Charm and strangeness in nuclear reactions at $\sqrt{s} \leq 19$ GeV

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New Journal of Physics 3 (2001) 16.1–16.21 (http://www.njp.org/)
Received 30 November 2000
Published 20 August 2001

Abstract. We propose to study $J/\Psi$ production in relation with open charm production in nuclear reactions. It appears that a suppression of the $J/\Psi$ over Drell Yan ($DY$) ratio has been observed by the CERN experiment NA50 in $\text{Pb}+\text{Pb}$ collisions at $\sqrt{s} = 17$ GeV above the initial energy density $\epsilon \sim 2.3$ GeV fm$^{-3}$, which was not seen in $\text{S}+\text{U}$ collisions at $\sqrt{s} = 19$ GeV at any $\epsilon$. In our view a clear interpretation of these results has not been achieved. The same experiment has measured an excess in $\mu^+\mu^-$, which can be interpreted as resulting from $D\overline{D}$ decay. We demonstrate that the suppression of the $J/\Psi$ does appear in $\text{S}+\text{U}$ collisions, as well as in $\text{Pb}+\text{Pb}$ collisions at a lower $\epsilon \sim 1$ GeV fm$^{-3}$, if the $J/\Psi$ is normalized to $D\overline{D}$, instead of $DY$. This underlines the importance of direct open charm measurements for the interpretation of charmonia suppression. Furthermore we study the dependence of the $J/\Psi$ and $D\overline{D}$ on the number of participating nucleons ($N_p$). The results indicate non-thermal charm production as expected, and $J/\Psi$ dissociation which is stronger than the absorption seen in other hadrons. We find that the $J/\Psi$ in central $\text{Pb}+\text{Pb}$ collisions is compatible with dominant production from $c\overline{c}$ pair coalescence out of a hadronizing quark and gluon environment. A significant change in the $(J/\Psi)/D\overline{D}$ ratio as well as in the number density of kaons is observed simultaneously above the initial energy density $\epsilon \sim 1$ GeV fm$^{-3}$, suggesting a change of phase associated with this $\epsilon$.

1. Introduction

Quantum chromodynamics (QCD) on the lattice predicts a phase transition of confined hadronic matter into deconfined quark and gluon matter (called the quark gluon plasma (QGP) state) at a critical temperature $T_c \sim 175$ MeV, respectively at an energy density $\epsilon_c \sim 1$ GeV fm$^{-3}$ [1]. The order of the transition is parameter dependent [2]. An investigation of relevant observables
in heavy ion collisions [3] as a function of energy and/or the impact parameter of the collision could/should reveal this transition, through a discontinuous behaviour of many QGP signatures at the transition point.

An anomalous suppression of $J/\Psi$ meson production predicted to be a signature of QGP formation [4] has been measured to occur in the ratio of the $J/\Psi$ over the Drell Yan ($DY$) process in Pb+Pb collisions at $\sqrt{s} = 17$ GeV investigated as a function of transverse energy ($E_T$) [5]. In S+U collisions at $\sqrt{s} = 19$ GeV and in the most peripheral Pb+Pb collisions, the $(J/\Psi)/DY$ ratio agrees with expectations [5]. The ratio $(J/\Psi)/DY$ is relevant for the investigation of the $J/\Psi$ suppression, under the assumption that $J/\Psi$ production in these collisions is a hard process.

Recent measurements of the dimuon invariant mass $m(\mu^+\mu^-)$ spectrum between the $\phi$ and the $J/\Psi$ mass (intermediate mass region (IMR)) revealed a dimuon enhancement above expectation, which increases with the number of nucleons participating in the collision ($N_p$) [6]. This enhancement can be understood as due to an excess of $D\bar{D}$ production† as suggested by several features of the data, e.g. the shape of the mass, rapidity and transverse momentum distributions of the dimuons [6]. The interpretation of the IMR enhancement as due to open charm is not unique though, because the open charm was extracted through a fit to the dimuon continuum and the $D\bar{D}$ meson signal was not directly identified. Recent work suggesting that the enhancement seen could be due to rescatterings of $D$ mesons in nuclear matter [7] is not supported by the data [8]. Another possible interpretation is that the IMR excess could be due to thermal dimuons [9].

Non-perturbative effects are known to play a role in heavy flavour hadron production in elementary reactions, showing up in deviations of data from perturbative QCD calculations [10]. Based on this fact, one could expect that theoretical investigation of non-perturbative effects and different reaction dynamics as in the plasma phase may result in an enhancement of open charm production in nuclear reactions over perturbative QCD expectations.

If the total charm produced in heavy ion collisions indeed deviates from the perturbative QCD expectations for a hard process as suggested by the NA50 data, it follows that the $(J/\Psi)/DY$ ratio is not the proper quantity for the search for $J/\Psi$ suppression as signature of QGP formation in nuclear reactions. It is only the ratio $(J/\Psi)/(\text{total } c\bar{c})$ that matters. We therefore investigate here first the dependence of the $J/\Psi$ and the $D\bar{D}$ yields per collision on $N_p$. We further investigate the dependence of the $(J/\Psi)/D\bar{D}$ ratio on $N_p$ and on the length of the nuclear matter traversed by the $J/\Psi$, as well as the dependence of both charm and strangeness production on the initial energy density reached in the collision.

2. $N_p$ dependence of charm yields in S+U, Pb+Pb collisions at $\sqrt{s} = 19$, 17 GeV

2.1. $N_p$ dependence of the DY yield

The NA50 collaboration measured the $DY$ yield per nucleus–nucleus collision, produced in Pb+Pb collisions at $\sqrt{s} = 17$ GeV per $N+N$ pair in arbitrary units, as a function of the transverse energy of the collision (figure 7 in [11]). In this figure it is shown that the theoretically expected $DY$ yield, assuming $DY$ production is a hard process, does partly reproduce the measured one; the deviations at low transverse energy could be understood to result from properties of the lead (Pb) nucleus, in particular from the different radii of the proton and neutron distributions in Pb [12]. It is therefore justified to use the theoretically calculated $E_T$ dependence of $DY$ yield

† By ‘$D\bar{D}$’ we denote the number of $D$ and $\bar{D}$ hadrons which were simultaneously found within the acceptance of the NA50 experiment ($D\bar{D} = (D + \bar{D})_{acc}/2$).
per collision, to estimate the dependence of $J/\Psi$ and $D\bar{D}$ yields on the number of participating nucleons in the collision.

2.2. $N_p$ dependence of the $D\bar{D}$ yield

The NA50 collaboration observed an excess ($E$) of the measured over the expected $D\bar{D}/DY$ ratio in $S + U$ and $Pb + Pb$ collisions at $\sqrt{s} = 19$, 17 GeV, which increases with the number of participants $N_p$ (figure 12 and table 4 in [6]). If we fit the $S + U$ and $Pb + Pb E$ values of the figure quoted above to a function $f = c \cdot N_p^\alpha$, we find that the excess increases with $N_p$ as $N_p^{\alpha=0.45\pm0.11}$ ($\chi^2$/degrees of freedom $(DOF) = 1.7$, $DOF = 13$). The data and the fit are shown in figure 1.

