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BI-TP 95/05**HARD PROBES OF DENSE MATTER\*****Helmut Satz**Theory Division, CERN  
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Direct probes for the QGP must be hard enough to resolve sub-hadronic scales ( $\ll \Lambda_{\text{QCD}}^{-1}$ ) and distinguish confined and deconfined media. This can be achieved by fast colour charges (jets) and heavy quark resonances (quarkonia). After a general survey, we study quarkonia as confinement probe and show in particular that confined matter is transparent, deconfined matter opaque to  $J/\psi$ 's.

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# HARD PROBES OF DENSE MATTER

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Direct probes for the QGP must be hard enough to resolve sub-hadronic scales ( $\ll \Lambda_{\text{QCD}}^{-1}$ ) and distinguish confined and deconfined media. This can be achieved by fast colour charges (jets) and heavy quark resonances (quarkonia). After a general survey, we study quarkonia as confinement probe and show in particular that confined matter is transparent, deconfined matter opaque to  $J/\psi$ 's.

## 1. Probing the Quark-Gluon Plasma

In high energy nuclear collisions, two beams of partons collide; the partons are initially confined to the colliding nucleons. This confinement can be verified, e.g., by studying primary high mass Drell-Yan dilepton production and observing, except for possible nuclear shadowing effects, the same parton distribution functions as in deep inelastic lepton-nucleon collisions. After the primary collision, we expect abundant multiple interactions, leading to a rapid increase of entropy, quick thermalisation and hence the production of strongly interacting matter. The fundamental question is whether confinement survives this thermalisation. If it does, we have hadronic matter – if not, a quark-gluon plasma (QGP). We expect confinement to be lost if the density of partons sufficiently surpasses that present in a hadron-hadron interaction, so that partons can no longer be assigned to specific hadrons. How can we probe if this has happened?

The QGP is a *dense* system of *deconfined* quarks and gluons. Its density is in fact the reason for deconfinement: in a sufficiently dense medium, the long-range confining forces become screened, so that only short-range ( $\ll \Lambda_{\text{QCD}}^{-1}$ ) interactions between quarks and gluons remain. To study such a medium and determine its nature, we therefore need probes which are *hard* enough to resolve the short sub-hadronic scales and which can distinguish between *confined* and *deconfined* quarks and gluons. In addition, the probe must survive the subsequent evolution of the medium; therefore it certainly cannot be in equilibrium with the later stages of matter. Two hard, strongly interacting signals

produced before equilibration and distinct from the medium have been proposed as *external* probes for confinement/deconfinement:

- *hard* quarks or gluons (jets) [1,2], and
- *heavy* quark-antiquark resonances (charmonium, bottonium) [3,4].

Jet and quarkonium production are rather well understood in hadron-hadron collisions, where they are accounted for in terms of perturbative QCD and hadronic parton distribution functions [5,6]. In both cases, the initially formed state ( $Q\bar{Q}$ ,  $q$  or  $g$ ) is in general coloured, and it has an intrinsic mass or momentum scale much larger than  $\Lambda_{\text{QCD}}$ . For jets, this is also the state to be used as probe, since the behaviour of a fast colour charge passing through confined matter differs from that in a deconfined medium [7]. In confined matter, the colour charge loses energy as it passes from one hadron to the next through the “interhadronic” vacuum, and the energy loss is determined by the string tension  $\sigma$  acting on the colour charge as it leaves the field of a hadron [8]. In a deconfined medium, the crucial quantity is the colour screening parameter  $\mu$  (the inverse of the screening radius), which determines with how many other charges the passing colour charge can interact and thus also how much energy it can lose per unit length [9,10].

For fast quarkonia, the situation is similar; they will pass through the medium while still in a coloured state [8], and hence they can be used as probe in the same way as jets. In addition, however, we can consider slow quarkonia, which have become full physical resonances within a hadronic volume around the  $Q\bar{Q}$  formation point and thus traverse the medium as colour singlets. Since the intrinsic spatial scales of  $J/\psi$  and  $\Upsilon$ , determined by the heavy quark masses and the binding energies, nevertheless remain much smaller than the hadronic size  $\Lambda_{\text{QCD}}^{-1}$ , they interact only with the partons within a big, light hadron and not with the hadron as a whole. They are thus able to probe the partonic state of any medium. In particular, they are essentially unaffected by the soft gluons which make up confined matter, while the hard gluons present in a QGP will dissociate them [3,4].

