psi/\psi'$ ratio measured in $pp$ and $pA$ collisions [4] implies that $8 \pm 2\%$ of the observed $J/\psi$'s are due to $\psi'$ decay. Since the $\psi'$ is suppressed in $S-U$ collisions, the corresponding fraction of the observed $J/\psi$'s must be suppressed as well. This correction reduces theoretical predictions on the average by $\simeq 5\%$. We show in Fig. 5 (left) the resulting corrected theoretical $E_T$ dependence of $J/\psi$ survival probabilities. The agreement between the data and predictions is seen to be excellent.

I wish to stress that we do not need to invoke any additional sources of direct $J/\psi$ suppression (apart from the nuclear absorption of pre-resonance charmonium state) to describe the data. On the other hand, the additional $\psi'$ suppression found in $S-U$ collisions clearly indicates the presence of produced matter at the stage when charmonium states are formed. The agreement of our Glauber calculations with the measured $J/\psi$ survival probabilities shows, however, that this matter cannot break up $J/\psi$ states. This can be explained by the smallness of $J/\psi$ dissociation rate in confined hadronic gas [10]-[12] advocated in sections 2 and 3.

4.3. Pb-Pb Collisions

We can further check our approach in $Pb-Pb$ collisions, since the NA50 experiment [17] is equipped with a zero degree calorimeter (ZDC), which determines at each $E_T$ the associated number of projectile spectators – those projectile nucleons which reach the ZDC with their full initial energy $E_{in} = 158$ GeV/c. This additional information is important, since it uniquely identifies the peripherality of the collision. Denoting the projectile as $A,$
the number of projectile spectators is evidently $A - N^A_w$, with $N^A_w$ of the $A$ nucleons in the projectile wounded. We thus have $E_{ZDC} = (A - N^A_w)E_{in}$; using $\bar{E}_T = q \bar{N}_w$, we predict the $E_T - E_{ZDC}$ correlation which agrees very well with the measured one [17], [38].

We are now ready to address the $J/\psi$ production in the NA50 experiment [17]. The $Pb - Pb$ results, plotted as a function of the average path $L$ of $J/\psi$ in nuclear matter, clearly show strong additional suppression beyond the expected on the basis of $\sim \exp(-\rho_0\sigma_{abs}L)$ dependence [17]. The conclusion on the “anomalous” nature of this suppression, however, crucially depends on the magnitude of $L$, assigned to the $Pb - Pb$ points. We would like therefore first to check the $L$ assignment of the NA50 Collaboration in our approach, which directly gives the $J/\psi$ survival probability at a given $E_T$. The results are presented in Fig. 5 (right). One can see that while the lowest $E_T$ point is still marginally consistent with Glauber theory, the suppression observed at higher $E_T$ indeed goes significantly beyond expected. Equating our calculated survival probability to the form used by the NA50, $S_{Gl} = \exp(-\rho_0\sigma_{abs}L)$, we confirm the NA50 $L$ assignments [17]. Since, as we have shown, the Glauber theory approach has been extremely successful in reproducing the bulk of $J/\psi$ production data in $p - A$ and $A - B$ collisions, the suppression observed in $Pb - Pb$ indeed can be called “anomalous”.

5. IS THE QUARK-GLUON PLASMA DISCOVERED?

Before we address this provocative question, posed at this Conference also by J.-P. Blaizot [39] and C.-Y. Wong [40], let us consider the possible differences between the collision dynamics in $S - U$ and $Pb - Pb$ systems. The success of Glauber theory in describing
the $J/\psi$ suppression in $S - U$ collisions and its failure in $Pb - Pb$ points to a difference in the properties of matter produced in these two reactions. We shall try to describe this difference in terms of two variables, one of which characterizes the energy density of produced matter, and the other its degree of equilibration.