The $N_p$ dependence of the excess $E$ of the $D\bar{D}/DY$ production in $S + U$ collisions at $\sqrt{s} = 19$ GeV and $Pb + Pb$ collisions at $\sqrt{s} = 17$ GeV over expectations reflects the $N_p$ dependence of the $D\bar{D}/DY$ ratio. This results from the fact that all other quantities involved in the definition of $E$ [6, 8] do not depend on $N_p$. Therefore the $N_p$ dependence of the $D\bar{D}$ production yield is given by the $N_p$ dependence of the quantity

$$n_{D\bar{D}} = E \cdot n_{DY} \quad (1)$$

where $n_{D\bar{D}}$, $n_{DY}$ denote the yields of $D\bar{D}$ and $DY$ per collision in arbitrary units. The arbitrary units are due to the fact that NA50 did not publish absolute yields per collision of the $J/\Psi$, $DY$ and $D\bar{D}$ separately, corrected for losses due to e.g. acceptance, as a function of $N_p$, $E_T$. We suggest that it would be important to do so. In short, $n_{D\bar{D}}$ has the same $N_p$ dependence as $(D\bar{D}/DY) \cdot n_{DY}$.

The $DY$ yield used for the above calculation has been extracted from the theoretical curve shown in figure 7 in [11], at the transverse energy ($E_T$) points in which the $D\bar{D}$ excess factor $E$ has been measured.

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Figure 2. $D\bar{D}$ yield per collision in arbitrary units in $\text{Pb} + \text{Pb}$ collisions at 158 A GeV, as a function of the number of participating nucleons $N_p$. The line shows the result of fitting the function $f = cN_p^{\alpha}$. See text for the fit results.

We found the $E_T$ points corresponding to the excess factor $E$ by interpolating between the $E_T$ values as a function of the mean impact parameter ($b$), given in table 1 of [11], to those values of mean impact parameter, at which the factor $E$ has been measured (listed in table 1 of [6]). For the most central and the most peripheral points, for which no mean $b$ are given in table 1 of [6], we estimated the values of $b$ from the dependence of $N_p$ on $b$ calculated for $\text{Pb} + \text{Pb}$ collisions by Ollitrault [13, 14]. These calculations [13] agree with the values ($N_p, b$) estimated by NA50, when compared in their common range.

The resulting $D\bar{D}$ yield in arbitrary units is shown in figure 2. It increases as $N_p^{(\alpha=1.70\pm0.12)}$ ($\chi^2/DOF = 2.5$, $DOF = 7$). This $N_p$ behaviour indicates that $D\bar{D}$ production in $\text{Pb} + \text{Pb}$ collisions at $\sqrt{s} = 17$ GeV has not yet established equilibrium. If equilibrium would be established, a proportionality with $N_p$—assuming $N_p$ to be proportional to the volume of the source†—is expected ($\alpha = 1$).

The evidence that $D\bar{D}$ is not yet thermalized, as demonstrated in figure 2, is further justified because the temperature in the collision zone—assuming local thermalization of light particles—is expected to be of the order $\sim 10^2$ MeV, which is much lower than the mass of charm quarks and/or charmed hadrons.

2.3. $N_p$ dependence of the $J/\Psi$ yield

In the following we estimate the $J/\Psi$ yield per collision as a function of $N_p$, at the same $N_p$ values where the $D\bar{D}$ production was measured. The $N_p$ dependence of the $J/\Psi$ yield per collision is given by the $N_p$ dependence of the quantity

$$n_{J/\Psi} = \frac{J/\Psi}{DY} \cdot n_{DY}$$

† The assumption $N_p \sim V$ is based on the observation that the freeze-out volume $V$ of the particle source is found to be proportional to $N_p$ [15].

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Figure 3. $J/\Psi$ yield per collision in arbitrary units in $\text{Pb+Pb}$ collisions at 158 A GeV, as a function of the number of participating nucleons $N_p$. The line shows the result of fitting the function $f = cN_p^\alpha$. See text for the fit results.

where $n_{J/\Psi}$, $n_{DY}$ denote the yields of $J/\Psi$ and $DY$ in arbitrary units. The $(J/\Psi)/DY$ values have been extracted from figure 4 of [5] at the $E_T$ values where the $E$ factor has been measured, interpolating between the different points.

The resulting $J/\Psi$ yield per collision produced in $\text{Pb+Pb}$ collisions in arbitrary units (figure 3) increases like $N_p^{\alpha=0.70\pm0.04}$ ($\chi^2/DOF = 1.43$, $DOF = 7$). This $N_p$ dependence indicates an increasing $J/\Psi$ dissociation with higher centrality. The strength of this dissociation as measured by the $\alpha$ parameter is higher for the $J/\Psi$ as compared to any other hadron† produced in these collisions, for example as compared to antiprotons. For the latter, a large annihilation cross section with baryons is expected and there is indeed experimental evidence that they are absorbed with increasing centrality in $\text{Pb+Pb}$ collisions ($\alpha(p) = 0.80\pm0.04$ ($\chi^2/DOF = 1.0$, $DOF = 3$) at $y = 3.7$, $p_T = 0$ [15]‡).

The $J/\Psi$ multiplicity as a function of $N_p$ extracted with another method [17] agrees with the results presented here within the errors.

3. The $(J/\Psi)/D\bar{D}$ ratio in nuclear collisions

3.1. The $N_p$ dependence of the $(J/\Psi)/D\bar{D}$ ratio in nuclear collisions

Assuming that the IMR excess is due to open charm allows us to search for an anomalous suppression of $J/\Psi$ as compared to the open charm production. The $N_p$ dependence of the $(J/\Psi)/D\bar{D}$ ratio in $\text{Pb+Pb}$ and $\text{S+U}$ collisions at $\sqrt{s}$ of 17 and 19 GeV, estimated as:

$$\frac{J/\Psi}{D\bar{D}} = \frac{(J/\Psi)/DY}{D\bar{D}/DY} \propto \frac{(J/\Psi)/DY}{E}$$

† Deuterons have an even smaller $\alpha$ parameter, but they are not elementary hadrons and are weakly bound (see the discussion in [15]).

