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HADRON GAS VERSUS QUARK PLASMA EFFECTS IN THE E_T-DEPENDENCE OF THE J/Ψ SUPPRESSION PATTERN

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Within a reaction kinetic model of heavy quarkonia suppression, reactive collisions with hadrons as well as with quasi-free quarks in a hot and dense nuclear environment are treated simultaneously. We especially deduce temperature and density dependent reactive collision frequencies. A pure hadronic model is compared with a simple two-phase hydrodynamic model with respect to the E_T-dependence of the J/Ψ suppression pattern.

I. INTRODUCTION

In recent relativistic heavy ion collisions performed at CERN [1], the suppression of the J/Ψ state relative to the Drell-Yan background has been observed for events with high transverse energy E_T. This effect was earlier proposed to be a signal of quark-gluon plasma formation [2] which one expects to see in the E_T-dependence of the suppression pattern.

During the last two years, different approaches have been discussed in order to describe the suppression of heavy quarkonia in hot and dense matter. Matsui and Satz [2] proposed the dissolution of heavy quark bound states in surroundings of free quarks at high density to be similar to the Mott-effect in plasma physics due to static screening. This model has been further elaborated to discuss more detailed effects as, e.g., the dependence of the suppression on the transverse momentum p_T, see Refs. [3—6]. However, the Mott dissolution of bound states occurs at temperatures which are well above the plasma phase transition temperature T_c and does not seem suitable to describe correct physics behind the observed suppressions. A more relevant approach should use reaction kinetics in order to estimate the lifetime of bound states in dense surroundings.

A reaction kinetic approach to heavy quarkonia suppression in a quark-gluon plasma has been worked out recently within a string-flip model for a manyquark system with confinement interaction [7, 8]. The lifetime for a J/Ψ state at $T_c = 180$ MeV was found to be about $\tau_{J/\Psi} = 15$ fm/c, and it was shown that the plasma lifetime t_m can be related to the suppression ratio $\mathscr{R}(p_T = 0)$ according to

$$\mathscr{R}_{J/\Psi}(p_T = 0) = 6\alpha^{-3}\left[1 - e^{-\alpha}\left(1 + \alpha + \frac{\alpha^2}{2}\right)\right] \tag{1}$$

where $\alpha = t_m/\tau_{J/\Psi}$. From the comparison with experiments [1], a plasma lifetime of the order $t_m = 20$ fm/c was obtained. However, reactive collisions with hadrons within these calculations were disregarded.

Alternatively, more conventional approaches have appeared which claim to describe the suppression effect without the formation of a plasma phase [9—13]. They considered reactive collisions of the J/Ψ with a surrounding dense hadron gas. However, in comparison with experiments, the determination of the reactive cross sections has so far remained an open problem.

The aim of this paper is to give a uniform picture to describe reactive processes with hadrons as well as with quasi-free quarks. From the point of view of a conventional model, this would correspond to the determination of a density dependent reactive cross section. The possible occurrence of a quark plasma phase, however, should lead to an abrupt change in the reactive cross section. Such an effect should be seen in the E_T-dependence of the J/Ψ suppression to be discussed in this paper.

II. A SIMPLE MODEL FOR THE SPACE-TIME EVOLUTION OF HOT NUCLEAR MATTER

In a relativistic nucleus-nucleus collision, a hot zone is produced, where the total thermal energy stems from the conversion o the transverse energy E_T of the collision. Assuming cylindrical symmetry of the collision process, we have

$$E_T = 2\pi l \int_0^{R_A} \mathrm{d}r\, r\varepsilon(T(r, t = t_i)), \tag{2}$$

where l is the length of the cylinder, and $R_A = 1.2A^{1/3}$ fm denotes the radius of the projectile nucleus with mass number A. The initial time t_i is the moment at which reactive collisions start to occur. The energy density ε is given in the hadronic phase according to

$$\varepsilon_h(T) = \sum_h g_h \int \frac{\mathrm{d}^3p}{(2\pi)^3} (p^2 + m_h^2)^{1/2} \left\{\exp\left[(p^2 + m_h^2)^{1/2}/T\right] \pm 1\right\}^{-1} \tag{3}$$

whereas in the quark plasma phase we have

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$$\varepsilon_{pl}(T) = \sum_q g_q \int \frac{d^3p}{(2\pi)^3} (p^2 + m_q^2)^{1/2} \left\{ \exp\left[(p^2 + m_q^2)^{1/2}/T \right] + 1 \right\}^{-1} + B, \quad (4)$$

with $B = 222$ GeV fm^{-3} being the bag constant.