In Glauber theory, the initial energy density achieved in the collision is proportional to the density of wounded nucleons $n_w$ (see Eq. (11)) in the transverse plane. The average energy densities achieved in $S - U$ and $Pb - Pb$ collisions are almost identical; at first glance this suggests that the matter seen by produced $J/\psi$'s should be the same in both cases. This is not so, however, for two reasons. First, the profile of the energy density in the two systems is different: central $Pb - Pb$ collisions produce a “hot core”, inside which the energy density is higher than the highest one attainable in $S - U$ system by about 25%. Second, the $J/\psi$'s are produced mostly in this central region (see Eq. (8)), and thus feel the matter which is hotter than average. These two effects combined lead to significant difference in the energy densities of matter seen by $J/\psi$’s in $S - U$ and $Pb - Pb$ collisions. This is illustrated in Fig. 6, where we plot the ratio of experimental $J/\psi$ suppression to the Glauber theory predictions versus the average density of matter seen by $J/\psi$’s (to calculate this latter quantity, we convolute the density distribution with the $J/\psi$ production profile). Apart from being more dense, the matter seen by $J/\psi$ is also likely to be more thermalized. We can quantify this statement introducing the variable

$$\kappa = \frac{\nu + 1}{w},$$

(13)

where $\nu$ is the number of inelastic $NN$ collisions and $w$ is the number of wounded nucleons these collisions produce. The value of $\kappa$ tells how many times, on the average, each wounded nucleon was hit. In a $pp$ collision, $\nu = 1$ and $w = 2$, so that $\kappa = 1$. In $pA$ collisions, the number of wounded nucleons in the target is equal to the number of collisions [35], which, after taking into account the wounded projectile nucleon, again yields $\kappa = 1$. In nucleus-nucleus collisions, however, the value of $\kappa$ can exceed unity because the nucleons once wounded can collide again and again. These collisions can break down the independence of fragmentation of wounded nucleons and provide initial conditions for the onset of collective behaviour in the system. Indeed, when $\kappa > 1$, the partons from different wounded nucleons interact, which is a necessary initial stage for producing deconfined matter – at large $\kappa$, partons can no longer be attributed to a particular pair of wounded nucleons and overlap in the transverse plane. It is evident that in nuclear collisions $\kappa$ grows with atomic number and/or energy (since the number of collisions depends on the inelastic cross section). In central $S - U$ collisions at SPS energy, the Glauber theory calculation yields $\bar{\kappa}_{SU} \approx 1.7$, whereas for a central $Pb - Pb$ collision we find $\bar{\kappa}_{PbPb} \approx 2.4$. The $Pb - Pb$ value thus is as far from the $S - U$ one as the $S - U$ is from $pA$. Central $Pb - Pb$ collisions therefore are likely to produce not only more dense, but also more thermalized matter.

It is important to note that the value of $\kappa$ and its variation with centrality can be determined in a model-independent way directly from the experimental data. Indeed, the number of collisions $\nu$ is proportional to the number of produced Drell-Yan pairs, and the number of wounded nucleons to the produced transverse energy (see Eq. (11)), so at a
Figure 6. The ratio of experimental $J/\psi$ suppression in $S-U$ \cite{4} (crosses) and $Pb-Pb$ \cite{17} (circles) collisions to the Glauber theory predictions versus the average density of wounded nucleons seen by $J/\psi$ (the latter quantity is proportional to the energy density).

given $E_T$ one has

$$\kappa(E_T) \sim q \frac{N_{DY}(E_T)}{E_T} = \frac{q}{E_T} \frac{1}{\sigma_{DY} \Delta E} \int_{\Delta E} \frac{d\sigma_{DY}}{dE_T} dE_T, \quad (14)$$

where $N_{DY}(E_T)$ is the number of Drell-Yan pairs associated with a given $E_T$ bin of the width $\Delta E_T$.

We thus conclude that the matter seen by $J/\psi$ in central $Pb-Pb$ collisions is more dense and more thermalized, so the occurrence of new phenomena at least cannot be excluded \textit{a priori}. If the observed $J/\psi$ suppression were indeed to be interpreted as a signal of deconfinement phase transition, apart from being “anomalous”, it also has to exhibit a threshold behaviour. This feature seems to be present in the data (see Fig. 6): a
slight increase in the energy density induces dramatic deviation from the trend established previously. Moreover, if one considers the profile of the density $n_w$ and $\kappa$ in the transverse plane and assumes that all $J/\psi$’s produced in the region where $n_w > n_{SU}^{max}$, $\kappa > \kappa_{SU}^{max}$ are dissociated, the resulting suppression falls below the data points by only $10 - 15\%$ (similar analysis has been presented at this Conference by J.-P. Blaizot [39]). This shows that the observed suppression is almost as strong as we could possibly accommodate!