‡ We extracted here the $\alpha$ parameter for $p$, after quadratically adding the statistical and a 5% systematic error.
Figure 4. Ratio of $J/\Psi$ to $D\bar{D}$ in arbitrary units in Pb + Pb collisions at 158 A GeV (full points) and in S + U collisions at 200 A GeV (open points), as a function of the number of participating nucleons $N_p$. The lines show the result of fitting the function $f = cN_p^\alpha$ to the S + U (dotted line) and to the Pb + Pb data points (full line). See text for the fit results.

in arbitrary units due to the $E$ factor in equation (3), is a decreasing function of $N_p$ (figure 4). The $(J/\Psi)/DY$ in S + U collisions was taken from [18, 19]. However NA50 estimated the $DY$ in a different way in the two ratios $(J/\Psi)/DY$ and $D\bar{D}/DY$, which are used in equation (3). Therefore possible deviations of the $DY$ yield from its theoretical calculation (as seen in figure 7 in [11]) do not drop out in the $(J/\Psi)/DY$/$D\bar{D}/DY$ ratio shown here, because the $D\bar{D}/DY$—unlike the $(J/\Psi)/DY$—was calculated by NA50 not using the minimum bias theoretical $DY$ yield values but the measured ones.

In order to smooth statistical oscillations coming from the pattern of transverse energy versus $N_p$, the $(J/\Psi)/DY$ ratio divided by $N_p^{0.45\pm0.11}$ is plotted as a function of $N_p$ in figure 5. This quantity resembles the $(J/\Psi)/D\bar{D}$ ratio

$$\frac{J/\Psi}{D\bar{D}} \propto \frac{(J/\Psi)/DY}{N_p^{0.45\pm0.11}}$$

in arbitrary units. The reason is that $N_p^{0.45\pm0.11}$ is the $N_p$ dependence of the $D\bar{D}/DY$ ratio which is illustrated in figure 1:

$$E \propto \frac{D\bar{D}}{DY} \propto N_p^{0.45\pm0.11}.$$  

Here we use the results of the fit to the data points of figure 1, instead of the points themselves. The gain is that we can now estimate the $(J/\Psi)/D\bar{D}$ ratio for more points than the nine bins measured in figure 1, as the $(J/\Psi)/DY$ ratio has been measured in more $E_T$ bins than the IMR dimuons, possibly due to the lower statistics available for the latter as seen by the errors.
Figure 5. Ratio of $(J/\Psi)/DY$ to $N_p^{0.45\pm0.11}$ in Pb+Pb collisions at 158 A GeV as a function of the number of participating nucleons $N_p$. The nine full star points correspond to the $N_p$ values at which the $D\bar{D}$ yield was measured. The lines show the result of fitting the function $f = cN_p^{\alpha}$ to the full stars. See text for the fit results.

The open points of figure 5 are extracted from the ‘minimum bias analysis’ results of figure 4 in [5]. The full points show the quantity $((J/\Psi)/DY)/N_p^{0.45}$ calculated here at the $N_p$ values where the $D\bar{D}$ excess factor was measured.

According to equation (3), the $(J/\Psi)/D\bar{D}$ ratio in Pb + Pb collisions, decreases with $N_p$ as $N_p^{(\alpha=-0.79\pm0.14)}$ ($\chi^2/DOF = 3.3, DOF = 7$), respectively like $N_p^{(\alpha=-1.17\pm0.14)}$ ($\chi^2/DOF = 1.54, DOF = 6$) when the first point is not fitted.

The $(J/\Psi)/D\bar{D}$ ratio in S + U collisions (figure 4) decreases with $N_p$ as $N_p^{(\alpha=-0.62\pm0.22)}$ ($\chi^2/DOF = 0.69, DOF = 3$).

According to equation (4) the $(J/\Psi)/D\bar{D}$ when fitted to the function $N_p^{\alpha}$ until $N_p = 380$ gives $N_p^{(\alpha=-1.07\pm0.07)}$ ($\chi^2/DOF = 0.93, DOF = 7$).

3.1.1. $J/\Psi$ production through coalescence of $c\bar{c}$ quarks. If the $J/\Psi$ is completely dissociated in a quark gluon plasma and is formed later mainly through $c$ and $\bar{c}$ quark coalescence, we expect that the $N_p$ dependence of the ratio $(J/\Psi)/D\bar{D}$—rather than the $(J/\Psi)/(D\bar{D})^2$—reflects the $N_p$ dependence of the volume of the charm environment [10]. This is due to the expectation that, because of the very low cross section of charm production at these energies, there is most often just one $c\bar{c}$ pair per event containing charm, whatever $N_p$. Then the probability to form a $J/\Psi$ from coalescence is proportional to $(J/\Psi)/D\bar{D}$ and inversely proportional to the volume

† ‘Minimum bias analysis’ in NA50 means that the $DY$ for the $(J/\Psi)/DY$ ratio was determined using the theoretically estimated $DY$ yield per collision as a function of $E_T$ and the measured $dN/dE_T$ versus $E_T$ spectrum of minimum bias trigger events (see [11]).

‡ The first point of the $D\bar{D}/DY$ enhancement factor $E$ lies significantly above the $N_p^\alpha$ function fit to the $E$ distribution (figure 12 in [6]).
of the particle source—made up by $u\overline{u}d\overline{d}s\overline{s}$ quarks and gluons—within which the $c$ and $\overline{c}$ quarks scatter. Assuming this volume is proportional to $N_p$ (see the footnote on p 16.4), one would expect that $(J/\Psi)/D\overline{D}$ decreases as $N_p^{-1}$, as actually derived here.

In this case, one can use the $(J/\Psi)/D\overline{D}$ ratio to extract the absolute value of the volume of its environment with a coalescence model. The ‘charm’ coalescence volume would reflect partly the QGP hot spot volume and partly the hadronic source volume from which hadrons with charm and anticharm can also form a $J/\Psi$. If the absolute yields per collision of $J/\Psi$ and $D\overline{D}$ as a function of $N_p$, needed for this calculation were published by NA50, the charm coalescence volume could be calculated. In the next section we give an approximate estimate of this volume.

Figure 5 suggests that the coalescence picture could hold for the full $N_p$ range of Pb + Pb collisions up to $N_p = 380$.† Indeed the results of the $f = cN_p^\alpha$ fit to data of figure 5 show that the $J/\Psi/D\overline{D}$ ratio decreases proportionally to $1/N_p$. This dependence as discussed above is the one expected if $J/\Psi$ forms out of coalescence of $c\overline{c}$ quarks.

On the other hand, if the multiplicity of charm quarks is high enough that often more than one charm quark pair per event with charm is produced, then it is the ratio $(J/\Psi)/(D\overline{D})^2$ which is expected to be inversely proportional to the volume of the charm source (this is exactly the case if $d$ coalescence out of $p$ and $n$ is investigated in a baryon-rich source). The $N_p$ dependence of the $(J/\Psi)/(D\overline{D})^2$ ratio, which would be relevant in the above discussed case, is $N_p^{\alpha=-2.26\pm0.48}$ $(\chi^2/DOF = 2.5, DOF = 7)$ respectively $N_p^{\alpha=-3.1\pm0.24}$ $(\chi^2/DOF = 1.2, DOF = 6)$ if the first point is not fitted. The question on the absolute multiplicity of charm in nuclear reactions should be answered by experiment.