In the following, we consider two approaches. In the first approach no phase transition occurs, and the temperature of the hot nuclear matter is determined by Eq. (3). In the second approach a plasma phase will be formed if T approaches the critical value T_c. Then, a two-phase system is defined with a phase limit at $R_{pl}(t = t_i)$ determined in our simple model by the ansatz

$$\varepsilon(T(r, t = t_i)) = \varepsilon_{pl}(T_c)\Theta(R_{pl} - r) + \varepsilon_h(T_c)\Theta(r - R_{pl}). \quad (5)$$

Inserting into Eq. (2) a relation between R_{pl} and E_T is found,

$$\left(\frac{R_{pl}}{R_A}\right)^2 = y^2 = \begin{cases} \dfrac{\varepsilon - \varepsilon_h(T_c)}{\varepsilon_{pl}(T_c) - \varepsilon_h(T_c)} & \text{for } 0 < y^2 < 1, \\ \varepsilon/\varepsilon_{pl}(T_c) & \text{for } y^2 > 1 \end{cases} \quad (6)$$

which is shown in Fig. 1.

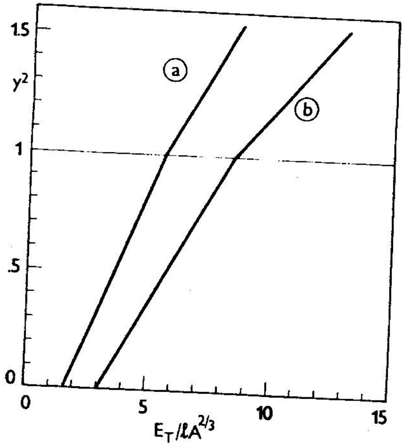

Fig. 1. Ratio of the plasma radius R_{pl} to the projectile radius R_A in dependence on the transverse energy E_T for two different critical temperatures: (a) $T_c = 180$ MeV, (b) $T_c = 200$ MeV.

For the time evolution we use the following simple model introducing the lifetime t_m of the plasma phase given by

$$t_m = x R_{pl}^{2/b}(t_i): \quad (7)$$

$$R_{pl}(t) = R_{pl}(t_i)\sqrt{1 - ((t - t_i)/t_m)^b} \quad \text{for } t_1 < t < t_m \quad (8)$$

$$T^3 t = T_c^3 t_m \quad \text{for } t > t_m. \quad (9)$$

We set $b = 2$ and consider x as a parameter to be specified below. Eq. (9) expresses the entropy conservation and defines the time dependence of temperature in the pure hadronic approach.

III. REACTION KINETICS FOR THE J/Ψ SUPPRESSION

After J/Ψ is formed at the distance r with the density $\varrho_{J/\Psi}(r)$, it propagates in the azimuthal direction ϑ with the transverse momentum p_T. Due to the reactive collisions it will be suppressed so that for the total yield, we can introduce the suppression ratio

$$\mathcal{R}(p_T, E_T) = \frac{\int_0^{2\pi} d\vartheta \int_0^{R_A} dr\, r \varrho_{J/\Psi}(r)\, e^{-N(r, p_T, E_T)}}{2\pi \int_0^{R_A} dr\, r \varrho_{J/\Psi}(r)}, \quad (10)$$

where

$$N(r, \vartheta; p_T, E_T) = \int_{t_i}^{t_f} dt\, \tau^{-1}(t) \quad (11)$$

is determined by the reactive collisions. The freeze-out time is denoted by t_f. For the two-phase approach, we have

$$\tau^{-1}(t) = \tau_{pl}^{-1}(T_c)\Theta(t_{pl} - t_i - t) + \tau_h^{-1}(T_c)\Theta(t + t_i + t_{pl})\Theta(t_m - t_i - t) + \tau_h^{-1}(T(t))\Theta(t + t_i - t_m), \quad (12)$$

where $t_{pl}(r, \vartheta, p_T, E_T)$ denotes the time-of-flight in the plasma zone.

As known from chemical reaction kinetics (see also Ref. [8]), the frequency of reactive collisions in the plasma phase can be expressed according to

$$\tau_{pl}^{-1}(T_c) = r_{J/\Psi}^2 \sum_q \left(\frac{8\pi T_c}{\mu_{J/\Psi, q}}\right)^{1/2} \frac{n_q(T_c)}{3} e^{-\Delta E/T_c}, \quad (13)$$

where $r_{J/\Psi} = 0.45$ fm is the radius of the J/Ψ, μ is the reduced mass, and ΔE is the activation energy for the dissolution reaction as given in Ref. [8] within the string-flip model. A similar relation has been used for the frequency of the reactive collisions in the hadronic phase (see Ref. [9])

$$\tau_h^{-1}(T) = \sum_h \left(\frac{8T}{\pi \mu_{J/\Psi, h}}\right)^{1/2} \sigma(h + J/\Psi) n_h(T) e^{-\Delta m/T}, \quad (14)$$

where Δm denotes the threshold energy of the reaction and σ is the collision cross section, which is of the order 1 ... 2 mb for these reactions [9, 10]. The temperature dependence of the density can be taken according to

$$n(T)t = n(T_c)t_m, \quad (15)$$

and usually one takes the approximation

$$\tau_h^{-1}(t) \approx \tau_h^{-1}(T_c)(t_m/t), \tag{16}$$

see Refs. [9—13].