For both quarkonia and jets, thermal production in the expected temperature range ( $T \lesssim 0.5$  GeV) is excluded by the mass or momentum scales involved; we can therefore be quite sure that such signals were produced prior to QGP formation. They will also not reach an equilibrium with later stages of the medium. Hard jets and fast quarkonia require too much of an energy loss for this, while slow quarkonia, as noted, are either dissociated or not affected by the medium.

For both proposed probes, initial state and/or pre-equilibrium nuclear effects can occur before QGP formation. Primary quarks and gluons may undergo multiple scattering or experience shadowing in the nucleus *before* they interact to form a  $Q\bar{Q}$  pair or a hard transverse parton. These effects have to be understood and taken into account before any QGP analysis [11,12]. It is therefore necessary to study them in processes which are not effected by the subsequent medium, such as the production of hard direct photons [13] or of high mass Drell-Yan dileptons [14]. In these cases, we have only annihilation or bremsstrahlung of the incident partons; the resulting electromagnetic signal

leaves the system unaffected by any subsequent medium and its evolution. If such reactions show nuclear effects, then these are presumably due to initial state phenomena. The overall rates for the production of open charm or beauty can fulfill similar functions [15,16].

In addition to the external probes just mentioned, there are hard electromagnetic signals (photons, dileptons), produced by annihilation or bremsstrahlung of the constituents of the medium [17,18]. These will escape unaffected by the subsequent evolution of the medium and could thus be *internal* probes of its early state. Thermal dileptons (or photons), if observable, will certainly provide information about the temperature of the medium from which they are emitted [19,20]. It is not clear if they can also tell us something about its nature. In contrast to the elementary annihilation process of a quark and an antiquark, the annihilation of two hadrons into a hard dilepton involves more than one  $q\bar{q}$  pair. This introduces a hadronic form factor, which in turn causes the hadronic annihilation cross section to decrease faster with dilepton mass  $M$  than the  $q\bar{q}$  annihilation cross section (see [21] for a recent discussion). This could in principle make the dependence of thermal dilepton production on  $M$  in a confined medium different from that in a deconfined medium. However, it is not clear up to now if hard thermal dileptons or photons can be experimentally identified and studied [22].

In the main part of this survey, we will now consider in detail the use of quarkonium production as a probe to check if dense strongly interacting matter is deconfined, i.e., if it forms a QGP. We concentrate on quarkonium for several reasons.  $J/\psi$  suppression was predicted [3] to be the consequence of QGP formation, and such a suppression was subsequently indeed observed in high energy nuclear collisions at the CERN-SPS [23]. This triggered an intensive study of possible alternative origins of such a suppression. Hence the analysis necessary to establish an unambiguous probe for deconfinement has been carried much further here than for jets and can provide a good illustration of what needs to be done before drawing any conclusions. In particular, we must understand theoretically and experimentally

- the dynamics of the process to be used as probe,
- how the probe reacts to confined matter,
- how it reacts to deconfined matter, and
- how it is influenced by initial state and/or pre-equilibrium effects.

In the following, we shall address mainly the first three points. The role of initial state and pre-equilibrium nuclear effects has been and still is under investigation, also for jet production in  $p - A$  and  $A - B$  collisions.

## 2. Quarkonium Production in Hadron-Hadron Collisions

In this section, we shall sketch the basic dynamics of quarkonium production in hadron-hadron collisions [6]. To be specific, we shall speak about charmonium states; but everything said holds for bottonium as well.

