Dissociation rates of J/ψ's with comoving mesons — thermal vs. nonequilibrium scenario

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Abstract

We study J/ψ dissociation processes in hadronic environments. The validity of a thermal meson gas ansatz is tested by confronting it with an alternative, nonequilibrium scenario. Heavy ion collisions are simulated in the framework of the microscopic transport model UrQMD, taking into account the production of charmonium states through hard parton-parton interactions and subsequent rescattering with hadrons. The thermal gas and microscopic transport scenarios are shown to be very dissimilar. Estimates of J/ψ survival probabilities based on thermal models of comover interactions in heavy ion collisions are therefore not reliable.

I. INTRODUCTION

The suppression of heavy quarkonia has long been proposed as a unique signature for the transient creation of a quark-gluon plasma in heavy ion collisions [1]. Preliminary reports on J/ψ and ψ' production cross sections in Pb+Pb reactions at SPS energies [2,3] in fact seem to indicate an anomalous charmonium suppression compared to pA and lighter AB interactions. It has been demonstrated that the framework of Glauber theory with some comover interactions [4,5] fails to describe all the data while assuming the onset of deconfinement at a certain interaction density leads to a better agreement with experiment. Starting from a similar ansatz, however, it was claimed that hadronic mechanisms alone could account for the observed suppression probabilities [6]. While in these studies universal comover absorption cross sections are parameters, there have been attempts to predict the actual comover cross sections for certain reaction channels and to estimate the resulting J/ψ survival probabilities [7,8]. From these studies one learns that the dissociation cross sections may depend strongly on the scattering energy as well as the meson species interacting with the charmonium state. Unfortunately only *thermal* absorption rates have been calculated on the basis of the predicted cross sections.

It is the goal of the present work to investigate, on the basis of a hadronic transport model, if the assumption of a thermal hadronic environment can be justified. This is analogous to studies of the nonequilibrium processes contributing to strangeness production [9] versus thermal model calculations [10]. Scattering rates and collision energies in the microscopic simulation are compared to the ideal hadron gas scenario. We also address the question of whether only the consideration of light mesons (π and ρ) suffices to account for the major part of all possible comover absorption processes.

II. THE MODEL

The production and subsequent absorption of charmonium states in relativistic heavy ion collisions are the result of an intricate interplay between hard and soft processes. Since the interactions are nonperturbative the calculation of their dynamics from first principles is prohibitive. Thus phenomenological models which account for both hadronic and partonic aspects are needed. We simulate charmonium production and absorption microscopically.

The charmonium states are produced exclusively in hard parton-parton interactions for which a simple Glauber-type picture of nucleus-nucleus reactions applies. This is supported by the fact that the experimentally measured dimuon continuum in the corresponding mass range can be well described by perturbative calculations of the Drell-Yan process[1]. In particular, a linear scaling of the Drell-Yan cross section with atomic mass A is observed in pA interactions [11]. Initial state interactions are assumed to be negligible. We apply perturbative QCD to nucleus-nucleus collisions without nuclear modifications of the parton distribution functions. (See Refs. [12,13] for the effects of such modifications.)

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[1]The production of $c\bar{c}$ pairs which eventually form the quarkonium state is, however, dominated by gluon-gluon scatterings.

Within perturbative QCD, the hard production process is completely decoupled from other possible interactions such as the creation and reinteraction of soft quarks and gluons and their rearrangement into color singlet states. In particular, the hard production process is not linked to soft hadron production, baryon stopping and hadronic rescattering.

The dissociation of charmonium states is assumed to be due to hadronic interactions. The space-time evolution of mesons and baryons, governed by soft physics, can be treated by transport theory on the hadronic level. The kinetics of each interaction is determined by appropriate hadronic scattering cross sections. In particular, charmonium dissociation can be studied by introducing cross sections for their absorption through interactions with baryons and mesons. In this work, we consider dissociation by comoving mesons only[2].

