Mass Shift of Charmonium near Deconfining Temperature and Possible Detection in Lepton-Pair Production

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The mass shift of charmonium near the critical temperature of the deconfining transition is investigated by a c-$\bar{c}$ potential model through the change of the string tension. On the basis of the results, detection of the shift by lepton-pair production is discussed by the use of the hydrodynamical model of ultrarelativistic nucleus-nucleus collisions. It is shown that the mass shift is detectable if the critical temperature is not lower than 300 MeV.

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Although there has been increasing support for the existence of deconfinement and/or chiral restoring transitions at finite temperature or high density in theoretical[1] and numerical[2] investigations, the possibility of detection of these transitions and the new phases is not yet clear.[3] On this problem, the hadronic mass shift related to the restoration of chiral symmetry has been discussed recently.[4,5] Despite the uniqueness of the phenomenon, detectability of the effect in actual collisions is still uncertain. In this Letter, we present some results for the mass shift of charmonium and the change of its leptonic width with variation of string tension, which is expected to be temperature dependent. Recent works in Monte Carlo simulation[6-8] and model investigation[9,10] suggest critical behavior of the string tension near the deconfining transition. Further, we discuss detection of the mass shift by lepton-pair production in heavy-ion collisions based on hydrodynamical development.[11-13] We see that the effect could be detectable if the deconfining temperature is not lower than 300 MeV.

The computation of the mass shift adopted here is based on the c-$\bar{c}$ potential model

$$V(r) = -\tfrac{4}{3}\alpha_s(r)/r + kr, \tag{1}$$

where the first term is the gluon-exchange Coulombic term given by Buchmüller and Tye,[14] i.e.,

$$\alpha_s(r) = \frac{8}{b_0}\int_0^\infty \frac{\sin(\Lambda tr)}{t}\left[\frac{1}{\ln(1+t^2)} - \frac{1}{t^2}\right], \tag{2}$$

with $\Lambda = 250$ MeV and $b_0 = 9$ (three flavors).

Since we consider the string tension k at finite temperature, our present interest is to solve for c-$\bar{c}$ states under variation of k. Generally speaking, the Coulombic term might also be temperature dependent. Here we restrict ourselves to variation of the string tension, because the long-range part, kr, would primarily show a finite-temperature effect below the critical temperature. The mass of the charm quark in the potential model may also be temperature dependent. In the case of heavy quarks, this would be a minor effect and is omitted in the present calculation. We shall comment further on this in later discussions.

Calculations are made by a variational method with variation of the string tension. In the calculation of the leptonic width, the reliability of the value of the variational wave function at the origin is rather poor. So we adopt the values from the sum rule for the potential, i.e.,

$$|\psi(0)|^2 = (m_c/2\pi)\langle dV/dr\rangle. \tag{3}$$

In Fig. 1, the dependence of masses and widths on the string tension is shown. We fix the charm-quark mass m_c to be 1.41 GeV and we can reproduce the results of Buchmüller and Tye at $k = 0.18\ \mathrm{GeV}^2$. We see that both quantities decrease gradually as the string tension decreases. The observed feature is understood as an effect due to broadening of the wave function. Our simple calculations suggest that mass shift of a few hundred megaelectronvolts is expected for charmonium near the critical temperature of the deconfining transition.

Let us consider actual heavy-ion collisions. We imagine that a well-thermalized hadronic fireball is formed in the collision. We assume that the initial temperature is close to, but below, the critical tem-

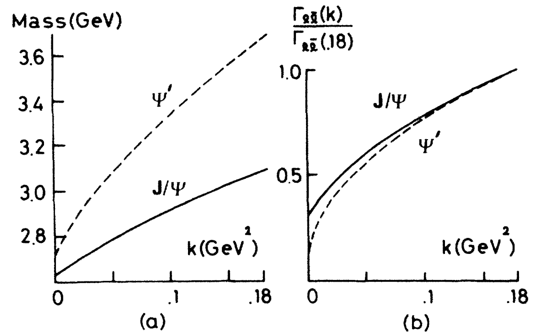

FIG. 1. (a) Mass shift of J/ψ and $\psi'(3.7)$ with respect to variation of string tension k. (b) Change of leptonic pair decay width of J/ψ and $\psi'(3.7)$ vs string tension.

