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J/ψ SUPPRESSION IN NUCLEAR COLLISIONS: DECONFINEMENT OR ABSORPTION?*

Helmut Satz

Theory Division, CERN
CH-1211 Geneva 23, Switzerland

and

Fakultät für Physik, Universität Bielefeld
D-48 Bielefeld, F. R. Germany

Abstract:

The characteristic features of J/ψ suppression by deconfinement due to colour screening are compared to those obtained by combining absorption in very dense hadronic matter with initial state gluon scattering.

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It was predicted that the formation of a deconfining medium in heavy ion collisions would lead to the suppression of the J/ψ signal relative to the Drell-Yan continuum[1]. Subsequently such a suppression was observed by the NA38 collaboration at CERN[2], and in model studies[3-6] the data were found to agree with the deconfinement predictions. This triggered an intensive investigation of alternative, more "conventional" suppression mechanisms[7-18], in order to check if the experimental results could be interpreted as evidence for quark deconfinement. While initially the suppression rate and the P_T dependence resulting from the alternative approaches were not in accord with the data, it is now possible to account for the measurements by combining initial state gluon scattering with final state J/ψ absorption in very dense hadronic matter[15-18]. Both deconfinement and absorption need a comparatively large-scale system of high density and of a life-time long enough to permit J/ψ melting or break-up. Where, if at all, do the predictions of the two scenarios differ, and how could future experiments decide which of the two is appropriate? This report will attempt to give some first and rather qualitative answers to these questions.

We begin by summarizing the essential features of the data to be accounted for so far. Present NA38 results show that[2,19,20]

(i) J/ψ production in O-U, O-Cu and S-U collisions is strongly dependent on the associated transverse hadronic energy E_T; this dependence in turn varies strongly with the transverse momentum P_T of the J/ψ;
(ii) J/ψ production by p-U collisions does not show a significant E_T dependence for any P_T;
(iii) the continuum (dileptons in the mass range 1.8 - 5.2 GeV, excluding the J/ψ interval 2.8 - 3.5 GeV) does not show a significant E_T dependence for any P_T;
(iv) the ratio of the J/ψ signal to the continuum is reduced by more than 50% between the highest and lowest E_T intervals studied. At low E_T, the ratio appears to approach the corresponding value from p-U collisions. Different nuclear targets and projectiles appear to follow a universal pattern as function of $E_T/A^{2/3}$;
(v) the J/ψ suppression seems to disappear for $P_T \geq 2-3$ GeV; for larger P_T, the ratio of high to low E_T J/ψ events is the same as for the corresponding continuum events.

It will be be particularly interesting to see if the results (ii) and (iii) survive a closer scrutiny of the present data - or future experiments with higher statistics.

How can the two scenarios account for this behaviour? Let us first see how the overall J/ψ suppression is obtained, and then return to its P_T dependence.

Absorption: Here the $c\bar{c}$ pair interacts with some $q\bar{q}$ system, which may or may not yet be a real hadron, and as a result it is broken up, leading to a $c\bar{q}$ and a $\bar{c}q$. This can happen at any density, but it is more likely when more interaction partners ($q\bar{q}$'s) are present. The dominant break-up reaction mechanism is

$$J/\psi + h \rightarrow D + \bar{D}, \qquad (1)$$

which requires a threshold energy of about 600 MeV, if the hadron is a π. The presence of higher mass mesons would reduce this, however[9].

Deconfinement: Here it is not an individual $q\bar{q}$ pair that causes the $c\bar{c}$ break-up; instead, it is the collective effect of the many other colour charges present that screens the binding force between the c and the $\bar{c}$. This phenomenon starts at a specific critical density: when the screening length of the medium has attained a value which makes the interquark potential so short-ranged that $c\bar{c}$ bound states cease to be possible[21].

Both mechanisms have in common the need for very dense matter. As just noted, J/ψ suppression by deconfinement does not occur at all unless the energy density ϵ is greater than some critical value ϵ_c. Lattice studies suggest[22] $\epsilon_c \simeq 2$ GeV/fm^3, an energy density more than ten times higher than that of normal nuclear matter ($\epsilon \simeq 0.15$ GeV/fm^3), and still a factor four higher than that found inside a single hadron ($\epsilon \simeq 0.5$ GeV/fm^3). Absorption can in simplest form be described by a J/ψ "survival" function