Technically, we generate a space-time distribution of charmonium production points for any impact parameter b by microscopically simulating Glauber-type nucleus-nucleus collisions assuming that the nuclei, *i.e.* sets of appropriately initialized nucleons, pass through each other on straight line trajectories without energy loss. At the space-time point of each nucleon-nucleon encounter, a charmonium state has a fixed production cross section.

To calculate the rescattering of charmonium states we generate a full hadronic cascade simulation with the Ultrarelativistic Quantum Molecular Dynamics, UrQMD, model [15] which takes stopping and particle production into account. The charmonia are inserted into the evolving hadronic environment at the appropriate space-time points according to the Glauber simulation of the nucleus-nucleus collision. The momenta of the charmonium states are assigned from the parametrization [16]:

$$E\frac{d\sigma}{dMdp^3} \sim (1 - x_F)^{3.55} \exp(-p_T \, 2.08 \, \mathrm{GeV}^{-1}) \ .$$

In principle, the total energy of the produced $c\bar{c}$ state has to be subtracted from the overall reaction. However, it is difficult to do so consistently since simulations of the charmonium production and rescattering processes are formulated within different conceptual frameworks. Therefore we allow for the small violation of energy-momentum conservation imposed by this procedure. In Pb+Pb collisions at 160 GeV/nucleon, $\sqrt{s} = A\sqrt{s}_{NN} \approx 3600$ GeV and with a typical charmonium energy of $E_{c\bar{c}} \approx 4$ GeV, $E_{c\bar{c}}/\sqrt{s} \approx 0.1\%$.

In the simulations we have used fixed dissociation cross sections, $\sigma_{J/\psi M} = 2\sigma^{\mathrm{tot}}_{J/\psi N}/3$ according to the additive quark model, for any meson species M. The value of the total $J/\psi N$ absorption cross section, taken from Ref. [17], is $\sigma^{\mathrm{tot}}_{J/\psi N} = 3.62$ mb. Since we do not consider elastic interactions, any collision above the kinematic threshold leads to the dissociation of the J/ψ so that we use the two terms synonymously. For this study, we have neglected the energy dependence of the dissociation cross sections which may be quite strong close to threshold. Also, we have not considered a possible (eigen)time dependence of the actual dissociation cross sections which may evolve from a small initial cross section at the production point to its asymptotic value (see [17]). We want to focus on the question

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[2]The calculation of *nuclear* absorption within our model framework shows interesting deviations from the standard Glauber-like prescription. Due to nuclear stopping in the UrQMD simulation, incident nucleons are slightly retarded which leads to an increase of the effective path length of J/ψ's in nuclear matter. This will be discussed in [14].

of whether or not the J/ψ-comover reactions in a heavy ion collision can be reasonably approximated by a thermal hadron gas interacting with the J/ψ. The qualitative answer to this question is rather insensitive to the actual parametrization of the cross section.

Note that we do include the formation time of the comovers (on average, $\tau_F \approx 1$ fm/c). Particles produced in a string fragmentation process are not allowed to interact with each other or with a J/ψ within their formation time[3].

We assume $E_{th} = 2m_D = 3730$ MeV is the kinematic threshold for J/ψ-meson dissociation processes. In the thermal model, a fixed ρ mass of 770 MeV is used, therefore the minimum $J/\psi\,\rho$ collision energy is $m_{J/\psi} + m_\rho = 3870$ MeV $> E_{th}$. In the UrQMD model however, the finite width of the ρ meson, $\Gamma = 151$ MeV, is taken into account. The ρ meson mass distribution is selected from the Breit-Wigner resonance formula. Therefore, in the microscopic model some of the $J/\psi\,\rho$ interactions are below threshold while no correpsonding threshold exists for the thermal model.