perature, and subsequent development is described by hydrodynamics. In order to incorporate the mass shift discussed above into this thermalized system, we need to specify dependence of the string tension on temperature. Here we use a form parametrized by a critical exponent b as

$$k(T)=k(0)[(T_{\rm dec}-T)/T_{\rm dec}]^b. \qquad (4)$$

As is well known, the expression (4) is suitable for the second-order phase transition. At present, the order of deconfining transition in a system including dynamical quark freedom is still an open question. In the case of a weak first-order transition, the critical behavior of the string tension can be effectively expressed by an appropriate choice of b. It is noted that critical behavior of the string tension has been observed by Monte Carlo simulation in an SU(3) gauge system in which the transition is first order.[6-8] On the other hand, in the string model, the transition is second order and the critical exponent is predicted to be 0.5.[9,10] In Fig. 2, dependence of the mass on temperature is shown for several values of b.

As for a model of hydrodynamical development in ultrarelativistic heavy-ion collisions, we choose the one-dimensional scaling expansion as an example.

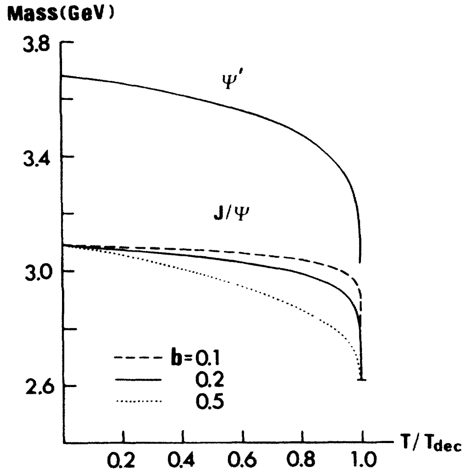

FIG. 2. Mass shift of J/ψ and $\psi'(3.7)$ with respect to temperature.

The temperature profile function is given[11-13] in this case by

$$\Phi(T)=\int dx^4\delta(T-T(x))$$
$$=6\pi(R\tau_0)^2(Y_{\rm c.m.}/T_0)(T/T_0)^7, \qquad (5)$$

where R is the radius of the fire disk; τ_0 and T_0 are the starting time of the evolution and starting temperature, respectively, while T_f is the temperature of the freeze-out (the decoupling temperature of J/ψ); $Y_{\rm c.m.}$ is the center-of-mass rapidity of the incident particles. The emission rate of leptonic pairs from the four-dimensional volume element dx^4 is given[13] by

$$dw/dx^4=n(M(T),T)\Gamma_{l\bar{l}}(T), \qquad (6)$$

with

$$n(M,T)=3(MT/2\pi)^{3/2}\exp(-M/T), \qquad (7)$$

for $T<M$. When we combine Eqs. (5), (6), and the results of mass shift and leptonic width of J/ψ, the invariant-mass distribution of lepton pairs is given by

$$(1/\sigma_{\rm FD})d\sigma_{\rm FD}/dM=\int_{T_f}^{T_0}dT\,\Phi(T)[dw(M(T),T)/dx^4]\delta(M-M(T))$$
$$=3|\partial T/\partial M(T)|\Phi(T)(MT/2\pi)^{3/2}\exp(-M/T)\Gamma_{l\bar{l}}(T)$$
$$\times\theta(M(T_f)-M)\theta(M-M(T_0)), \qquad (8)$$

where T is such that $M(T)=M$ and $\sigma_{\rm FD}$ is a formation cross section of the fire disk. In the above expression, we have assumed that the total width of J/ψ does not change drastically and the narrow-width approximation has been used.