The first stage of charmonium formation is the production of a  $c\bar{c}$  pair; because of the large quark mass, this process can be described by perturbative QCD (Fig. 1). A

parton from the projectile interacts with one from the target; the parton distributions within the hadrons determined e.g. by deep inelastic lepton-hadron scattering. Initially, the  $c\bar{c}$  pair will in general be in a colour octet state. It subsequently neutralises its colour and binds to a physical resonance, such as  $J/\psi$ ,  $\chi_c$  or  $\psi'$ . Colour neutralisation occurs by interaction with the surrounding colour field; this and the subsequent resonance binding are presumably of non-perturbative nature (“colour evaporation” [24]). In the evaporation process, the  $c\bar{c}$  pair can either combine with light quarks to form open charm mesons ( $D$  and  $\bar{D}$ ) or bind with each other to form a charmonium state.

Fig. 1: Production of a  $c\bar{c}$  pair by gluon fusion (a) and  $q\bar{q}$  annihilation (b)

The basic quantity in this description is the total sub-threshold charm cross section, obtained by integrating the perturbative  $c\bar{c}$  production over the mass interval from  $2m_c$  to  $2m_D$ . At high energy, the dominant part of  $\tilde{\sigma}_{c\bar{c}}$  comes from gluon fusion (Fig. 1a), so that we have

$$\tilde{\sigma}_{c\bar{c}}(s) = \int_{2m_c}^{2m_D} d\hat{s} \int dx_1 dx_2 g(x_1) g(x_2) \sigma(\hat{s}) \delta(\hat{s} - x_1 x_2 s), \quad (1)$$

with  $g(x)$  denoting the gluon density and  $\sigma$  the  $gg \rightarrow c\bar{c}$  cross section. In pion-nucleon collisions, there are also significant quark-antiquark contributions (Fig. 1b), which become dominant at low energies. The essential prediction of the colour evaporation model is that the production cross section of any charmonium state  $i$  is given by

$$\sigma_i(s) = f_i \tilde{\sigma}_{c\bar{c}}(s), \quad (2)$$

where  $f_i$  is a constant which for the time being has to be determined empirically. In other words, the energy dependence of any charmonium production cross section is predicted to be that of the perturbatively calculated sub-threshold charm cross section. As a consequence, the production ratios of different charmonium states

$$\frac{\sigma_i(s)}{\sigma_j(s)} = \frac{f_i}{f_j} = \text{const.} \quad (3)$$

are predicted to be energy-independent.

These predictions have recently been compared [6] to the available data. In Figs. 2 and 3, we see that the energy-dependence is well described for both  $J/\psi$  and  $\Upsilon$  production. We note in particular that for  $\Upsilon$  production this holds up to 1.8 TeV, so that these rates can be given with considerable confidence for RHIC and LHC energies. In Figs. 4 and 5, also the predicted energy-independence of production ratios is found to hold, again up to Tevatron energy. Here it should be noted that the CDF data for the ratio  $\psi'/(J/\psi)$  are taken at large transverse momenta ( $5 \leq p_T \leq 15$  GeV), while the lower energy data are integrated over  $p_T$ , with the low  $p_T$  region dominant. Hence colour evaporation appears to proceed in the same way at both small and large  $p_T$ . An understanding of this and the theoretical determination of the coefficients  $f_i$  in eq. (2) are presently the great challenges in the study of quarkonium production.