The results in the equilibrium scenario are easily obtained. Consider an ideal gas of J/ψ's and one meson species M (π or ρ). We calculate the rate R of dissociation processes for an arbitrarily chosen J/ψ in the rest frame of the J/ψ:

$$R = g_M \int \mathrm{d}^3 p_M f(p_M) j(p_M) \sigma_{J/\psi M} \, ,$$

where the spin and isospin degeneracy, g_M, is 3 for π's and 9 for ρ's. The mesons are distributed according to the Bose-Einstein distribution,

$$f(p_M) = \frac{1}{(2\pi)^3}(\exp(E_M/T) - 1)^{-1}$$

where $E_M = \sqrt{m_M^2 + p_M^2}$ is the total energy, p_M is the momentum of mesons in the rest frame of the J/ψ and $j(p_M) = p_M/E_M$ is the meson flux. The dissociation cross section has a fixed value, $\sigma_{J/\psi M} = 2.41$ mb. The above integral can be rewritten in terms of the center of mass collision energy, E_{cm},

$$R = \int \mathrm{d}E_{cm} \frac{g_M}{2\pi^2} p_M^2 \frac{E_{cm}}{m_{J/\psi}}(\exp(E_M/T) - 1)^{-1}\sigma_{J/\psi M} = \int \mathrm{d}E_{cm} r(E_{cm}, T) \, ,$$

where $r(E_{cm}, T)$ is the (unnormalized) collision spectrum for a given temperature T. Consequently, the average collision energy is given by

$$< E_{cm}(T) > = \frac{1}{R} \int \mathrm{d}E_{cm} E_{cm}\, r(E_{cm}, T) \, .$$

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[3]It is conceivable that a nonvanishing parton content of the yet-to-be-formed hadrons leads to a finite dissociation cross section before τ_F. Dimuon production has been shown to be enhanced by partonic interactions of preformed mesons in a similar context [18].

III. RESULTS

We first study very central Pb+Pb reactions ($b = 0$) at $E_\mathrm{lab} = 160$ GeV with the microscopic nonequilibrium model. Figure 1 shows the J/ψ dissociation rates as functions of time. Comover dissociation processes occur most frequently about 1 fm/c after the nuclear reaction begins. At that time, the total dissociation rate reaches a value of more than 0.1 c/fm. However, it is dropping rapidly, an order of magnitude within the first 10 fm/c of the reaction. The individual $J/\psi\,\pi$ and $J/\psi\,\rho$ interaction rates are plotted along with the total comover absorption rates. It is clear that π's and ρ's alone are not responsible for J/ψ dissociation by comovers due to the large number of transient meson renonances present in the microscopic model. The string fragmentation scheme used in UrQMD [15] determines the relative abundances of these states. This choice is far from unique since the model can be compared to data only for the hadrons observable in the final state. In UrQMD, all states of eight different meson multiplets ($J^{PC} = 0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 1^{++}, 2^{++}$ plus two excited 1^{--} multiplets) may be populated in a string fragmentation process. The probability to form a meson from one of these multiplets is chosen to be proportional to the spin degeneracy and inversely proportional to the average mass of the multiplet.

Table I shows the relative importance of the mesons which contribute most to J/ψ dissociation. Scatterings of the J/ψ's with π's and ρ's are indeed the dominant dissociation processes. However, together they are responsible for only 37% of the total comover absorption. Twenty channels are left out of Table I, each of them contributing about 1% or less. However, they account for more than 15% of the total absorption.

It is important to remember that the same dissociation cross section is used for all J/ψ-meson interactions, most probably a crude approximation. For a better estimate of the J/ψ dissociation rates, one would need to calculate the cross sections in all possible channels. Of course, even if this whole set of cross sections was completely determined it is uncertain that the hadronic transport model describes all the details of rescattering correctly. In any case, it is questionable if a model of J/ψ-comover absorption which includes only the light mesons can be used for reasonable quantitative predictions.

Figure 2 shows the average J/ψ-meson collision energies in central Pb(160 GeV)+Pb reactions as functions of time for $J/\psi\,\pi$ and $J/\psi\,\rho$ interactions. As one expects, the average collision energies are highest in the early stage of the reaction where the rates are also at their maximum.