Results for the case of $T_{\rm dec}=250$–350 MeV, $T_f=100$ MeV, and $b=0.1$–0.5 at $T_0=T_{\rm dec}$ are presented in Fig. 3. As for the values of parameters of the fire disk, we take $R=3$ fm, $\tau_0=1$ fm/c, and $Y_{\rm c.m.}=3$ as an example. For the sake of comparison, the figure includes data of 225-GeV/c proton-carbon collisions[15] multiplied by factors of 3 and 12 as a simple estimation for carbon-carbon and tungsten-carbon collisions in a superposition picture.[16] As shown in the figure, the yield of a lepton pair from mass-shifted J/ψ

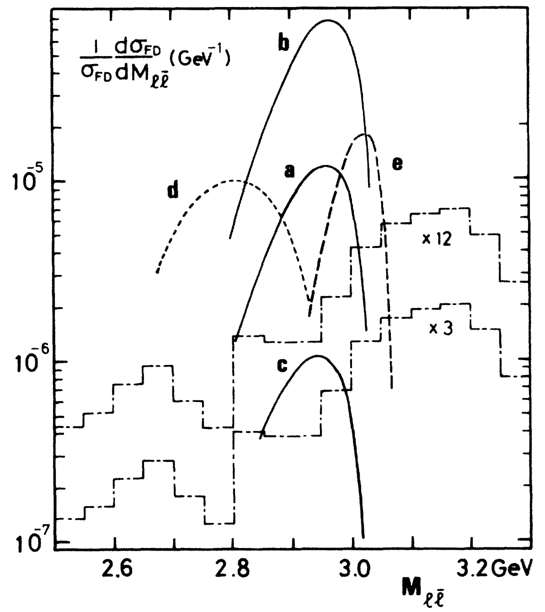

FIG. 3. Lepton-pair yield from mass shifted J/ψ for different values of deconfinement temperature $T_{\rm dec}$ and critical exponent b of string tension. The dot-dashed curves correspond to the data of proton-carbon collisions at 225 GeV/c (see Ref. 19) multiplied by 3 and 12. (a) $T_{\rm dec}=300$ MeV, $b=0.2$; (b) $T_{\rm dec}=350$ MeV, $b=0.2$; (c) $T_{\rm dec}=250$ MeV, $b=0.2$; (d) $T_{\rm dec}=300$ MeV, $b=0.5$; and (e) $T_{\rm dec}=300$ MeV, $b=0.1$.

has enough strength for $T_{\rm dec}\geqslant 300$ MeV in this example. In the case of lower $T_{\rm dec}$, the yield is strongly suppressed.

So far, we have discussed the lepton-pair emission from mass-shifted J/ψ. However, normal J/ψ which comes out after the freeze-out also has a contribution at the normal position $M=3.1$ GeV and this might mask the signal. To discuss this point, we investigate a ratio Y_h/Y_c, where Y_h is the total yield of lepton pairs from hot J/ψ, i.e., integral of Eq. (8),

$$Y_h=\int_{2.7}^{3.1} dM(1/\sigma_{\rm FD})\, d\sigma_{\rm FD}/dM. \qquad (9)$$

On the other hand, Y_c is that from normal J/ψ after decoupling and given by

$$Y_c=V(T_f)\,n(T_f)\Gamma_{l\bar l}(T=0)/\Gamma_t(T=0), \qquad (10)$$

where $V(T_f)$ is the volume of the fireball at $T=T_f$. Y_c is strongly dependent on T_f through the Boltzmann factor in $n(T_f)$ whereas Y_h is rather insensitive to T_f. Using the one-dimensional expansion model [Eq. (5)], we obtain