### 3.1.2. An estimate of the size of the charm source.

In the following we give an estimate of the volume of the charm source in central Pb + Pb collisions. We first estimate the $J/\Psi/D\overline{D}$ ratio in absolute units, using the following information. We take the cross section for $c\overline{c}$ production in $p + p$ collisions at 200 GeV per nucleon from [20, 21]:

$$\sigma(pp \rightarrow c\overline{c}) = 5\mu b$$

and the cross section for $J/\Psi$ production in the same reactions from [20, 22]:

$$\sigma(pp \rightarrow J/\Psi) = 143 \text{ nb}.$$ 

Therefore the ratio of $J/\Psi$ to total $c\overline{c}$ production in $p + p$ collisions at 200 GeV per nucleon is 

$$\frac{J/\Psi}{c\overline{c}} = 0.0286.$$

However, the expectation value of the $(J/\Psi)/D\overline{D}$ in central Pb + Pb collisions is lower as compared to $p + p$ collisions, due to absorption of the $J/\Psi$. This is indicated by the curve in figure 6, which represents the expectation for the $(J/\Psi)/DY$ ratio as a function of the path $L$ of $J/\Psi$ through nuclear matter‡. The expectation value of the $(J/\Psi)/DY$ ratio for the central Pb + Pb data (very last point, at the highest $L$ value) is smaller by a factor 2.8 as compared to the expectation for the $p + p$ collisions (first point, at the lowest $L$ value).

† Obviously, it would be better to use the $D\overline{D}$ data themselves instead of the $N_p$ parametrization if high enough statistics were available.

‡ The $J/\Psi/DY$ and the $(J/\Psi)/D\overline{D}$ ratios expected from $p + p$ collisions both have the same $L$ dependence.
Figure 6. The open points show the ratio of $J/\Psi$ to $DY$ in $p+A$, $S+U$ and $Pb+Pb$ collisions normalized to 200 A GeV, as a function of the path of $J/\Psi$ through nuclear matter $L$ [18, 19]. The full points show the ratio of $J/\Psi$ to $DD$ in $S+U$ and $Pb+Pb$ collisions at 200 A GeV estimated here. The open stars show the $L$ dependence of the $(J/\Psi)/DY$ and the $(J/\Psi)/DD$ ratio in $p+A$ collisions. All $(J/\Psi)/DD$ ratios shown in this figure are in arbitrary units.

We therefore correct the above found value for $(J/\Psi)/\sigma = 0.0286$, by the factor 2.8 and arrive at an approximate estimate for the ratio $(J/\Psi)/\sigma$ in central $Pb+Pb$ collisions of

$$\frac{J/\Psi}{\sigma_{\text{expected, central Pb + Pb}}} = 0.0102.$$ 

The measured over the expected $(J/\Psi)/DD$ ratio, for central $Pb+Pb$ events from figure 9(a) (second point from the end), is

$$\frac{J/\Psi}{DD_{\text{measured/expected, central Pb + Pb}}} = 0.145.$$ 

We assume that

$$\frac{(J/\Psi)/DD_{\text{measured, central Pb + Pb}}}{(J/\Psi)/DD_{\text{expected, central Pb + Pb}}} \sim \frac{(J/\Psi)/\sigma_{\text{measured, central Pb + Pb}}}{(J/\Psi)/\sigma_{\text{expected, central Pb + Pb}}}.$$ 

Finally we estimate the measured $(J/\Psi)/\sigma$ in absolute units as follows:

$$\frac{J/\Psi}{\sigma_{\text{measured, abs. units, central Pb + Pb}}} \sim \frac{(J/\Psi)/\sigma_{\text{measured, central Pb + Pb}}}{(J/\Psi)/\sigma_{\text{expected, central Pb + Pb}}} \cdot \frac{J/\Psi}{\sigma_{\text{expected, central Pb + Pb}}} = 0.145 \times 0.0102 = 0.00415.$$
We use now this value of \((J/\Psi)/c\bar{c}\) to estimate the volume of the charm source for the most central Pb + Pb collisions at 158 A GeV, with the simple Ansatz:

\[
\frac{J/\Psi}{c\bar{c}} = \frac{V_{J/\Psi}}{V_{charm\ source}} \rightarrow V_{charm\ source} = \frac{c\bar{c}}{J/\Psi} \cdot V_{J/\Psi}
\]

where \(V_{J/\Psi}\) is the volume of the \(J/\Psi\) and \(V_{charm\ source}\) the total volume of the charm source. Assuming that \(V_{J/\Psi}\) is equal to \(\frac{4}{3}\pi0.43 \text{ fm}^3 = 0.268 \text{ fm}^3\) [23] we find

\[
V_{charm\ source} = 64.6 \text{ fm}^3.
\]

The radius of this source (assuming a sphere) is \(R_{charm\ source} = 2.49 \text{ fm}\).

We can further compare the above value of the charm source radius with the expectation for the radius of the source of most hadrons (\(\pi, K\) etc) at the thermal freeze-out. For this we have to take into account the decrease of the radius with transverse mass [15]. We estimate this from the parametrization given in [15]:

\[
R = 10.4 \cdot (1 + m_T \cdot 9.3)^{-1/2} \quad (R \text{ in fm, } m_T \text{ in GeV}).
\]

This parametrization fits well the radii extracted from \(\pi\pi\) correlations measured by NA49, as well as coalescence radii from the \(d/p^2\) ratio measured by NA52 [15], both measured in central Pb + Pb collisions at 158 A GeV.

The expected radius of the charm source at transverse mass equal to the mass of the \(D\) meson and near zero transverse momentum (1.86 GeV) is \(\sim 2.43 \text{ fm}\), which is therefore very similar to the estimation of \(R_{charm\ source} \sim 2.49 \text{ fm}\).

### 3.2. The \(L\) dependence of the \((J/\Psi)/D\bar{D}\) ratio in nuclear collisions

The two distributions of \((J/\Psi)/D\bar{D}\) ratio for \(S + U\) and Pb + Pb collisions in figure 4 are measured at different energies, and therefore they cannot be compared in terms of their absolute yields but only with respect to their shapes. In order to compare their absolute yields, the data from figure 5 of [19] will be used. There the \((J/\Psi)/DY\) ratio in \(p + A, S + U\) and Pb + Pb collisions is shown as a function of \(L\), all normalized to the same energy (\(\sqrt{s} = 19 \text{ GeV}\)) and corrected for the isospin dependence of \(DY\) production. The parameter \(L\) is the length that the \(J/\Psi\) traverses through nuclear matter. In order to convert figure 5 of [19] to the \((J/\Psi)/D\bar{D}\) ratio as a function of the \(L\) parameter, the \((J/\Psi)/DY\) ratio data points have been divided by the \(E\) factor as described in equation (3). The correlation of the \(L\) parameter with \(N_{\ell}\) and \(b\) for Pb + Pb collisions has been estimated using the theoretical calculation of [13].