We now compare the microscopic nonequilibrium scenario with a thermal meson gas. Figure 3 shows the rates and the averaged thermal dissociation energies in an ideal gas of π's and ρ's as functions of temperature. The rates in the later stage of the reaction, shown in Fig. 1, when $t > 2$ fm/c, correspond to a temperature of $T = 140 \pm 20$ MeV in the equilibrated system. The temperatures one would deduce from the collision energies of Fig. 2 roughly agree with these values. Thus, the concept of a thermal hadron gas may be approximately valid in the later stage of a nuclear reaction. The survival probability of charmonium states, however, is to a large extent determined by the early reaction dynamics, $t \approx 1$ fm/c. Here, the rates roughly correspond to a thermal π and ρ gas with $T \approx 220$ MeV. In contrast, the average collision energies at this time are much higher than one could ever expect in a thermal hadron gas. As can be read off from Fig. 2 and Fig. 3, the collision energies would correspond to temperatures greater than 800 MeV. We can therefore conclude

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that a major part of the J/ψ dissociation processes cannot reasonably be approximated by a thermal scenario. Much higher collision energies are observed than can be expected in a thermal system indicating that the underlying π and ρ momentum distributions are out of equilibrium and the probability of high relative velocities is enhanced.

The nonequilibrium character of J/ψ rescattering is also reflected by the time integrated collision energy spectrum. The prediction of the nonequilibrium model is shown in Fig. 4, together with the collision spectra of a thermal gas at $T = 200$ and 300 MeV. Obviously, in the microscopic simulation collisions with high center of mass energy are much more probable than in a thermal hadron gas at reasonable temperatures.

As mentioned above, we have used fixed dissociation cross sections, $\sigma_{J/\psi M} = 2.41$ mb, in this study. However, absorption by light mesons has recently been calculated in the framework of a meson exchange model [8] where the cross sections are strongly energy dependent. Thus, at a fixed comover density, the assumption of thermal velocity distributions would considerably underestimate the absorption rates. At $E_{cm} = 5$ GeV, the energy dependent cross sections of Ref. [8] are $\sigma_{J/\psi\,\pi} = 2.3$ mb and $\sigma_{J/\psi\,\rho} = 1.6$ mb. As a result, using these cross sections [8] in the nonequilibrium UrQMD simulation leads to slightly lower maximum absorption rates at $t \approx 1$ fm/c than do the fixed cross sections. In the later stages of the reaction, the energy dependent absorption rates are more strongly suppressed since most of the collisions occur closer to threshold, as shown in Fig. 2. Typically, for $t > 3$ fm/c, the collision energies are $E_{cm} \approx 4$ GeV which implies $\sigma_{J/\psi\,\pi} \approx \sigma_{J/\psi\,\rho} \approx 0.3$ mb, considerably smaller than the cross sections when $t \approx 1$ fm/c.

Certainly, different parametrizations of the energy and eigentime dependencies for all possible comover dissociation cross sections would yield different integrated survival probilities. In this work we explore only the influence of the comover dynamics on the absorption rates. Comparison to experimental data with a refined prescription of charmonium production and absorption in the microscopic framework will be presented elsewhere [14].

IV. CONCLUSION

We have presented a microscopic model of J/ψ production and absorption in relativistic heavy ion collisions. Averaged dissociation rates and collision energies have been analyzed as functions of time. In this model, scattering of J/ψ's with π's and ρ's account for only about 37% of the total absorption by comovers. The J/ψ absorption by comovers is strongly time dependent with dissociation rates peaking at $t \approx 1$ fm/c. The collision energies at that time are much higher than can be expected in a thermal scenario.

An equilibrated gas of light mesons seems to be too simple an approximation to the actual hadronic environment in which J/ψ's interact. In order to reliably calculate the survival probabilities of charmonium states in heavy ion collisions, one must employ more realistic simulations of the meson dynamics. Many different reaction channels contribute to the total absorption. The corresponding dissociation cross sections and their energy dependencies need to be explored further with the help of phenomenological models.

TABLE I. Contributions of different meson species to the total J/ψ comover absorption according to the UrQMD simulation. Only the most dominant channels are shown.