### 3. Quarkonium Production in Hadron-Nucleus Collisions

Given the theory of quarkonium production in hadron-hadron collisions, we want to use hadron-nucleus collisions to study the effect of a confined medium on the proposed probe. Before doing this, however, we have to return to the evolution of quarkonium production already mentioned above. Experimentally, quarkonium production is studied through its decay dileptons (generally dimuons); hence these have to be sufficiently hard to pass through the absorber of a muon spectrometer. As a consequence, the quarkonia measured so far in fixed nuclear target  $p - A$  collisions are always fast in the nuclear rest frame. This means that they traverse the nucleus in the very early stage of their evolution, in which the  $Q\bar{Q}$  pair is still in a colour octet state. To confirm this experimentally, we compare  $J/\psi$  and  $\psi'$  production; the fully formed resonances differ in size by a factor four, so that their interaction in a nucleus should be quite different. As nascent small colour singlets, they would suffer little or no interaction, because of colour transparency. Data [25], however, show that there is a significant suppression of fast quarkonium production in nuclei, compared to that on nucleons, but that this suppression is the same for  $\psi'$  and  $J/\psi$ . The production ratio of the two states is moreover found to be  $A$ -independent and the same as in hadron-hadron collisions (Fig. 6), indicating that the colour evaporation occurs well outside the nucleus. What such experiments study is therefore the passage of a colour charge through (confined) nuclear matter. This is also studied in jet production, and it would certainly be interesting to compare in detail jet and quarkonium data from  $p - A$  collisions. The passage of fast charges through matter is a very fascinating topic; one of the most striking theoretical conclusions, the suppression of soft radiation – the so-called Landau-Pomeranchuk effect [26] – has just recently been confirmed experimentally in high energy experiments [27]. It is due to quantum-mechanical coherence effects, and these can occur as well in the case of colour charges [12]. In a confined QCD medium, the colour charge will in addition to such “nuclear shadowing” suffer an energy loss on its way “out”, and this will shift both quarkonium and jet production in nuclei to lower momenta [8].

We want to concentrate here on the use of fully formed quarkonium states as probes. For  $p - A$  collisions, this requires the study of slow quarkonia in the nuclear

rest frame and hence seems experimentally very difficult, since slow charmonium decay dimuons will not make it through the absorber. A rather novel solution to this problem is offered by the advent of heavy ion *beams* [4]. Fast quarkonia produced by a lead beam incident on a hydrogen target lead to fast decay dimuons in the lab system, so these would be readily detectible. Sufficiently fast quarkonia, on the other hand, would now be slow in the nuclear (beam) rest frame, and so provide information about their fate in nuclear matter. The kinematic region of interest for this consists of quarkonia with “thermal” momenta, i.e., some 1 - 3 GeV; this is attained in the forward region, with rapidities  $y \geq 5$  (or  $0.4 \leq x_F \leq 1.0$ ) for  $A - p$  collisions. Any  $J/\psi$ 's measured in such an experiment would have been fully formed before leaving the interaction zone of a single nucleon; it would thus indeed probe confined matter.

Fig. 6: The  $A$ -dependence of the ratio  $\psi'/J/\psi$

#### 4. Quarkonium Production as Deconfinement Probe

The ultimate constituents of matter are evidently always quarks and gluons. What we want to know is if these quarks and gluons are confined to hadrons or not. As prototype for matter in a confined state, let us consider an ideal gas of pions. Their momentum distribution is thermal, i.e., for temperatures not too low it is given by  $\exp(-E_\pi/T) \simeq \exp(-p_\pi/T)$ . Hence the average momentum of a pion in this medium is  $\langle p_\pi \rangle = 3 T$ . The distribution of quarks and gluons within a pion is known from structure function studies; the gluon density is  $g(x) \simeq 0.5(1-x)^3$  for large  $x = p_g/p_\pi$ .<sup>1)</sup> As a consequence, the average momentum of a gluon in confined matter is given by

$$\langle p_g \rangle_{\text{conf}} = \frac{1}{5} \langle p_\pi \rangle = \frac{3}{5} T. \quad (4)$$

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<sup>1)</sup> For very small  $x$ , recent results from HERA indicate a steeper increase; however, this does not affect our considerations here.

Hence in a medium of temperature  $T \simeq 0.2$  GeV, the average gluon momentum is around 0.1 GeV. In contrast, the distribution of gluons in a deconfined medium is directly thermal, i.e.,  $\exp(-p_g/T)$ , so that

$$\langle p_g \rangle_{\text{deconf}} = 3T. \quad (5)$$

Hence the average momentum of a gluon in a deconfined medium is five times higher than in a confined medium<sup>2)</sup>; for  $T = 0.2$  GeV, it becomes 0.6 GeV. We thus have to find a way to look for such a hardening of the gluon distribution in deconfined matter.