The \(L\) dependence of the \((J/\Psi)/D\bar{D}\) ratio in arbitrary units in \(p + A, S + U\) and Pb + Pb collisions calculated here is shown in figure 6, together with the \((J/\Psi)/DY\) ratio published in [18, 19]. The full points show the \((J/\Psi)/D\bar{D}\) ratio in \(S + U\) and Pb + Pb collisions extracted as indicated in equation (3). The open squares and circles show the \((J/\Psi)/DY\) ratio in \(S + U\) and Pb + Pb collisions from [18, 19]. The open stars show both the \(L\) dependence of the \((J/\Psi)/D\bar{D}\) as well as the \(L\) dependence of the \((J/\Psi)/DY\) in \(p + A\) collisions which are the same, since the factor \(E\) has the value 1 for the latter.

The \(J/\Psi\) over the \(D\bar{D}\) production investigated as a function of \(L\) (respectively as a function of the volume, since \(V \sim L^3\)), is suppressed as compared to the shape of the exponential fit going through the \((J/\Psi)/D\bar{D}\ p + A\) data, in both the \(S + U\) and Pb + Pb collisions at all \(L\) points (line in figure 6).
The initial energy density of the lowest S + U point has been estimated to be \( \sim 1.1 \) GeV fm\(^{-3}\) [5], which is comparable to the predicted critical energy density for the QGP phase transition of \( \sim 1 \) GeV fm\(^{-3}\). A similar energy density of 1.2 GeV fm\(^{-3}\) has been estimated [5] to be reached in the most peripheral Pb + Pb collisions measured by NA50.

In the following we investigate the initial energy density, rather than only the volume of the particle source \( (V \sim L^3) \), as a critical parameter for the appearance of the QGP phase transition.

4. The \( \epsilon \) dependence of charm and strangeness in nuclear collisions

4.1. Charm

We estimate here the \((J/\Psi)/D\bar{D}\) ratio as a function of the initial energy density \( \epsilon \). For this purpose we use part of the data shown in figure 7 in [5]. There the ratio of \((J/\Psi)/DY)_{measured}\) over the \((J/\Psi)/DY)_{expected}\) is shown. The \('((J/\Psi)/DY)_{expected}'\) is taken to be the exponential fit seen in figure 6, which represents the ‘normal’ \( J/\Psi \) dissociation (i.e. understood without invoking QGP formation). Dividing these data points by \( N_p^{0.45 \pm 0.11} \), and normalizing the distribution of S + U and Pb + Pb points to the p + p and p + A data as in figure 6, we estimate the \((J/\Psi)/D\bar{D}\) ratio over the expectation expressed by the above-mentioned exponential curve, which fits the \((J/\Psi)/D\bar{D}\) data points for p + p, p + d and p + A collisions.

The result of this calculation is shown in figure 7 on a logarithmic scale and in figure 9(a) on a linear scale. It demonstrates a deviation of the \((J/\Psi)/D\bar{D}\) ratio both in S + U and Pb + Pb collisions, from the p + p and p + A expectation curve, occurring above \( \epsilon \sim 1 \) GeV fm\(^{-3}\). The logarithmic scale is shown to reveal small changes in the slope of the \((J/\Psi)/D\bar{D}\) distribution as a function of \( \epsilon \), appearing at \( \epsilon \sim 2.2 \) and 3.2 GeV fm\(^{-3}\).
Figure 8. (a) The kaon ($\sim K^+$) multiplicity per participant nucleon is shown as a function of the initial energy density ($\epsilon$). (b) The kaon ($\sim K^+$) multiplicity over the effective volume of the particle source at chemical freeze-out, in the centre of mass frame, is shown as a function of the initial energy density ($\epsilon$). The above effective volume is smaller than the real source volume but proportional to it.

4.2. Strangeness

Figure 8(a) shows the multiplicity of kaons per event ($K^+$, but also some $K^0$ data scaled to $K^+$, are shown) divided by the number of participating nucleons $N_p$ as a function of the initial energy density (see below for the calculation details). A change in the behaviour of kaons per participant nucleon occurs around $\epsilon \sim 1 \text{ GeV fm}^{-3}$.

As previously mentioned (see footnote on p 16.4) we assume that the number of participant nucleons is proportional to the volume of the source at freeze-out. However the proportionality factor may be different at different $\sqrt{s}$. We therefore estimate in the following the volume at thermal and chemical freeze-out and investigate the kaon yield per volume as a function of $\epsilon$. The results are shown in figure 8(b) for the chemical freeze-out and in figure 9(b) for the thermal freeze-out (see below for the calculation details).

Figure 9 compares the two QGP signatures of $J/\Psi$ suppression and of strangeness enhancement. For this purpose we represent all data points as a function of the estimated energy density. Note that the energy density as critical scale variable has the advantage that, unlike the temperature, it is defined irrespective of whether equilibrium is reached in the collisions studied.

Figure 9(b) shows the multiplicity of kaons per event ($K^+$, but also some $K^0$ data scaled to $K^+$, are shown) divided by the effective volume of the particle source at thermal freeze-out in the centre of mass frame, as a function of the initial energy density. The effective volume represents the part of the real source volume, within which pions are correlated with each other (called ‘homogeneity’ volume in the literature [24]). The effective volume is smaller than but proportional to the real source volume. For a more precise calculation of the freeze-out source
Figure 9. (a) The $(J/\Psi)/D\bar{D}$ (measured/‘expected’) ratio is shown as a function of the initial energy density ($\epsilon$) achieved in the collisions investigated. (b) The kaon ($\sim K^+$) multiplicity over the effective volume ($V = (\pi \cdot 4 \cdot R_{side}^2) \cdot (\sqrt{12} \cdot R_{long})$) of the particle source at thermal freeze-out, in the centre of mass frame, is shown as a function of the initial energy density ($\epsilon$). The above effective volume is smaller than the real source volume but proportional to it.

Note that we compare the kaon data without rescaling for the different energy between Alternating Gradient Synchrotron (AGS) and Super Proton Synchrotron (SPS)†. The reason for this omission is the following: kaons due to their small mass can be produced easily in secondary and tertiary interactions of initial nucleons or of secondary produced particles ($\pi$), in contrast to charm at SPS energy which is mainly produced in the first interaction. Because of this, the rescaling of kaons produced in $A+A$ collisions at different energies using kaon production in $p+p$ collisions is only approximately right, as the secondary and tertiary collisions occur at a smaller effective $\sqrt{s}$. It would be exactly right if kaon production were only the result of first collisions occurring at the nominal $\sqrt{s}$ of the projectiles. Furthermore, figures 8(b) and 9(b) do not compare the expected with the measured kaon yield, but the kaon number density itself, at different $\sqrt{s}$.