In this way, we find for N (11)

$$N(r, p_T = 0, E_T) = \int_{t_i}^{t_i + t_{pl}} \mathrm{d}t\, \tau_{pl}^{-1}(T_c) + \int_{t_i + t_{pl}}^{t_i + t_m} \mathrm{d}t\, \tau_h^{-1}(T_c) + \int_{t_i + t_m}^{t_m + t_f} \mathrm{d}t\, \tau_h^{-1}(T(t)) =$$

$$= t_{pl}\tau_Q^{-1} + t_m\tau_h^{-1} + (t_i + t_m)\tau_h^{-1}(T_c)\ln\left(\frac{t_f + t_m}{t_i + t_m}\right). \tag{17}$$

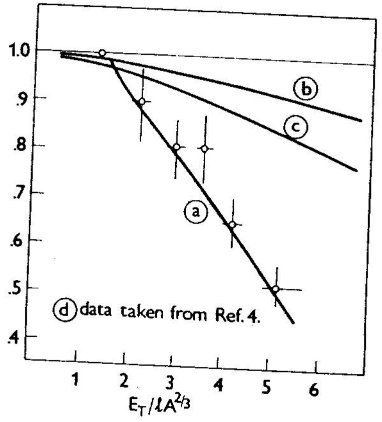

Fig. 2. Suppression ratio in dependence on the transverse energy E_T for different approaches: (a) two-phase model, (b) pure hadronic model, $\sigma = 1$ mb, (c) pure hadronic model, $\sigma = 2$ mb, (d) experimental results according to Ref. 4, parameter values are given in the text.

The evaluation of the suppression ratio can be performed for the value $p_T = 0$ and the density distribution $\varrho_{J/\Psi}(r) = \varrho_0\,\Theta(R_A - r)$ with the result

$$\mathscr{R}(p_T = 0, E_T) = \left(\frac{t_i + t_m}{t_f + t_m}\right)^{(t_i + t_m)/\tau_h} \mathrm{e}^{-t_m/\tau_h}\mathscr{R}_{pl}(\alpha, y), \tag{18}$$

$$\mathscr{R}_{pl}(\alpha, y) = 1 - y^2 + 2y^2\alpha^{-2}[1 - \mathrm{e}^{-\alpha}(1 + \alpha)] \quad \text{for } 0 < y < 1,$$

$$\mathscr{R}_{pl}(\alpha, y) = 2y^2\alpha^{-2}(1 + \alpha)\mathrm{e}^{-\alpha}\left[\mathrm{e}^{\alpha/y^2}\left(1 - \frac{\alpha}{(1 + \alpha)y^2}\right) - 1\right] \quad \text{for } y > 1.$$

The parameter $\alpha = t_m/t_Q$ depends on E_T according to (6), (7) and contains the parameter x which can be adapted to the experimental results, see also Eq. (1). The results for the suppression ratio (18) are shown in Fig. 2 with the parameter value $\alpha = 1$. Furthermore, results within the alternative approach without plasma phase transition are shown for the cross sections $\sigma = 1$ mb and $\sigma = 2$ mb. For comparison, experimental results are also shown with the parameter value $l = 3$ fm.

IV. DISCUSSION

As shown in Fig. 2, the two approaches discussed here show a quite different behaviour. Below the E_T value necessary for plasma formation, both models for the J/Ψ suppression show identical results. However, above this critical value of E_T, the suppression ratio of the two-phase approach is significantly lower when compared with the pure hadronic suppression, because the formation of a quark plasma phase leads to a drastic enhancement of the reactive cross sections. Therefore, an abrupt change in the slope of the E_T-dependence of the J/Ψ suppression would indicate the formation of a quark plasma phase. The experimental results [1] support the existence of such a change in the slope but have to be improved in future to make a decisive distinction between both approaches.

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АДРОННЫЙ ГАЗ И ЭФФЕКТЫ КВАРКОВОЙ ПЛАЗМЫ В ЗАВИСИМОСТИ E_T НА ПОДАВЛЕНИИ КАРТИНЫ J/Ψ

В рамках реактивной кинетической модели подавления тяжелего кварkония, рассматриваются одновременно реактиввные соударения адронами а также с квазисвободными кварками в горячей и плотной ядерной среде. Вычислена частота реактивных соударений в зависимости от температуры и плотности. Сравнивается чисто адронная модель с простой двухфазной гидродинамической моделью. Рассмотрена зависимость E_T на картину подавления J/Ψ.