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Quarkonium polarization in heavy ion collisions as a possible signature of the quark-gluon plasma

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The polarization of quarkonium states produced in hadron collisions exhibits strong nonperturbative effects—for example, at small transverse momentum p_t charmonia appear unpolarized, in sharp contradiction to the predictions of perturbation theory. The quark-gluon plasma is expected to screen away the nonperturbative physics; therefore those quarkonia which escape from the plasma should possess polarization as predicted by perturbative QCD. We estimate the expected J/ψ polarization at small p_t, and find that it translates into the asymmetry of the $e^+e^-(\mu^+\mu^-)$ angular distribution $W(\theta)\sim 1+\alpha\cos^2\theta$, with $\alpha\simeq 0.35$–0.4.

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The possibility to form quark-gluon plasma in heavy ion collisions is an intriguing problem of strong interaction physics. To establish the formation of plasma, a number of signatures were proposed; here we will concentrate on heavy quarkonia. Suppression of heavy quarkonium states has been suggested long time ago by Matsui and Satz [1] as a signature of the deconfinement phase transition in heavy ion collisions. Their by now well-known idea is that the Debye screening of the gluon exchanges will make the binding of heavy quarks into the bound states impossible or unlikely once a sufficiently high temperature is reached. The lack of quarkonium states would thus signal deconfinement; this effect was indeed observed and studied in detail at CERN SPS by the NA38 [2] and NA50 Collaborations [3]. The results on J/ψ production at RHIC have recently been presented by the PHENIX Collaboration [4]. The observations of quarkonium suppression have been interpreted as a signal of quark-gluon plasma formation [5]. However, different conclusions were reached in Ref. [6], where it was argued that the effect may arise due to quarkonium collisions with the comoving hadrons. Additional tests of the quark-gluon plasma formation could help to clarify the situation.

In this Rapid Communication we propose to use for the diagnostics of the quark-gluon plasma those heavy quarkonia which *escape* from it. This would require experimental measurements of quarkonium polarization, which can be reconstructed from the angular distributions of quarkonium decays—dileptons and/or photons. For J/ψ states, one would need to measure the angular distribution of electrons (or muons) in the $J/\psi\to e^+e^-$ decay in J/ψ rest frame relative to the direction of its momentum. (We will concentrate on J/ψ's at relatively small p_t, which dominate the total production cross section.)

Let us first formulate what we mean by the quark-gluon plasma, since different definitions sometimes may result in misunderstanding. We define the quark-gluon plasma as a gas of quarks and gluons in which the interactions can be described by perturbative QCD and nonperturbative effects are either absent or can be neglected. We will not need to specify the properties of this state of matter in more detail to develop our idea; let us now turn to the dynamics of quarkonium production.

It is well known that the description of the data on heavy quarkonium production within the framework of perturbative QCD (pQCD) meets with siginificant difficulties. Both the absolute values of the measured production cross sections of hidden heavy flavor states and the relative abundances of different quarkonia are not described well within the perturbative framework, but perhaps the most spectacular failure of pQCD is the polarization of the produced quarkonia. Even an extension of a perturbative approach based on nonrelativistic QCD [7], which allows certain nonperturbative physics, does not allow to explain the polarization measurements [8].

Meanwhile, the description of heavy flavor production in perturbative framework has been largely successful (even though there are some problems there as well). The reason for this is easy to understand—the production of heavy flavors occurs at short time scale $\sim 1/(2\,m_Q)$, where m_Q is the heavy quark mass, whereas the binding of the produced heavy quarks into quarkonium is a softer process characterized by the time scale of $\tau_{bind}\sim 1/\epsilon$, where ϵ is the typical binding energy; for a Coulomb interaction, $\epsilon\sim\alpha_s m_Q^2 \ll m_Q$. The binding process is thus far more likely to be affected by nonperturbative phenomena, which manifest themselves both in the magnitude of the production cross section and in the polarization of the produced quarkonia.

Consider now the production of quarkonium states in relativistic heavy ion collisions. The typical time scale for the production of semihard partons with transverse momentum k_t is $\tau\sim 1/k_t$; for example, in the gluon saturation scenario $\tau_{prod}\sim 1/Q_s$, where Q_s is the saturation scale which at RHIC energies is about $Q_s\simeq 1$–2 GeV [9]. It is thus likely that while these produced partons will not significantly affect the production of heavy quarks (which happens at earlier time), they will influence the binding of heavy quarks in quarkonia since $\tau_{prod}\leq\tau_{bind}$.