4.2.1. Estimation of the source volume at thermal freeze-out. The effective volume $V$ of the particle source has been estimated in the centre of mass frame, assuming a cylindrical shape of the source:

$$V = (\pi \cdot Radius_{cylinder}^2) \cdot Length_{cylinder} = (\pi \cdot 4 \cdot R_{side}^2) \cdot (\sqrt{12} \cdot R_{long})$$

† The total $K^+$ multiplicity in $p+p$ collisions increases by a factor of $\sim 5$, from 11.1 to 158 GeV per nucleon [25].
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where $R_{\text{side}}$ is a measure of the transverse radius and $R_{\text{long}}$ is a measure of the longitudinal radius of the particle source, and the factors 4 and $\sqrt{12}$ arise from the definition of $R_{\text{side}}$, $R_{\text{long}}$ [24]. The $R_{\text{side}}$ and $R_{\text{long}}$ values for central Au + Au collisions at 10.8 A GeV and for central Pb + Pb collisions at 158 A GeV have been taken from [26]. We haven’t used the more elaborated estimation of the homogeneity volume given in [27], because the $R_{\text{ol}}$ component is not given in [26]. For the definitions of the radii $R_{\text{side}}$, $R_{\text{long}}$ and $R_{\text{ol}}$ see [27]. Based on the data of [26] we estimated the effective volume of the source at thermal freeze-out in central Au + Au collisions at 10.8 A GeV ($V \sim 1949$ fm$^3$) and central Pb + Pb collisions at 158 A GeV ($V \sim 6532$ fm$^3$). The effective volume increases by a factor of 3.35 from AGS to SPS energy.

The ratio $K/N_p$ is expected to be proportional to the number density of kaons $\sim K/V$, (V = volume), assuming $V \sim N_p$ (for justification of this assumption see † on p 1.4, [26] and [30]). Based on this expectation, we estimated here the $K/V$ ratios from the $K/N_p$ ratios, by normalizing the $K/N_p$ ratios to the $K/V$ value of the most central Au + Au events of E866, respectively Pb + Pb events of NA49, for which the value of the volume has been estimated above.

The kaon data from Au+Au collisions at 11.1 A GeV (E866 and E802 experiments) [31] and from Pb + Pb collisions at 158 A GeV (NA49 experiment) [32] are kaon multiplicities extrapolated to full acceptance. Therefore NA49 and E866 data are absolutely normalized. We estimated $K/N_p$ from the NA49 experiment using the kaon multiplicities from [32] and the number of wounded nucleons from [33] as available†, otherwise we used the $N_p$ estimated from the experimental baryon distribution [32].

The data from NA52 [15, 16] and WA97 [34] have been measured in a small phase space acceptance and have been scaled here arbitrarily, in order to match the NA49 data in figure 9. This scaling is justified since all NA52, NA49 and WA97 measurements are kaons produced in Pb + Pb collisions at 158 A GeV, and ‘extrapolates’ the NA52 and WA97 data to the NA49 full acceptance multiplicities, allowing for comparison of the shapes of the distributions. It is assumed that the $N_p$ and $\epsilon$ dependence of kaons does not change significantly with the phase space acceptance.

4.2.2. Estimation of the source volume at chemical freeze-out. Based on the temperature at thermal and chemical freeze-out which has been estimated from measurements using thermal models [28], and the above-estimated volumes at thermal freeze-out, we can further estimate the volume at chemical freeze-out. For this we assume that the relation $V \sim T^{-3}$, which holds in the universe for massless particles in thermal equilibrium and for adiabatic expansion [29], holds approximately for heavy ion collisions at AGS and SPS energy. Then from the temperature values at thermal and chemical freeze-out given in [28] averaged over all models, we find that the ratio $V_{\text{chemical}}/V_{\text{thermal}}$ (AGS Si + Au 14.6 A GeV) = 0.45 and $V_{\text{chemical}}/V_{\text{thermal}}$ (SPS Pb + Pb 158 A GeV) = 0.28. Using the volume at chemical freeze-out as estimated above would stretch apart the $K/V$ ratio in figure 9(b) between SPS and AGS, by a factor $\sim 1.6$. We haven’t used these values in figure 9, because the above calculation is model dependent, e.g. the assumption of massless particles is not met, while the assumption of thermal equilibrium may not be true.

Figure 8(b) shows the multiplicity of kaons per event divided by the effective volume of the source at chemical freeze-out, as a function of the initial energy density.

† We take $N_p$ equal to the number of wounded nucleons for NA49, because it is used in all other experiments presented here, and allows for a straightforward geometrical interpretation of $N_p$.

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4.2.3. Estimation of the initial energy density. In order to calculate the energy density we have performed the following steps. The energy density for all colliding systems has been estimated using the Bjorken formula [35] and data given in [31, 36, 37]. The transverse radius of the overlapping region of the colliding nuclei is found as: 
\[ R_{trans} = 1.13 \cdot \left( \frac{N_p}{2} \right)^{1/3} \], where \( N_p \) is the total number of participant nucleons. The formation time was taken to be 1 fm/c [35].

The E866 experiment did not measure \( \epsilon_T \), but instead the forward going energy \( E_{forward} \) of the nucleons which did not interact (spectators). Therefore in order to estimate the \( \epsilon \) for E866 we did the following. We assumed that the transverse energy at midrapidity is proportional to the total energy of the nucleons participating in the collision:
\[
(d\epsilon_T/d\eta)_{ycm} \propto E_{tot,part}
\]
and therefore to the number of participant nucleons. In this way, we estimate the \( (d\epsilon_T/d\eta)_{ycm} \) in arbitrary units, from the number of participants and the Bjorken estimate.

In order to normalize properly to the absolute units of energy density, we use one value of \( \epsilon \) from the literature, namely the energy density in the most central Au+Au events at this energy of 1.3 GeV fm\(^{-3}\), given in [36].

We then normalized the results in such a way that the maximum energy density of our estimate matches the absolute value of the maximal achieved energy density in the most central Au+Au events of 1.3 GeV fm\(^{-3}\).

We estimate the \( N_p \) dependence of the initial energy density in Si+Au collisions at 14.6 GeV per nucleon in the same way [51]. We normalized the results in such a way that the maximum energy density of our estimate matches the absolute value of the maximal achieved energy density in the most central Si+Au collisions, which is estimated to be \( \sim 0.9 \) GeV fm\(^{-3}\) [50]. See below for an estimate of the systematic error associated with this approximation.

NA52 measures \( E_T \) near midrapidity (\( y \sim 3.3 \)). These values were used to estimate the energy density as a function of \( N_p \). However NA52 did not correct the measured \( E_T \) value e.g. for the phase space acceptance. For this reason NA52 does not give an estimate of the fully corrected \( d\epsilon_T/d\eta \) near midrapidity. The NA52 \( E_T \) results have therefore been normalized to match the maximum energy density reached in Pb + Pb collisions of \( \epsilon_{max} = 3.2 \) GeV fm\(^{-3}\), extracted by NA49 in [37], in events with the same centrality. Parametrizing the dependence of the energy density on the number of participants found from the NA52 data as described above, we estimated the energy density corresponding to the \( N_p \) values of the WA97 and the NA49 kaon measurements, given in [32, 34]. Data from S + S collisions at 200 GeV per nucleon and p + p collisions at 158 GeV per nucleon [51] taken from [32] and [37, 38] are also shown.