$$S = e^{-xn\sigma}, \qquad (2)$$

where x denotes the spatial size of the absorbing system, n the density of the scattering centers, and σ the total cross-section for all J/ψ break-up reactions. For normal nuclear density ($n = 0.17$ fm^{-3}) and a typical J/ψ-hadron cross-section $\sigma = 1\text{mb} = 0.1\text{fm}^{-3}$, we get with $x \simeq 7$ fm for the radius of a heavy target nucleus the value $S \simeq 0.89$, i.e., a suppression of only 11 %. Even if we double the J/ψ break-up cross-section, we still only have 21 % suppression. On the other hand, a small but very dense system can lead to much higher suppression rates. For the CERN oxygen or sulphur runs at high E_T, $\epsilon \simeq 2$ GeV/fm^3 is a reasonable energy density estimate. Partitioned among pions of 0.5 GeV energy each, this implies $n \simeq 4$ pions/fm^3. With such a density for a system of the size of the incoming oxygen nucleus ($x \simeq 2.5$ fm) and with $\sigma = 1$ mb, as before, we get $S \simeq 0.37$, i.e., more than 60 % suppression. The absorption picture used here is certainly very crude, but more refined formulations[7-10] lead to quite similar conclusions.

We should note here, however, that such a density implies eight pions compressed into the volume of a single pion - a situation which conceptually does not appear very meaningful. This is not meant as a criticism of the absorption approach as such, but rather as a reminder that the nature of the absorbing matter and that of the scattering centers in this approach must still be clarified[23]. Hadronic matter of such an extreme density is certainly not "conventional", and if it is not a quark-gluon plasma, we must still find out what it really consists of.

Let us now turn to the transverse momentum behaviour of J/ψ suppression. The deconfinement approach contains an inherent momentum dependence, due to the finite size and life-time of any plasma system produced in nuclear collisions[24,25]. Sufficiently fast $c\bar{c}$ pairs will, when they leave the deconfining medium, still be close enough together to bind to a J/ψ. In the $c\bar{c}$ rest frame, the c and the $\bar{c}$ need a time of about $\tau_0 \simeq 0.9$ fm to separate a distance of $r_{J/\psi} \simeq 0.45$ fm, the radius of the J/ψ. In the overall plasma rest frame, the time τ_0 becomes

$$t_0 = \tau_0(1 + P^2/M^2_{J/\psi})^{1/2}, \qquad (3)$$

where P denotes the momentum of the $c\bar{c}$ pair. During this time, the pair will have travelled a distance

$$r_0 = \tau_0(P/M_{J/\psi}) \qquad (4)$$

away from its formation point, again measured in the overall cms. If either

$$t_0 \geq t_{plasma} \tag{5}$$

or

$$r_0 \geq r_{plasma}, \tag{6}$$

where t_{plasma} and r_{plasma} denote the plasma life-time and radius, respectively, then the $c\bar{c}$ pair can still bind to form a J/ψ, and hence in this case we will not encounter any suppression. Turned around, this argument allows us to estimate the plasma size or life-time from the value of P_T above which no suppression is observed. The data suggest that it is the plasma life-time which is responsible for the P_T behaviour, with $t_{plasma} \simeq 1$ - 2 fm; detailed calculations account well for the measured distributions[3-6].

J/ψ suppression by absorption, on the other hand, has a rather weak momentum dependence. In fact, in the absence of hadronic resonances as scattering partners, the threshold for reaction (1) even implies an increase of suppression for higher P_T of the J/ψ[8]. In general, fast J/ψ's undergo as many collisions as slow ones, and hence suffer as much break-up. Since the life-time of the absorbing medium is quite large (much larger than the life-time of a deconfining plasma with its high energy density), eq.(6) leads to an end of suppression only for very large momenta (typically for $P_T \geq 10$ GeV or more[8-10]). Absorption alone thus cannot account for the P_T behaviour observed in high E_T nuclear collisions.

To obtain a viable alternative explanation for J/ψ suppression, final state absorption has to be combined with an initial state interaction of the partons which produce the $c\bar{c}$ pair. Such an interaction is in fact to be expected, since the P_T distribution of Drell-Yan pairs in $p-A$ collisions is with increasing A shifted towards higher transverse momenta[26], and such pairs should not experience any final state interactions. In accord with this, the integrated cross-section retains the form $\sigma_{pA}^{DY} = A\sigma_{pp}^{DY}$, so that we really just have a shift in phase space, and not a net suppression. This shift was predicted[27,28]: a quark in the projectile, which eventually annihilates with an antiquark in the target to form the Drell-Yan pair, can in a nuclear target undergo elastic scattering before the annihilation takes place. It is thus deviated from the beam axis, resulting in a shift towards higher P_T for the lepton pair. J/ψ production is assumed to occur through gluon fusion, and if the gluons also undergo such initial state scattering in nuclear matter, their P_T distribution will be broadened as well, and this is in fact observed in $p-A$ experiments[29,30].