Species	Percentage of comover absorption
π	18.5 ± 0.3
ρ	18.4 ± 0.3
K	10.7 ± 0.3
$K^*(892)$	7.4 ± 0.2
η	6.4 ± 0.2
ω	6.4 ± 0.2
$a_2(1320)$	4.8 ± 0.2
$a_1(1260)$	4.3 ± 0.2
$b_1(1235)$	3.8 ± 0.2
$a_0(980)$	3.0 ± 0.1
Sum:	83.7 ± 0.7
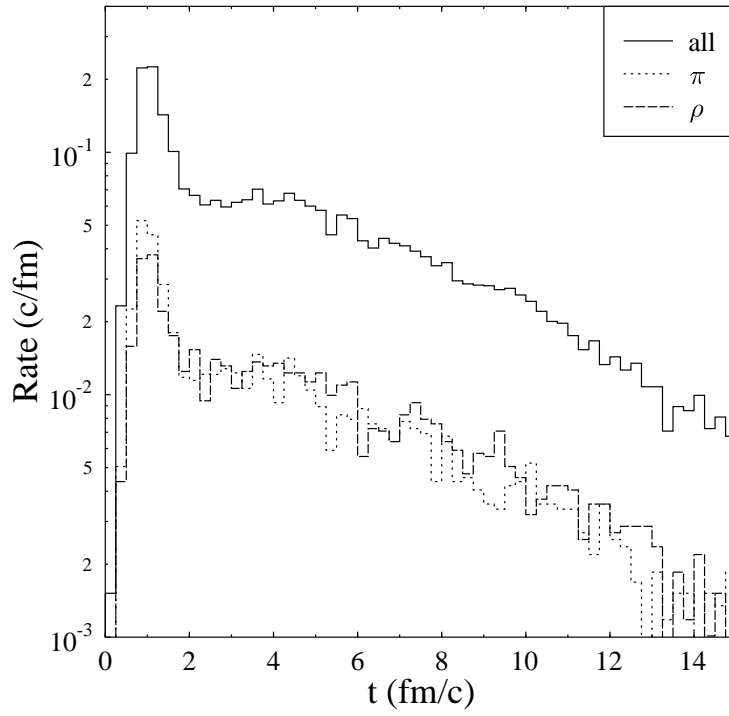
FIG. 1. J/ψ dissociation rates in central Pb(160 GeV)+Pb reactions according to the UrQMD calculation as functions of time. Shown are the rates for all J/ψ-meson interactions (full line), those for $J/\psi\,\pi$ (dotted line) and those for $J/\psi\,\rho$ (dashed line). A fixed dissociation cross section of $\sigma_{J/\psi M} = 2.41$ mb is used for all mesons.
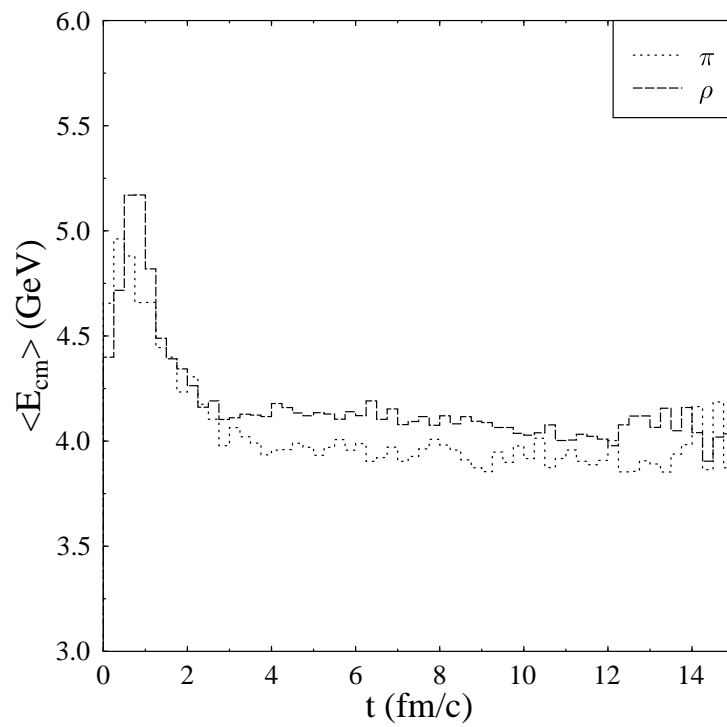
FIG. 2. Average J/ψ-meson collision energies in central Pb(160 GeV)+Pb reactions as a function of time for $J/\psi\,\pi$ (dotted line) and $J/\psi\,\rho$ interactions (dashed line). A fixed dissociation cross section of $\sigma_{J/\psi M} = 2.41$ mb is used.