To estimate the systematic error on the energy density found with the above methods, we calculated the energy density in Pb + Pb collisions at 158 A GeV, using the VENUS 4.12 [39] event generator. We estimated with VENUS the \( (d\epsilon_T/d\eta)_{ycm} \) at \( y_{cm} = \text{midrapidity} \) and the number of participant nucleons and used them to find the energy density from the Bjorken formula [35]. The deviation of the energy density calculated with VENUS \( (d\epsilon_T/d\eta)_{ycm} \) from the energy density found using the NA52 transverse energy measurements is \( \leq 30\% \) of the latter. The deviation of the energy density calculated with VENUS \( d\epsilon_T/d\eta \) from the energy density found using the total energy of the participant nucleons and of the newly produced particles (which is similar to the method used to estimate the energy density for the AGS data), over the latter energy density, is at the same level.

In this context, it appears important for a more precise comparison of data as a function of \( \epsilon \) that experiments publish together with the number of participants also the \( d\epsilon_T/d\eta \) at midrapidity.
for each centrality region, for both nucleus + nucleus and for p + p collisions, estimated by models or measured if available (e.g. in NA49).

4.3. Comparison of charm and strangeness

Figure 9(b) suggests that kaons below $\epsilon \sim 1$ GeV fm$^{-3}$ did not reach equilibrium, while this seems to be the case above. Indeed kaons produced in Au + Au collisions at 11.1 A GeV [31] and in very peripheral Pb + Pb collisions at 158 A GeV [15, 16, 40, 41] increase faster than linear with $N_p$, indicating non-thermal kaon production, while they increase nearly proportional to $N_p$ above $\epsilon \sim 1$ GeV fm$^{-3}$ [15, 16, 34, 41]. The connection of strangeness equilibrium and the QGP phase transition has been discussed e.g. in [42]. There it is shown that strangeness in heavy ion collisions is expected to reach equilibrium values if the system runs through a QGP phase, while this is less probable in a purely hadronic system.

Figure 9 demonstrates that both the $J/\Psi$ and kaon production exhibit a dramatic change above the energy density of $\sim 1$ GeV fm$^{-3}$. While the equilibration of strange particles as suggested by their $\sim N_p^1$ dependence above 1 GeV fm$^{-3}$ could in principle also be due to equilibrium reached in a hadronic environment, the combined appearance of this effect and of the $(J/\Psi)/D\bar{D}$ suppression at the same energy density value is a striking result, indicating a change of phase above $\epsilon_c = 1$ GeV fm$^{-3}$.

The absolute value of the energy density $\epsilon$ and therefore of the $N_p$ values at which these changes could be observed are not exactly given by the models. The critical energy densities for the dissociation of the states $\Psi'$, $\chi_c$ and $J/\Psi$ could even be so near to each other that no clear multistep behaviour is seen in $(J/\Psi)/D\bar{D}$. A possible reason for this to happen is that the binding energies of charmonia change once the potential becomes deconfined and come much closer to each other and to the ‘ionization’ energy. This is also in agreement with the expectations of [54].

Figure 9 suggests that the breaks in the $(J/\Psi)/D\bar{D}$ ratio at $\epsilon \sim 2.2$ and 3.2 GeV fm$^{-3}$, are less dramatic than the change above $\epsilon \sim 1$ GeV fm$^{-3}$. Therefore, all bound $c\bar{c}$ states could be dissociated at similar energy densities, which lie near 1 GeV fm$^{-3}$.

Alternatively, the $\psi'$ and the $\chi_c$ could dissociate above $\epsilon \sim 1$ GeV fm$^{-3}$ and the dissociation of the $J/\Psi$ could start at $\epsilon = 2.2$ GeV fm$^{-3}$, if we interpret the change in the $(J/\Psi)/D\bar{D}$ ratio, below and above $\epsilon = 2.2$ GeV fm$^{-3}$, as a step behaviour. In this context, the steep drop of the $(J/\Psi)/D\bar{D}$ ratio in the bin(s) of largest $N_p$ (figures 5, 7 and 9) cannot be interpreted in a natural way. The steps of $(J/\Psi)/D\bar{D}$ remain to be established through a direct measurement of $J/\Psi$ and $D\bar{D}$ absolute yields as a function of $(E_T, N_p, \epsilon)$.

In the picture discussed above, three QGP signatures appear in nuclear collisions at energy density larger than $\sim 1$ GeV fm$^{-3}$:

(a) $J/\Psi$ suppression (figure 9(a))—which could be due to bound $c\bar{c}$ states dissociation,
(b) enhancement of strangeness density (figure 9(b)),

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(c) the invariant mass $m(e^+e^-)$ excess at $m$ below the $\rho$ mass [44], possibly due to a $\rho$ change [45] and/or to increased production of the lowest mass glueball state in QGP [46]. This coincidence of QGP signatures, suggests a change of phase at $\epsilon \sim 1$ GeV fm$^{-3}$ as expected [1].

From the above discussion, it follows that a direct measurement of open charm production in nuclear collisions appears essential for the physics of the QGP phase transition. Furthermore, if enhanced over expectations, open charm in nuclear collisions defies theoretical understanding.

5. Possibilities for future measurements

A measurement of open and closed charm production in $^{16}$O+$^{16}$O collisions as a function of energy below the SPS top energy of $\sqrt{s} = 17$ GeV, searching for the disappearance of the observed $J/\Psi$ suppression in central $^{16}$O+$^{16}$O collisions at a certain $\sqrt{s}$, could prove clearly the QGP phase transition. Using the same nuclei at different $\sqrt{s}$ and looking only at central collisions, differences due to different nuclear profiles drop out. No currently existing experiment at SPS is however able to perform this measurement without major upgrades, although one future experiment (NA60) could significantly improve the identification of open charm production through a better determination of the decay vertex [47]. The study could also be performed at the Relativistic Heavy Ion Collider (RHIC) using lower energy and/or large and small nuclei, and in fixed target experiments at RHIC favoured because of higher luminosity as compared to the collider mode, which is important for a low-energy scan.

It would also be important (and easier than the above) to measure the $J/\Psi$, $D\bar{D}$ and $DY$ absolute yields per collision, below $\epsilon = 1$ GeV fm$^{-3}$, by using the most peripheral (not yet investigated) $^{16}$O+$^{16}$O collisions or collisions of lighter nuclei at the highest beam energy at SPS ($\sqrt{s} = 17, 19$ GeV).

