A Brief History of $J/\psi$ Suppression

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Statistical QCD predicts that strongly interacting matter will become deconfined at high temperatures and/or densities. The aim of high energy nuclear collisions is to study the onset of deconfinement and the properties of deconfined media in the laboratory. Hence it is essential to define an unambiguous and experimentally viable probe for deconfinement. Twelve years ago, T. Matsui and I proposed that $J/\psi$ production should constitute such a probe [1], and I want to sketch here rather briefly the evolution of this idea in the light of subsequent experimental and theoretical work. To keep my report really brief, I will concentrate on what seems to me the main line of development, with sincere apologies to all those whose work is not adequately considered or mentioned.

Matsui and I had argued that in a quark-gluon plasma colour screening dissolves the $J/\psi$ into its $c$ and $\bar{c}$ constituents, which separate and thus at hadronisation have to combine with light quarks to form a $D$ and a $\bar{D}$ instead of a $J/\psi$. Since the overall Drell-Yan dilepton rates remain unaffected, deconfinement must lead to a suppression of $J/\psi$ production relative to that of Drell-Yan pairs. Hotter media dissolve more $J/\psi$'s, so the suppression should increase with centrality.

Less than a year later, the NA38 collaboration at the CERN SPS observed in $O-U$ interactions a considerable suppression of $J/\psi$ production, increasing with the centrality of the collision [2, 3]. This result was subsequently corroborated in $S-U$ collisions [4].

Since $J/\psi$ production was known to be attenuated also in $p-A$ collisions [5], it was natural to ask if the observed $O-U$ and $S-U$ suppression could be understood simply in terms of a $J/\psi$ absorption in the nuclear matter of target and projectile [6, 7]. With a value of $\sigma_{J/\psi-N}^{in} \approx 4$ mb as determined by the $p-A$ data of [6], nuclear absorption alone was found to produce considerably less $J/\psi$ suppression than observed in $O-U$ and $S-U$ collisions. On the other hand, nucleus-nucleus collisions lead to the abundant production of hadronic secondaries, and such 'comovers' could also dissociate $J/\psi$'s [8] - [13]. Subsequently, a suitable combination of absorption on nucleons and comovers was indeed shown to reproduce the observed suppression [14, 15], indicating that dense hadronic matter alone, without any deconfinement, would be sufficient.

It thus became necessary to look for features which distinguish between absorption and deconfinement as suppression mechanisms. The main difference is obviously the sudden onset of deconfinement as a critical phenomenon, in contrast to absorption as an effect always present and hence increasing gradually with density. The well-defined onset of

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deconfinement moreover leads to a characteristic step-wise suppression pattern for the measured $J/\psi$'s. It is known that only about 60% of these are produced directly as $1S$ states; of the remainder, about 30% come from $\chi$ and about 10% from $\psi'$ decay \cite{15, 16}. Colour screening studies of charmonium dissociation show that the larger excited states are dissolved at lower densities than the tightly bound ground state $J/\psi$ \cite{18, 19}. In particular, the $\chi$ and the $\psi'$ are expected to ‘melt’ at the deconfinement point, while the direct $J/\psi$ needs an energy density about twice as high. As a result, deconfinement leads for the measured $J/\psi$'s to the successive suppression pattern shown in Fig. 1, in contrast to the monotonic decrease of the survival probability obtained from absorption. The generic step pattern shown here will of course be softened by nuclear profile effects, impact parameter uncertainties, etc.; on the other hand, this could be partially compensated if there is a really discontinuous onset of deconfinement as function of the energy density of the medium.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig1.png}
\caption{The $J/\psi$ survival probability $S_{J/\psi}$ as function of the energy density $\epsilon$, for suppression by deconfinement and by hadronic comover absorption.}
\end{figure}

As a sideline, we note that the observed $J/\psi$ attenuation occurs mainly at low transverse momentum \cite{20}. It was first thought that high $p_T$ $J/\psi$'s could ‘escape’ in space or time from suppression by deconfinement \cite{21}, so that the $p_T$-dependence could be used to determine size or life-time of the suppressing medium \cite{22}. However, subsequent studies showed that initial state parton interactions, prior to the formation of the $c\bar{c}$ pair, can in fact account for all of the measured $p_T$ dependence of $J/\psi$ suppression \cite{23} - \cite{25}.