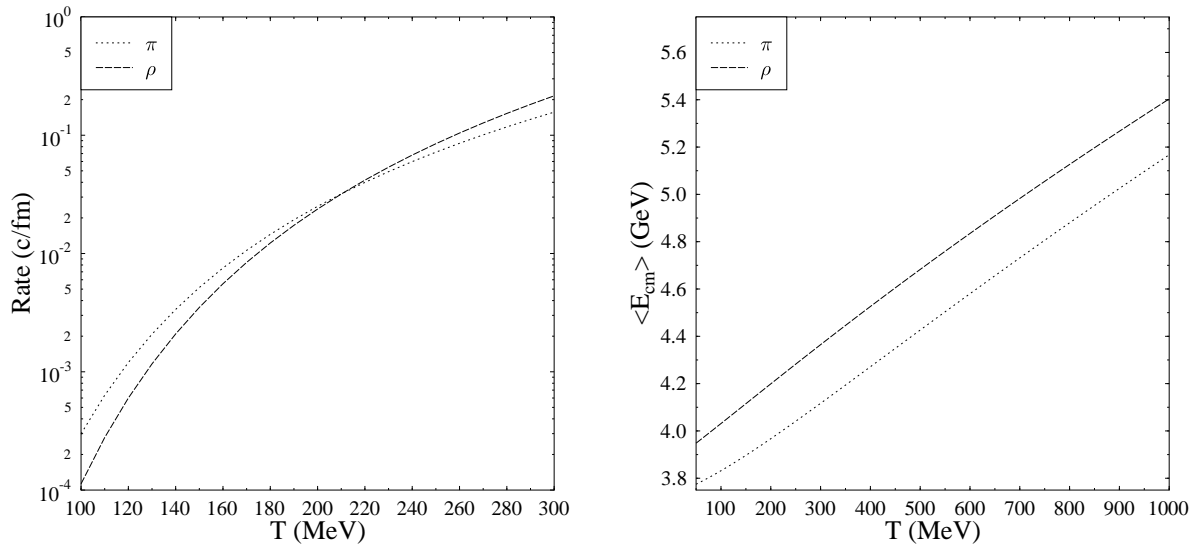
FIG. 3. Left: J/ψ dissociation rates in an ideal gas of pions and ρ's as a function of temperature. A fixed dissociation cross section of $\sigma_{J/\psi M} = 2.41$ mb is used. Right: Average collision energies in the same system as a function of temperature.
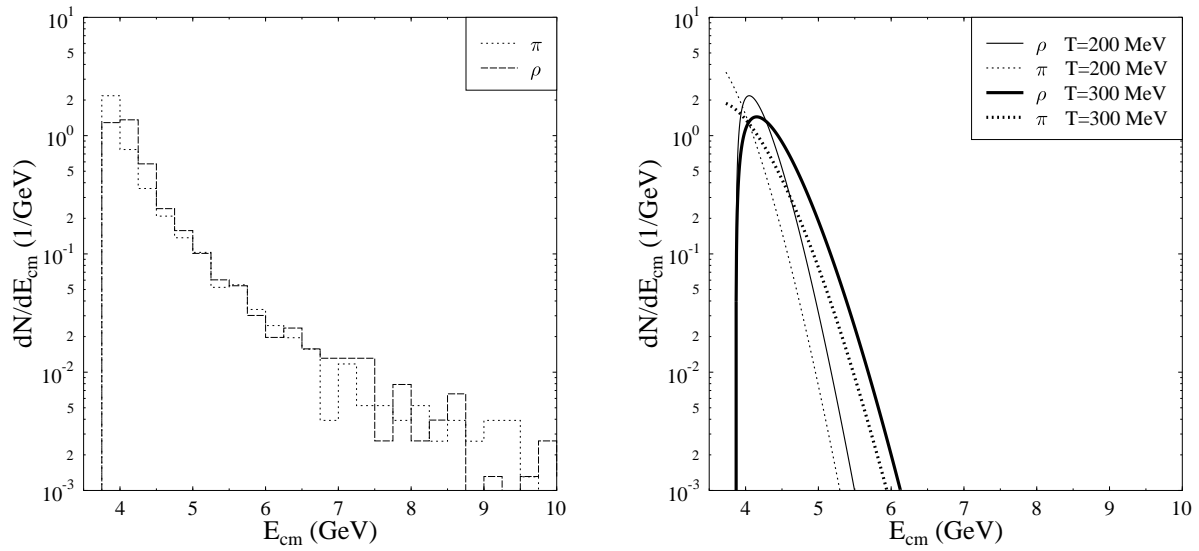
FIG. 4. Left: J/ψ collision spectrum in central Pb(160 GeV)+Pb reactions according to the UrQMD calculation (normalized to one collision). Shown are the energy spectra for $J/\psi\,\pi$ interactions (dotted line) and for $J/\psi\,\rho$ interactions (dashed line). A fixed dissociation cross section of $\sigma_{J/\psi M} = 2.41$ mb is used. Right: J/ψ collision spectra in an ideal gas of π's and ρ's for $T = 200$ and 300 MeV, normalized to one collision. A fixed dissociation cross section of $\sigma_{J/\psi M} = 2.41$ mb is used. Note that the scales are identical in both plots.