$$Y_h/Y_c\simeq 30,\ 2,\ \text{and}\ 0.015$$

$$\text{at}\ T_f=130,\ 150,\ \text{and}\ 200\ \text{MeV},$$

respectively, for the case $T_0=T_{\rm dec}=300$ MeV. Therefore, we can expect a clean signal of the mass shift for $T_f<150$ MeV; otherwise there may arise difficulty in the separation of "mass-shift events" from the tail of "normal J/ψ events." To obtain $T_f<150$ MeV, one may need a rather large total cross section (~ 10 mb) due to processes $\pi+J/\psi\rightarrow D+\bar D$, $\eta_c+\pi$; $K+J/\psi\rightarrow\eta_c+K,\ldots,$ though we do not have sufficient information on these processes at the present stage.[17] Thus, in the case of $T_{\rm dec}\geqslant 300$ MeV and $T_f\leqslant 150$ MeV, we have a good chance to observe the mass shift of J/ψ by lepton-pair production. In other cases, detection requires the use of a high-resolution counter.

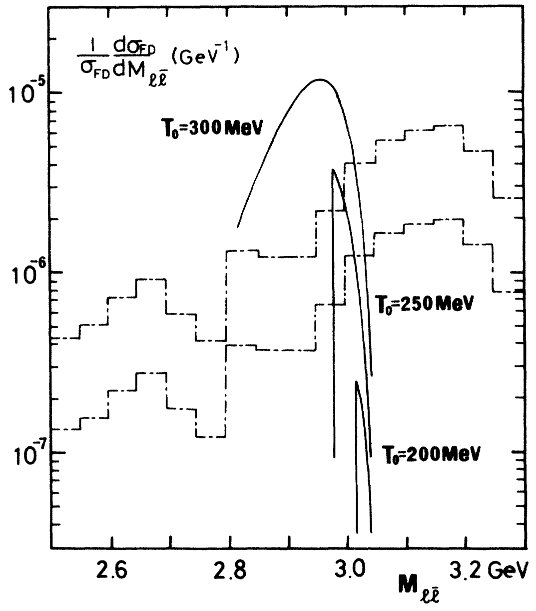

FIG. 4. Lepton-pair yield for different value of starting temperature T_0. The deconfinement temperature is fixed at 300 MeV.

In Fig. 4, dependence on the starting temperature is shown. As shown in the figure, the mass shift is revealed only when T_0 becomes close to $T_{\rm dec}$, and would be observed as a signal of the phase transition if we can control T_0 as a function of the incident energy. As a summary of present calculations, the observability of the mass shift of charmonium by lepton-pair production in heavy-ion experiments at energies 10^2 GeV/nucleon to 1 TeV/nucleon is feasible and should be examined if the deconfinement temperature is not lower than 300 MeV.

We have assumed that the charm-quark mass is independent of temperature. However, if chiral restoration occurs and light-quark condensation $\langle\bar q q\rangle$ decreases, the dressed mass also may decrease. This means that further reduction of the mass of charmonium is expected. As for the temperature dependence of the Coulombic term (1), a finite-temperature effect would be important in the deconfinement phase. In fact, screening of the color charge has been observed in Monte Carlo analyses.[7,8] A related question is whether charmoniumlike clusters may still exist in a quark-gluon plasma. We have made tentative calculations by screened Coulombic potential and found that possibility small. Thus, contribution to lepton pair in the J/ψ mass region from the deconfinement phase would be mainly thermal quark-antiquark annihilation.[18] In connection with this point, we make a comment on our calculation for the case $T_0 \geqslant T_{\text{dec}}$. If there is a considerable period for the mixed phase of hadron and quark-gluon plasma, this gives an additional δ function to the temperature profile function and we expect a spike in the lepton-pair invariant-mass spectrum.

One may consider that the hot era of the fireball is too short for thermal production of the charm component from hadronic matter.[19] However, J/ψ and charm production in hadron-hadron collision at high energies are not so small.[15] Thus the initial collision among constituent nucleons could be a considerable source of the charm component.

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