The next step in the development came from Fermilab $p - A$ data, based on four different nuclear targets \cite{26}; these data confirmed the nuclear attenuation previously observed \cite{5}, but in addition they showed the same amount of suppression for $J/\psi$ and $\psi'$. This excluded the interpretation of $J/\psi$ suppression in $p - A$ interactions as absorption of physical charmonium states, since the $\psi'$ is more than four times larger than the $J/\psi$, which should show up in the dissociation cross sections \cite{27} and hence in nuclear absorption. Nevertheless, using an ‘effective’ dissociation cross section of some $6 - 7$ mb
was found to account for all $J/\psi$ suppression data available at that time, from $p - A$ to central $S - U$ collisions [28]. Both the size of the required cross section and the equality of $J/\psi$ and $\psi'$ suppression remained as puzzles.

The solution of these puzzles came from a combination of several different theoretical and experimental developments. First, it was rediscovered [29, 30] that short distance QCD allows the calculation of the cross section for the dissociation of heavy quarkonia by incident light hadrons [31]. The calculation is based on the known $J/\psi$ parameters (binding energy, charm quark mass) and on the gluon distribution function in hadrons as determined from deep inelastic scattering. The resulting value of the dissociation cross section for light hadrons of momenta $p_h \leq 3$ GeV/c incident on a stationary $J/\psi$ is found to lie by some $10^{-1}$ to $10^{-3}$ below the geometric cross section of about 3 mb. Hence hadrons in this momentum range cannot really break up a $J/\psi$. On the other hand, dissociation by gluons (the QCD version of the photo-effect) peaks for gluon momenta around 0.8 - 1.0 GeV/c, making a quark-gluon plasma of temperatures $T \geq 250$ MeV very effective for $J/\psi$ dissociation. If we are provided with physical charmonium states and a strongly interacting medium, the fate of the $J/\psi$ thus becomes an unambiguous deconfinement test [30].

The calculated extremely small dissociation cross section for slow light hadrons incident on $J/\psi$'s effectively rules out suppression by hadronic comovers at present energies. However, the short distance QCD calculations on which this conclusion is based become exact only in the limit of large heavy quark mass. It must therefore be checked experimentally if the charm quark is already heavy enough to apply such considerations, and such a check is indeed possible [32].

Besides the threshold behaviour, short distance QCD also provides the high energy value of the $J/\psi$ dissociation cross section; the result of some 2 - 3 mb indicates once more that something else must be absorbed in the mentioned $p - A$, $O - U$ and $S - U$ data.

On the experimental side, a crucial contribution came from a study of high $p_T$ charmonium production in $p\bar{p}$ interactions at the Fermilab Tevatron [34]. In such collisions, charmonium production was believed to be accountable in terms of the colour singlet model [33]: ‘perturbative’ parton interactions produce a $c\bar{c}$ pair in a colour octet state, which subsequently neutralizes its colour and forms a colour singlet $c\bar{c}$ of $J/\psi$ quantum numbers by the emission of hard gluons. The model definitely disagreed with low $p_T$ data on charmonium production [17, 35], but in this kinematic regime it was not really expected to be reliable. The Fermilab data, in contrast, were in a suitable kinematic region and nevertheless turned out to disagree with the colour singlet model predictions by factors 10 - 100. This clearly ruled out such a description and showed that non-perturbative effects are important in charmonium production.

Enter: the colour octet model. Based on the formalism of non-relativistic QCD [36], it assumes that in order to form a charmonium state, the perturbatively produced $c\bar{c}$ pair first neutralizes its colour by combining with one or more soft collinear gluon comovers [37]. This pre-resonance charmonium state, a colour singlet formed by the $c\bar{c}$ colour octet plus the smallest number of gluons required to provide the relevant quantum numbers, then is quickly transformed into the basic colour singlet $c\bar{c}$ charmonium resonance. For the hadroproduction of $J/\psi$’s or $\psi''$s at small transverse momentum, the lowest possible
pre-resonance states of this type are colour singlets of the octet $c\bar{c}$ and one gluon; such a state turns into the basic colour singlet $c\bar{c}$ states in a time of about 0.2 - 0.3 fm [38]. The charmonia produced in present $p - A$ data, i. e., around $x_F \simeq 0.1$, traverse the entire nucleus during the pre-resonance time, so that the nuclear medium ‘sees’ only the passage of the $c\bar{c} - g$ state. Since this is of the same structure for $J/\psi$ and $\psi'$, these states also suffer the same absorption during their passage. Moreover, the break-up of a state consisting of colour octet components leads to a cross section which is $9/4$ times larger than that of a compact state consisting of colour triplet components; this suggests some $5 - 7$ mb as the absorption cross section for the $c\bar{c} - g$ in nuclear matter, in accord with the result of the phenomenological fit in [25].

