J/ψ production in a quark-gluon plasma

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The suppression of the production of J/ψ particles in a quark-gluon plasma is shown to depend on their transverse momentum $q_\perp$: The fraction of J/ψ particles with $q_\perp < 1$ GeV/c in the $dN/dq_\perp^2$ spectrum decreases by a factor ~ 5. The spectrum thus acquires a shape distinct from those corresponding to other J/ψ production mechanisms.

Programs of experiments on collisions of heavy ions are now beginning at CERN.[1] One of the principal purposes of these experiments is to detect a new state of hadronic matter: a quark-gluon plasma.[2–4] In this letter we wish to suggest a result which would signal the formation of a quark-gluon plasma and which would stem from the dynamics of the production and evolution of heavy quarks in a quark-gluon plasma.

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Let us assume that a medium consisting of light (u, d) quarks, antiquarks, and gluons forms in a certain volume in heavy-ion collisions at a temperature T above that ($T_c = 200$ MeV) of the phase transition from hadrons to a quark gluon plasma. Several momentum scales and thus several length scales can be distinguished in a medium of this nature.[4] If $g = g(T)$ is the effective coupling constant of the gauge fields at the temperature T, then a Debye screening of a chromoelectric component of the gauge fields will occur at a momentum scale $p_E \simeq gT$, while a screening of a chromomagnetic component of the gauge fields will occur at a scale $p_M \simeq g^2 T$. In lattice gauge theories[5] a screening of the color charge arises at the scale of the correlation length $\xi(T)$.

In a medium consisting of light quarks, antiquarks, and gluons, the production of heavy (s, c) quarks and antiquarks will occur with a Boltzmann probability. A heavy quark (e.g., a c quark) would then be capable of capturing a light quark (or antiquark) and forming a D meson. Another possibility is the production of a bound state of a c quark and a $\bar{c}$ antiquark, i.e., a J/ψ particle. However, if the correlation length $\xi(T)$ at the given temperature is shorter than the radius of the bound state, $r_{J/\psi}(T)$, at the given temperature, the screening of the color charge will result in a suppression of the production of the $c\bar{c}$ bound state.[6] According to calculations on a space-time lattice,[7] the correlation length is $\xi(T) \simeq 0.2$–0.3 fm at temperatures $T \gtrsim 250$ MeV. The radii of the J/ψ particle at the temperatures $T = 0$ and $T \simeq T_c \simeq 200$ MeV were estimated in Ref. 6: $r_{J/\psi} \simeq 0.3$–0.5 fm. If the temperature of the quark-gluon plasma satisfies $T \gtrsim 250$ MeV, the emission of J/ψ particles will therefore be suppressed because of screening.

Let us examine a simple model for the suppression of the J/ψ particles in a quark-gluon plasma. In hadron-hadron interactions in which a quark-gluon plasma would not be produced, more than 50% of the J/ψ particles are produced as a result of radiative decays of the radial excitations $\chi_0(3415)$, $\chi_2(3515)$, and ψ'. In the lowest-order perturbation theory of quantum chromodynanmics, the J/ψ particles are produced in the two-gluon process[8] represented by the Feynman diagram in Fig. 1. In calculations for this diagram it was assumed that $\chi_{0,2}$ and thus J/ψ are produced if the relative 3-momentum of the c and $\bar{c}$ quarks satisfies $|\mathbf{q}| > 1/\xi(T)$. The temperature dependence of the correlation length was chosen on the basis of the lattice calculations.[7]

In the standard procedure[4] for calculating the yields of particles from a quark-gluon plasma, one first carries out calculations for the process (Fig. 1) in the rest frame of an element of the quark-gluon plasma and then integrates over the expansion of the plasma. After several analytic integrations we find

$$\frac{dN^{J/\psi}}{dq_\perp^2\, dy} = C \int_{T_c}^{T_i} \frac{dT}{T^6} \int_{-Y_m}^{Y_m} \frac{dY}{\sqrt{E_\psi^2 - M_\psi^2}} \int_{E_-}^{E_+} \frac{dE f(E, T)\, \theta(E^2 - M^2 - \xi^{-2}(T))}{\sqrt{E^2 - M^2}\, |1 - \exp(E/T)|}, \tag{1}$$

where

$$f(E, T) = \ln \frac{(e^{E/2T} e^{\sqrt{E^2 - M^2}/2T} - e^{E/T})(e^{E/2T} e^{-\sqrt{E^2 - M^2}/2T} - 1)}{(e^{E/2T} e^{-\sqrt{E^2 - M^2}/2T} - e^{E/T})(e^{E/2T} e^{\sqrt{E^2 - M^2}/2T} - 1)}.$$

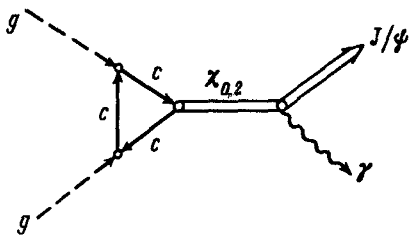

FIG. 1. Feynman diagram of the production of a J/ψ particle in a quark-gluon plasma.