The lowest charmonium state  $J/\psi$  provides an ideal probe for this. It is very small, with a radius  $r_\psi \simeq 0.2$  fm  $\ll \Lambda_{QCD}^{-1}$ , so that  $J/\psi$  interactions with the conventional light quark hadrons probe the short distance features, the parton infra-structure, of the latter. It is very strongly bound, with a binding energy  $\epsilon_\psi \simeq 0.65$  GeV  $\gg \Lambda_{QCD}$ ; hence it can be broken up only by hard partons. Since it shares no quarks or antiquarks with pions or nucleons, the dominant perturbative interaction for such a break-up is the exchange of a hard gluon.

We thus see qualitatively how a deconfinement test can be carried out. If we put a  $J/\psi$  into matter of temperature  $T = 0.2$  GeV, then

- if the matter is confined,  $\langle p_g \rangle_{\text{conf}} \simeq 0.1$  GeV, which is too soft to resolve the  $J/\psi$  as a  $c\bar{c}$  bound state and less than the binding energy  $\epsilon_\psi$ , so that the  $J/\psi$  survives;
- if the matter is deconfined,  $\langle p_g \rangle_{\text{deconf}} \simeq 0.6$  GeV, which (with some spread in the momentum distribution) is hard enough to resolve the  $J/\psi$  and to break the binding, so that the  $J/\psi$  will disappear.

The latter part of our result is in accord with the mentioned prediction that the formation of a QGP should lead to  $J/\psi$  suppression [3]. There it was argued that colour screening would prevent any resonance binding between the perturbatively produced  $c$  and  $\bar{c}$ , allowing the heavy quarks to separate. At the hadronisation 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  $\bar{D}$ . Although the details of such a picture agreed well with the observed  $J/\psi$  suppression [28], it seemed possible to obtain a similar suppression by absorption in a purely hadronic medium [29], through by collisions of the type

$$J/\psi + h \rightarrow D + \bar{D} + X. \quad (6)$$

Taking into account the partonic substructure of such hadronic break-up processes, we now see that this is in fact not possible for hadrons of reasonable thermal momentum. Our picture thus not only provides a dynamical basis for  $J/\psi$  suppression by colour screening, but it also indicates that in fact  $J/\psi$  suppression in dense matter will occur *if and only if* there is deconfinement.

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<sup>2)</sup> We could equally well assume matter at a fixed energy density, instead of temperature. This would lead to gluons which in case of deconfinement are approximately three times harder than for confinement.



The theoretical basis of these arguments is provided by the calculation of the inelastic  $J/\psi$ -hadron cross section,  $\sigma_{\psi h}$ , which we can then use to check if a  $J/\psi$  can be broken up on its passage through hadronic matter. Because of the small radius and large binding energy of the  $J/\psi$ ,  $\sigma_{\psi h}$  can be calculated in the short-distance analysis of QCD [30–4]. The crucial feature for this calculation is the fact that heavy and tightly bound quarkonium states can be broken up by scattering on usual light hadrons only through the exchange of sufficiently hard gluons. The cross section for this is given by [31]

$$\sigma_{g-\psi}(p_g) \simeq 65 \text{ mb} \left[ \frac{p_g}{E_\psi} - 1 \right]^{3/2} \left[ \frac{E_\psi}{p_g} \right]^5 \Theta(p_g - E_\psi), \quad (7)$$

where  $E_\psi = 2M_D - M_\psi \simeq 0.64 \text{ GeV}$  is the  $J/\psi$  binding energy and  $p_g$  the momentum of the gluon. The behaviour of  $\sigma_{g-\psi}$  as function of the gluon momentum is shown in Fig. 7; it is seen that gluons in the momentum range from 0.8 to 2.0 GeV are most effective in breaking up  $J/\psi$ 's.