Can we still find a “conventional” explanation of the NA50 effect? It is of course too early to try to answer this question; let us therefore limit ourselves to some preliminary observations. Since Glauber calculations show that nuclear absorption of pre-resonance state cannot explain the $Pb - Pb$ data, a conventional explanation has to invoke additional suppression of $J/\psi$’s in the produced confined matter. This suppression would be characterized by a smooth (basically, exponential) dependence on the density of produced matter. Looking at Fig. 6, one realizes that it would not be easy to fit the data by this kind of a smooth dependence – the fits would most likely overestimate the slope of the $S - U$ data and underestimate it for the $Pb - Pb$ points. The physical reason for this is transparent – if hadronic comovers do not induce an additional $J/\psi$ suppression in $S - U$ collisions, it is difficult to make them effective in $Pb - Pb$ system. One may try to assume a larger density variation with $E_T$ (sometimes the density is assumed to be directly proportional to $E_T$ [41]). Indeed, a large variation of density is possible in very central collisions due to fluctuations in the number of produced hadrons. However the measured $E_T - E_{ZDC}$ correlation discussed in section 4.3 shows that in the presented $Pb - Pb$ data the variation of $E_T$ results from the variation of the collision centrality. Even the highest $E_T$ point of NA50 is not entirely in the fluctuation domain, and corresponds to the mean impact parameter of $\bar{b} \simeq 2$ fm. In this regime, the $E_T$ measured by the NA50 varies by more than four times, but this leads only to $\sim 30\%$ variation of the initial energy density (see Figs. 5 and 6). Additional constraint on a conventional scenario is imposed by the $\psi'/\psi$ ratio: if the density of comovers in $Pb - Pb$ were much higher than the density in $S - U$, this would imply a smaller $\psi'/\psi'$ ratio in the former case – the prediction that would bring us in conflict with the data [14]. A possible way to describe the $Pb - Pb$ points conventionally would be to decrease artificially the value of the nuclear absorption cross section $\sigma_{abs}$, leaving thus room for comover absorption already in $S - U$ collisions (the need for comover effects to explain the $S - U$ data was advocated at this Conference by S. Gavin [41]). This, however, would contradict to the $pA$ data, that fix the value of $\sigma_{abs}$ rather precisely (see section 4.1). Of course, it remains to be seen if a convincing conventional explanation can eventually be found.

To summarize, the NA50 $Pb - Pb$ results indeed seem to suggest that a new mechanism of $J/\psi$ suppression sets in at higher energy densities. The observed effect can be considered as a strong evidence of some kind of deconfinement in nuclear collisions. What can we do to turn this evidence into a proof, or to discard it?

6. WHAT HAS TO BE DONE NEXT?

New precision data on quarkonium production coming from CERN SPS, Fermilab, HERA and elsewhere allow us today to get rid of many uncertainties inherent to the analyses of $J/\psi$ suppression over the years. A coherent picture, providing a good descrip-
tion of the bulk of existing pp, pA and AB data, has started to emerge – this makes us ready to recognize and study unusual phenomena. It is therefore particularly important to learn more about the onset of anomalous behaviour of J/ψ suppression seen by the NA50 Collaboration. More statistics and more data points, both in the transition regime of small $E_T$ and in the fluctuation region of the highest $E_T$, are needed to establish the threshold behaviour suggested by the present data. An important information would be also provided by the J/ψ transverse momentum distributions [42].

Direct measurement of the low-energy J/ψ absorption cross section in the proposed inverse kinematics experiment [10],[18] has become possible with the advent of Pb beam at CERN SPS. This experiment would allow us to directly constrain the J/ψ absorption possible in a hadronic medium, providing important additional check of the deconfinement transition as the cause of “anomalous” J/ψ suppression.

Heavy quarkonium represents a rare example of a strongly interacting system that is simple enough to be systematically analyzed by the current theoretical methods. It has already proved to be extremely useful for understanding the properties of QCD and its ground state - the vacuum. I believe that quarkonium will tell us much also about the critical behaviour of QCD matter produced by relativistic heavy ion collisions.

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