Here T_i is the initial temperature of the plasma, Y_m is the maximum spatial rapidity ($Y_m \simeq 3$) of the J/ψ production, E is the energy of the $\chi_{0,2}$, M is the mass of the $\chi_{0,2}$, M_ψ is the mass of the J/ψ particle, E_ψ is the energy of the J/ψ particle, given by

$$E_\psi \simeq \frac{1}{2}\sqrt{M_\psi^2 + q_\perp^2}\,\mathrm{ch}y\,[(Y - \mathrm{th}y)^2 + 2 - \mathrm{th}^2 y],$$

the quantities $E_\pm$ are given by

$$E_\pm = \frac{1}{2M_\psi^2}[E(M_\psi^2 + M^2) \pm \sqrt{E_\psi^2 - M_\psi^2}(M^2 - M_\psi^2)],$$

and C is a numerical constant.

Figure 2 shows transverse-momentum spectra of the J/ψ particles for rapidities $y = 0$ which were found through a numerical integration of expression (1). The solid line corresponds to a quark-gluon plasma without screening, while the dashed line incorporates lattice screenings. It can be seen from this figure that screening in the plasma reduces the fraction of J/ψ particles with small transverse momenta ($q_\perp \leqslant 1$ GeV) by a factor of five. Nonplasma (parton) production mechanisms[9] are known to predict a maximum in the $q_\perp$ distributions at $q_\perp \simeq 0$. For J/ψ particles produced from a quark-gluon plasma we would expect to see a maximum at $q_\perp \simeq 1$ GeV. Such a change in the shape of the transverse-momentum distribution would be hard to explain in terms of the absorption in nuclear matter of the J/ψ particles that

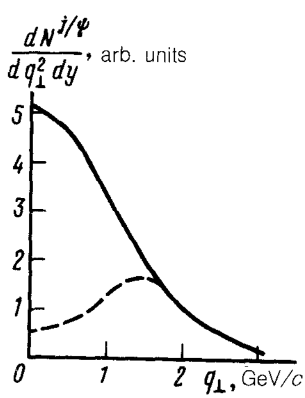

FIG. 2. Transverse-momentum distribution of the J/ψ particles produced in a quark-gluon plasma. Solid line—without screening; dashed—with screenings in the quark-gluon plasma.

are produced, since the cross section for interaction of the J/ψ particles with a nucleon is ~ 1 mb. In other words, the mean free path of the J/ψ particles would be ~ 10 fm at energies ~ 200 GeV.

It is important to note that expression (1) is a steep function of the initial temperature T_i (most of the J/ψ particles are produced at $T \simeq T_i$). The prediction of the yield of J/ψ particles from a quark-gluon plasma is therefore insensitive to the model regarding the nature of the expansion of the quark-gluon plasma. In addition to the plasma mechanism, however, there is always the parton mechanism for the production of the J/ψ particles (e.g., as the result of the sea c and $\bar{c}$ quarks of colliding nuclei). In order to distinguish between these mechanisms, we should make an assumption regarding the nature of the expansion of the quark-gluon plasma. In a standard[1] one-dimensional expansion of a quark-gluon plasma with conservation of entropy, the multiplicity of secondary charged particles, dN_{ch}/dy, can be related to the initial temperature in the nucleus-nucleus collision[10]:

$$\frac{dN_{ch}}{dy} \simeq 12\left(\frac{T_i}{0.2\,\mathrm{GeV}}\right)^2 B^{2/3}, \tag{2}$$

where B is the mass number of the light nucleus. As has already been mentioned, screening should affect the J/ψ yields at temperatures $T_i > 0.25$ GeV. In the CERN experiments we would have $B = 16$, so that screening in the plasma could change the transverse-momentum spectrum of the J/ψ particles at multiplicities $dN_{ch}/dy \gtrsim 100$. In events with a multiplicity $dN_{ch}/dy \gtrsim 100$, the transverse-momentum distribution of the J/ψ particles might possibly have, in addition to the maximum at $q_\perp = 0$ (which corresponds to the parton production mechanism), a maximum at $q_\perp \simeq 1$ GeV, due to the emission of J/ψ particles from the quark-gluon plasma.

Another experimentally testable consequence of the suppression of the yield of J/ψ particles from a quark-gluon plasma might be seen in a study of the behavior of the J/ψ cross section as a function of the mass number of the target nucleus. It is easy to see that the cross section for the J/ψ production in events in which a quark-gluon plasma is produced should have the behavior $\sim A^\alpha$ with $\alpha < 1$. The NA3 data may indicate such a behavior.[11]

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