The A dependence of the J/ψ and Drell-Yan P_T distributions from $p-A$ data now has to be generalized to provide an E_T dependence in nuclear collisions, if it is to explain the NA38 results. To achieve this, one relates the number of initial state parton scatterings to an effective number $\bar{\nu}$ of proton-nucleon collisions in $p-A$ reactions. Extrapolating this picture to nucleus-nucleus collisions, one expects a larger $\bar{\nu}$ and hence more P_T broadening as the impact parameter decreases, or E_T increases. Using a $\bar{\nu}$ from nuclear scattering models and fitting the available $p-A$ data to fix all parameters, one thus obtains a prediction for the P_T distribution of the J/ψ's from nucleus-nucleus collsions. To describe the actual data, this now is combined with final state absorption in very dense hadronic matter; the result[15-17] agrees as well

with the measured P_T and E_T behaviour as that from the deconfinement approach. It is clear, however, that in particular the $\bar{\nu} - E_T$ relation is rather dependent on the nuclear scattering model used and on the details of the nuclear geometry.

Let us now look at some crucial features in each scenario. The absorption picture, as indicated, relies very much on the extrapolation of $p-A$ data to nuclear collisions. Larger E_T values are related to more initial state interactions, and this must clearly effect also the Drell-Yan continuum. This approach therefore predicts a significant broadening of the Drell-Yan P_T distribution with increasing E_T, and that can certainly be tested. Present data do not seem to show such an effect, but the experimental errors so far are probably too large for any significant test.

The actual parametrisations[15-17] of the initial state quark and gluon distributions give a larger P_T shift to gluons than to quarks. This implies that the J/ψ-to-continuum ratio at high E_T should for large P_T not approach unity, but become larger than one. Again present errors are too large to allow a test, but this prediction as well could be checked with data of higher statistics.

With both these predictions, we essentially test the validity of the extrapolation from $p-A$ collisions to nucleus-nucleus interactions. It is conceivable that in the E_T range studied, the number of effective nucleon-nucleon collisions does not vary so much; if that is the case, the basis for the $E_T - P_T$ correlation in the absorption picture becomes incorrect.

On the other hand, if one does observe a significant E_T dependence of the Drell-Yan P_T distribution in nuclear collisions, then there may not be much "room" for the additional intrinsic P_T dependence of the deconfinement picture. Hence a study of the E_T dependence of the Drell-Yan spectra is very important for the screening approach as well.

The most crucial feature of deconfinement, however, arises from its nature as a critical phenomenon. The J/ψ suppression as function of the energy density must have a form of the type shown in fig. 1. A large range of ϵ does not lead to any suppression, and there is a critical value ϵ_c where the suppression starts. As a consequence, central nucleus-nucleus collisions below a certain beam energy should not show a reduction of the signal-to-continuum ratio as E_T is increased. Absorption, however, should occur at all energies and at a given energy increase with increasing nuclear volume. Thus at least in principle, absorption and deconfinement lead to quite distinct patterns, schematically illustrated in fig. 1. One continuous suppression pattern from $p-p$ collisions to high E_T nucleus-nucleus interactions would be difficult to understand in the deconfinement approach; a noticeable break in the suppression pattern between $p-p$, $p-A$ and nucleus-nucleus collisons would seem to require more than just absorption in matter of increasing density.

In conclusion: we do seem to reach the regime of very dense matter. To understand what such matter really consists of, we need more experimental information.

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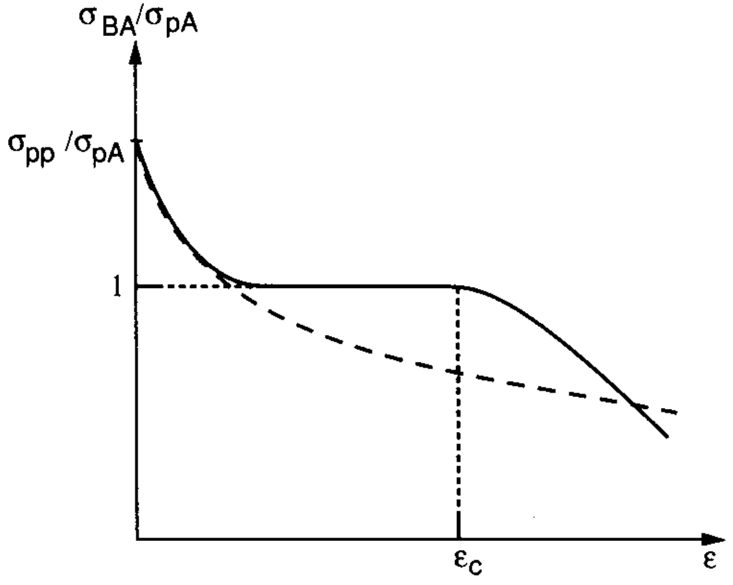

Fig. 1: The schematic dependence of J/ψ production on the initial energy density produced in the collision, in the deconfinement (solid line) and the absorption approach (dashed line).