REFERENCES

[1] T. Matsui and H. Satz, Phys. Lett. **B178** (1986) 416.

[2] M.C. Abreu *et al.* (NA50 Coll.), Phys. Lett. **B410** (1997) 327, 337.

[3] A. Romana for the NA50 Collab., Contribution to XXXIIIrd Rencontres de Moriond, 21-28 Mar 1998, Les Arcs, France.

[4] D. Kharzeev, C. Lourenço, M. Nardi and H. Satz, Z. Phys. **C74** (1997) 307.

[5] R. Vogt, Phys. Lett. **B430** (1998) 15.

[6] N. Armesto and A. Capella, Phys. Lett. **B430** (1998) 23.

[7] K. Martins, D. Blaschke and E. Quack, Phys. Rev. **C51** (1995) 2723.

[8] S.G. Matinian and B. Müller, nucl-th/9806027.

[9] R. Mattiello, H. Sorge, H. Stöcker, W. Greiner, Phys. Rev. Lett. **63** (1989) 1459.

[10] P. Koch, B. Müller, J. Rafelski, Phys. Rep. **142** (1986) 167.

[11] D.M. Alde *et al.* (E772 Coll.), Phys. Rev. Lett. **64** (1990) 2479.

[12] V. Emel'yanov, A. Khodinov, S. R. Klein and R. Vogt, hep-ph/9809222.

[13] N. Hammon, L. Gerland, H. Stöcker and W. Greiner, hep-ph/9807546.

[14] C. Spieles, R. Vogt, L. Gerland and H. Stöcker, in preparation.

[15] S.A. Bass *et al.*, Prog. Part. Nucl. Phys. **41** (1998) 225.

[16] R. Vogt, Atomic Data and Nuclear Data Tables **50** (1992) 343.

[17] L. Gerland, L. Frankfurt, M. Strikman, H. Stöcker and W. Greiner, Phys. Rev. Lett. **81** (1998) 762.

[18] C. Spieles, L. Gerland, N. Hammon, M. Bleicher, S.A. Bass, H. Stöcker, W. Greiner, C. Lourenço, R. Vogt, Eur. Phys. J. **C5** (1998) 349.