The momentum distribution of gluons within a light hadron of momentum  $p_h$  incident on a  $J/\psi$ ,  $g(x)$ , with  $x = p_g/p_h$ , is a universal non-perturbative input, determined e.g. from parton counting rules or from deep inelastic processes. For large  $x$  it has the form  $g(x) \simeq (1-x)^k$ , with  $k \simeq 3$  for mesons, as used above, and  $k \simeq 4$  for nucleons. The resulting inelastic  $J/\psi - h$  cross section then becomes [4]

$$\sigma_{h-\psi}(s) \simeq 3 \text{ mb} \left[ 1 - \frac{\lambda_o}{E_h} \right]^{k+5/2} \Theta(E_h - \lambda_o), \quad (8)$$

with  $E_h = (m_h^2 + p_h^2)^{1/2}$  and  $\lambda_o \simeq (\epsilon_\psi + m_h)$ . For low collision energies  $\sqrt{s}$ , the cross section is thus determined by the behaviour of the gluon distribution at large  $x$ , as already noted above, and this leads to a very slow growth from threshold towards the asymptotic value of 3 mb. The functional form of this behaviour is also shown in Fig. 7 for  $\pi - \psi$  interactions; it is essentially unchanged for  $\rho - \psi$  or  $A - \psi$  collisions, since it is the gluon distribution in the meson, not the meson mass, which matters.

The short-distance calculation of the quarkonium-hadron cross section becomes exact in the limit of large quark mass. Is the charm quark mass sufficiently large to apply the results of heavy quark theory? Let us first consider this question theoretically and check possible non-perturbative contributions to the break-up process in the threshold region [34]. These can be pictured most simply as a quark rearrangement. Consider putting a  $J/\psi$  “into” a stationary light hadron; the quarks could then just rearrange their binding pattern to give rise to transitions such as  $J/\psi + N \rightarrow \Lambda_c + \bar{D}$  or  $J/\psi + \rho \rightarrow D + \bar{D}$ . The probability for such a rearrangement transition can be written as

$$P_{ra} \sim \int d^3r R_h(r) |\phi_\psi(r)|^2, \quad (9)$$

where the spatial distribution of the  $c\bar{c}$  bound state is given by the squared wave function  $|\phi_\psi(r)|^2$ . The function  $R_h(r)$  in eq. (4) describes the resolution power of the colour field

inside the light hadron  $h$ . The average wave length of this colour field is of order  $\Lambda_{\text{QCD}}^{-1}$ , and so it cannot resolve the charge content of a very much smaller bound state; in other words, it doesn't "see" the heavy quarks in a bound state of radius  $r_\psi \ll \Lambda_{\text{QCD}}^{-1}$  and hence can't rearrange bonds. The resolution  $R(r)$  approaches unity for  $r \simeq \Lambda_{\text{QCD}}^{-1}$ ; for  $r < \Lambda_{\text{QCD}}^{-1}$ , it rapidly decreases as

$$R_h(r) \simeq (r\Lambda_{\text{QCD}})^n, \quad r\Lambda_{\text{QCD}} < 1, \quad (10)$$

with  $n = 2$  [35] or 3 [30]. Note that  $R_h(r)$  describes the colour field of the light hadron and is independent of the heavy quark state. However, the quarkonium radius decreases with increasing quark mass, and hence the same holds for the overlap of  $R_h(r)$  and the squared quarkonium wave function: the light hadron quarks can no longer resolve the small heavy quark bound state.

Quantitatively, this problem can be solved by calculating the tunnelling rate of the charm quarks inside the  $J/\psi$  from  $r = r_\psi$  out to a distance  $r \sim \Lambda_{\text{QCD}}^{-1}$  at which the light quarks can resolve them. Such tunneling processes are truly non-perturbative: they cover a large space-time region, of linear size  $\Lambda_{\text{QCD}}^{-1}$ , and do not involve any hard interactions. Here the resulting tunnelling rate is found to be [34]

$$R_{\text{tun}} = E_\psi \exp\{-1.2\sqrt{m_c E_\psi}/\Lambda_{\text{QCD}}\}, \quad (11)$$

where  $E_\psi \simeq 0.64$  GeV again denotes the  $J/\psi$  binding energy. With  $m_c = 1.5$  GeV and  $\Lambda_{\text{QCD}} = 0.3$  GeV, this yields  $R_{\text{tun}} \simeq 9.0 \times 10^{-3} \text{ fm}^{-1}$  for the rate of  $J/\psi$  dissociation by tunnelling. From it, we get

$$S_{\text{tun}} = \exp\left\{-\int_0^{t_{\text{max}}} dt R_{\text{tun}}\right\}, \quad (12)$$

for the  $J/\psi$  survival probability. The maximum time  $t_{\text{max}}$  which the  $J/\psi$  can spend adjacent to the light hadron is by the uncertainty relation about 4 - 5 fm. The resulting survival probability remains more than 95 %, so that there is effectively no  $J/\psi$  break-up by non-perturbative hadron interactions either.