Pre-resonance charmonium absorption thus provides the needed explanation for the required size of the dissociation cross section as well as for the equal absorption suffered by the different charmonium states [30]. It also removes the necessity for any additional absorption by hadronic comovers in $O - U$ or $S - U$ collisions; pre-resonance absorption in nuclear matter alone reproduces well all $J/\psi$ suppression from $p - A$ to central $S - U$ data, including the centrality dependence of nucleus-nucleus collisions [39]. The absence of comover suppression for the $J/\psi$, however, does not imply the absence of hadronic comovers. This is shown by the fact that the loosely bound and hence easily broken $\psi'$ does in fact suffer more than just pre-resonance suppression in central $S - U$ interactions [11]. So hadronic comovers appear, but they do not affect the $J/\psi$, in accord with the mentioned short distance QCD calculations [30]. The conclusion at the end of the ‘sulphur era’ thus found the observed $J/\psi$ suppression, from $p - A$ to $S - U$ collisions, to be ‘normal’: it could be understood in terms of ‘conventional’ pre-resonance absorption in nuclear matter and required no additional suppression by hadronic comovers or by colour deconfinement [38] - [40].

The data from the 1995 $Pb - Pb$ run of NA50 marked the end of this normality and the advent of ‘anomalous’ $J/\psi$ suppression [12, 13]: increasing with centrality, the $J/\psi$ data fell about 30 % below the value expected from pre-resonance absorption, indicating the onset of a new suppression mechanism. Such an additional decrease would in fact occur if all $J/\psi$ in the hot inner collision region would ‘melt’ [14, 15], with the energy density in central $S - U$ collisions taken as critical deconfinement threshold. Explanations in terms of absorption by hadronic comovers were also considered once more [16, 17]; since any such absorption sets in gradually, this required some effect to be present already in $S - U$ data, where it was not really needed [39]. Nevertheless, by admitting less than optimal fits to $p - A$ and $S - U$ data, hadronic comover absorption remained an alternative to be considered. In particular, the rather crucial relation between central $S - U$ and peripheral $Pb - Pb$ data still remained unclear.

A year later, the much more precise data of the 1996 $Pb - Pb$ run appeared [48] - [50], showing peripheral $Pb - Pb$ data in accord with pre-resonance absorption (and thus with the $S - U$ results). But in addition, these data indicated with increasing centrality an abrupt onset of the anomalous suppression (Fig. 2): at an impact parameter of about 8 fm (corresponding to an associated transverse energy of about 40 GeV), the ratio of $J/\psi$ production to that of Drell-Yan pairs suddenly dropped by about 25 %.

Since an abrupt change of physical variables is in general related to critical behaviour, this observation might well be the first indication of deconfinement; hence it quite naturally triggered numerous questions. Are the $J/\psi$ and the Drell-Yan data in the different
kinematic regions absolutely reliable? If yes, how abrupt is the onset, and how does it show up as function of other variables? How abrupt can it realistically be, given impact parameter smearing, resolution, etc.? How precise do data have to be to rule out models based on a smooth transition? Which variable governs the onset of anomalous suppression? What further data are best suited to corroborate and eventually confirm the observation? – to name just some of the many questions. Clearly, the primary objective of the experimentalists must be to establish their results beyond any reasonable doubt.

Until that is done, perhaps the best a theorist can do is to go back to basics and ask what QCD can tell us in more detail about the phenomena expected to occur at the onset of deconfinement. Some first work in this direction, studying the relation of deconfinement and percolation, is reported elsewhere [51]; its application to $J/\psi$ suppression will be presented at this meeting by M. Nardi [52].

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