Another piece of information important for the understanding of charm production in nuclear collisions would be the direct comparison of the $(J/\Psi)/DY$ and $(J/\Psi)/D\bar{D}$ ratios in nuclear collisions at $\sqrt{s} < 19$ GeV and in $p + \bar{p}$ collisions at the Tevatron. Tevatron reaches an energy density similar to or larger than the one estimated in very central $S+S$ collisions at 200 A GeV [48]. Therefore it would supply a comparison for these points and a continuation of the absorption line fitted through the $p + p$ and $p + A$ data measured by NA50 (figure 6), or otherwise. Differences due to the change of dominant production mechanisms of charm in $p + \bar{p}$ collisions as compared to $A + B$ and $p + p$ can be accounted for theoretically. A high $E_T$ cut could additionally help in sorting out ‘central’ $p + \bar{p}$ collisions. This comparison should be done possibly in the very same dimuon mass region for all processes (also $DY$), e.g. using Monte Carlo’s tuned to $p + \bar{p}$ Tevatron data.

This comparison would answer the question whether the energy density is indeed the only critical variable for the appearance of a thermalized QGP state with three effective flavours $u, d, s$, or whether there is also a critical volume (e.g. as measured by the $L$ variable: $V \sim L^3$). Furthermore, at present the comparison of nuclear collisions to $p + p$ and $p + A$ data is done at the same energy and not at the same energy density. This issue is important, since if for example the energy density is the only critical scale variable, the QGP should be formed also in elementary collisions like $p + \bar{p}$ at a higher beam energy and the same energy density.

Further it is important to search for thresholds in the production of many particles, e.g. $\Omega$, which was found to be enhanced by a factor 15 above $p + A$ data in $^{16}$O+$^{16}$O collisions at
158 A GeV [49] in the energy density region corresponding to the green stars in figure 9(b). Similarly interesting would be a measurement of the invariant mass of $e^+e^-$ in low energy densities.

6. Conclusions

In this paper, consequences resulting from the viable possibility that the dimuon invariant mass $(m(\mu^+\mu^-))$ enhancement, measured by the NA50 experiment in the IMR between the $\phi$ and the $J/\Psi$ mass, in S + U and Pb + Pb collisions at $\sqrt{s} = 19$, 17 GeV, reflects a $D\overline{D}$ enhancement over expectations are worked out.

The dependence of the $J/\Psi$ and the $D\overline{D}$ yields per collision in Pb + Pb collisions on the mean number of participants has been estimated. This dependence reveals the non-thermal features of charm production at this energy. The $\sim N_p^{0.7}$ dependence of the $J/\Psi$ yield (figure 3) suggests stronger dissociation of $J/\Psi$ with higher centrality. The dissociation is stronger than the absorption seen in any other hadron, e.g. $p$ in Pb + Pb collisions. The $N_p$ dependence of the $D\overline{D}$ yield of $N_p^{1.7}$ (figure 2) also indicates non-thermal open charm production at this energy, showing up in an excess rather than reduction as compared to the thermal expectation.

If the dimuon excess observed by NA50 is due to open charm, and even otherwise, it is appropriate to search for an anomalous suppression of $J/\Psi$ as compared to the total open charm production, rather than to the $DY$ process. We therefore investigated here the $(J/\Psi)/D\overline{D}$ ratio in Pb + Pb collisions and we found that it decreases approximately as $\sim N_p^{-1}$ (figures 4 and 5).

Note that if the $J/\Psi$ were completely dissociated in quark gluon matter and were later dominantly formed through $c\bar{c}$ quark coalescence, we would expect that $(J/\Psi)/D\overline{D}$ is $\sim N_p^{-1}$, as actually seen†. In that case, based on coalescence arguments, the $(J/\Psi)/D\overline{D}$ ratio could be used to estimate the volume of the charm source, which may reflect the size of the quark gluon plasma. This is probable under the assumption that the final measured $J/\Psi$ is dominated by the $J/\Psi$ originating from $c\bar{c}$ pairs which travel through the plasma volume, an assumption which may hold only for large plasma volumes, i.e. for the most central collisions.

We give an estimate of the volume of the charm source for the most central Pb + Pb collisions assuming a coalescence Ansatz. The volume of the charm source is estimated to be $V_{charm\ source} \sim 64.6\ fm^3$, and assuming a sphere the radius $R_{charm\ source}$ is 2.49 fm. The latter value is similar to the expectation of $\sim 2.43\ fm$ for the charm source radius at the thermal freeze-out, if the $m_T$ dependence of the radius is taken into account.

A further consequence of a possible open charm enhancement is that the $J/\Psi$ over the $D\overline{D}$ ratio appears to be suppressed already in S + U collisions as compared to p+A collisions, unlike the $(J/\Psi)/DY$ ratio (figure 6). The $\psi'/D\overline{D}$ ratio would also be additionally suppressed as compared to the $\psi'/DY$ in both S + U and Pb + Pb collisions. These phenomena could be interpreted as the onset of dissociation of bound charm states above the energy density $\epsilon \sim 1\ GeV\ fm^{-3}$.

We have estimated and compared the dependence of the $(J/\Psi)/D\overline{D}$ ratio and of the kaon multiplicity per volume in several collisions and $\sqrt{s}$ as a function of the initial energy density. We find that both the kaon number density and the ratio $(J/\Psi)/D\overline{D}$ exhibit dramatic changes

† We assumed that $N_p$ is proportional to the volume of the $c\bar{c}$ source and the charm quark multiplicity is approximately one, in the events in which charm particles are produced.
at the energy density of $1 \text{ GeV } \text{fm}^{-3}$, as demonstrated in figure 9. This is the main result of this paper.

It follows that three major QGP signatures ($s\bar{s}$ enhancement, $\rho$ changes and $J/\Psi$ suppression) all appear above the energy density of $\sim 1 \text{ GeV } \text{fm}^{-3}$, which is the critical energy density for the QGP phase transition according to lattice QCD.

This discussion underlines the importance of a direct measurement of open charm production in nuclear collisions, and of other experimental investigations proposed in section 5, for the understanding of ultrarelativistic nuclear reactions and the dynamics of the QGP phase transition.

Acknowledgments

I would like to thank Professors P Minkowski, K Pretzl, U Heinz and J Rafelski for stimulating discussions, and Doctors C Cicalo, O Drapier, C Gerschel, E Scomparin, P Seyboth, F Sikler, P Sonderegger, M Tannenbaum, U Wiedemann, and especially J Y Ollitrault for clarifying discussions on their data and/or for communicating their results to me. We thank the Swiss National Science Foundation for their support.

Note added in proof. In the time since the preprint of the present paper has been completed (SLAC preprint server hep-ph/0004138), a second possible interpretation of figure 7(b) was realized in [51] and followed in [52]. A discussion of strangeness production as QGP signature can be found in [53].

The dependence of charm in nucleus + nucleus collisions on the number of participant nucleons, the production of charm through coalescence mechanisms and other features of charm production in ultrarelativistic nucleus + nucleus collisions are discussed in many recent papers, for example [55]–[60].

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