As emphasized, the inelastic  $J/\psi$ -hadron cross section calculated in short-distance QCD implies that a  $J/\psi$  of "thermal" momentum (1 - 3 GeV) cannot be dissociated in a confined medium. The direct experimental test for this prediction was already indicated in section 3: it requires the study of slow  $J/\psi$ 's in nuclear matter, which is now possible with a nuclear beam incident on a hydrogen (or other light) target. Such experiment is evidently of great importance to have a clear experimental basis for the distinction of  $J/\psi$  production in confined and deconfined matter.

In the meantime, the approach can be checked on similar processes. Using the same short-distance analysis, one can calculate the cross section for the photoproduction of open charm,  $\sigma_{\gamma h \rightarrow c\bar{c}}(s)$ . For this reaction, there are data [36], and they agree well with the prediction of the heavy quark analysis [4].

From short-distance QCD we have thus learned that confined matter cannot dissociate  $J/\psi$ 's. In deconfined matter this is possible, however: the cross section for the dissociation of a  $J/\psi$  by gluon collisions was already given above (eq. (7)) and found to be most effective for momenta around 1 - 2 GeV, i.e., for momenta in the “thermal” range. To compare the two cases directly, we average the corresponding cross sections with a Boltzmann distribution for gluons or pions,

$$\sigma(T) = \int d^3p e^{-|p|/T} \sigma(p) / \int d^3p e^{-|p|/T}. \quad (13)$$

The result is shown in Fig. 8. For gluon-dissociation, the peak occurs for temperatures around 300 - 400 MeV; for hadrons, the cross section becomes comparable only for  $T \simeq 1$  GeV or higher.

In closing this section, we comment briefly on the experimental consequences for charmonium production in nucleus-nucleus collisions. There are two ways to probe:

- compare charmonium production to an unaffected signal, e.g., study  $J/\psi$  production with respect to the Drell-Yan continuum, or
- compare different charmonium states with each other, e.g., study the ratio of  $\psi'/(J/\psi)$  production.

In both cases, the behaviour of the relevant ratio as function of the initial energy density  $\epsilon_0$  is of particular interest. As illustration, we consider the  $\epsilon_0$  dependence of  $J/\psi$  production. The observed  $J/\psi$ 's are in part ( $\sim 40\%$ ) due to  $\chi$ -decay ( $\chi \rightarrow J/\psi + \gamma$ ) [37]. The larger and more loosely bound  $\chi$ 's can be broken up by softer gluons than needed for the dissociation of ground state  $J/\psi$ 's, so that they could also be suppressed in confined matter. Confinement thus allows (at most) a suppression of the  $\chi$  component of the  $J/\psi$ 's and hence requires a saturation of the suppression with increasing energy density, at a survival probability of about 60%. In deconfined matter, on the other hand, also the ground state  $J/\psi$  can be broken up, leading to complete suppression at large  $\epsilon_0$ .

## 5. Summary

To study the dense primordial QGP, we need probes which are sufficiently hard to resolve subhadronic scales ( $\ll \Lambda_{\text{QCD}}^{-1}$ ) and which can distinguish confined and deconfined media. Suitable probes can be either colourless (fully formed quarkonia) or coloured (fast  $Q\bar{Q}$  pairs or hard jets). For  $J/\psi$ 's, confined matter is transparent, while deconfined matter dissolves them. The situation here is thus particularly clear: even if the medium undergoes the quark-hadron transition during the passage of the  $J/\psi$ , the only effect will come from the QGP phase. For jets or fast colour-octet  $Q\bar{Q}$  pairs, the energy loss in deconfined matter differs from that in a deconfined medium [1,2]; interesting recent work [9,10] may help to turn this difference into a viable probe.

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