High energy density of the produced partonic state is expected to result in the destruction of the nonperturbative vacuum structure. Indeed, lattice QCD calculations show that quark and gluon condensates "evaporate" above the deconfinement phase transition [10]. It may be expected that nonperturbative vacuum fluctuations are suppressed even if the thermalization does not take place—a specific example is given by the suppression of instantons in the saturated gluon environment [11]. As a result, the processes in this high-density partonic state of matter should be described by the weak coupling, perturbative methods. As a matter of fact, as we assumed above, one may *define* the quark-gluon plasma as a collective state of quarks and gluons the dynamics of which is governed by perturbative interactions. Therefore, the formation of heavy quarkonium states should also be adequately described by perturbation theory, and the predictions of pQCD for the polarization of heavy quarkonia should be vindicated. Dense parton matter may then screen out of existence a large part of quarkonia, as proposed originally [1], but those of them that survive will carry the information about the mechanism of their formation throughout the collision. Of course, the interactions of quarkonia at the later stages of the heavy ion collision may wash out their polarization somewhat, but relatively small interaction cross sections and the heavy quark symmetry, suppressing the spin flips of heavy quarks, should prevent quarkonia from "forgetting" their initial polarization entirely.

Let us illustrate this idea in more detail using the example of J/ψ polarization. There are two mechanisms of J/ψ production in hadron collisions—direct, when J/ψ is produced by perturbative and nonperturbative interactions of gluons and quarks, and cascade, when J/ψ is created as a result of decays of C-even $\bar{c}c$ states, $\chi_c \to J/\psi + \gamma$. In quark-gluon plasma, the cascade production mechanism should be at least as important as direct production. Indeed, in the lowest order of perturbation theory, J/ψ is produced by the three-gluon fusion or by two-gluon fusion followed by the gluon emission off the $\bar{c}c$ system. In both cases the probability of J/ψ production is proportional to $\alpha_s^3(m_c)$. The probability of $\chi_c^{0,2}$ production is proportional to $\alpha_s^2(m_c)$, i.e., it is of lower order in α_s, which however is largely compensated by the branching ratio $B(\chi_2 \to J/\psi + \gamma) \simeq 20\%$ for the J/ψ production.

In hadron collisions the direct mechanism comprises typically about 60% of the observed J/ψ's (for a review of the data, see Ref. [12]), which seems to suggest that an essential part of J/ψ production in hadron collisions is of nonperturbative origin. Direct calculations confirm this conclusion. In Ref. [13] J/ψ production cross section in πN interactions was calculated in perturbation theory: two-gluon fusion into $\bar{c}c$ with the subsequent gluon emission (the so-called color-singlet model [14]). The result is about eight times smaller than the data. Similar situation holds also for χ_2 production: the calculated cross section is by factor of 2 smaller than the experimental one (see Ref. [13] for details). Additional mechanism of χ_2 production [15] in the framework of the color-octet model [7] involves the formation of the color-octet $\bar{c}c$ state which then decays by color $E1$ transition to χ_2. Evidently, this mechanism perturbatively is suppressed by extra power of α_s and is essential only if it is nonperturbative. The cross section of χ_1 production is very small in perturbation theory, but noticeable experimentally (χ_0 does not contribute substantially to the J/ψ production because of a small branching ratio of $\chi_0 \to J/\psi + \gamma$ decay—about 1%). (The contributions from various sources to the J/ψ production in $\pi^- N$ collisions at the incident energy of 185 and 300 GeV and the results of theoretical calculations can be found in Ref. [13]; the comparison shows that the production of charmonium states in hadronic collisions is in an essential way nonperturbative).

Let us now turn to J/ψ polarization as reconstructed from the angular distributions of electrons (muons) from the $J/\psi \to e^+ e^- (\mu^+ \mu^-)$ decays. Generally the electron (muon) distribution has the form

$$W(\theta) \sim 1 + \alpha \cos^2\theta, \tag{1}$$

where θ is the emission angle of e^+ (or μ^+) relative to the direction of J/ψ motion in its rest frame; at small p_t, this direction coincides with the direction of the beam. The value $\alpha = 1$ corresponds to the transverse polarization, $\alpha = -1$ to the longitudinal polarization, and $\alpha = 0$ to unpolarized J/ψ.

In perturbation theory, in the case when J/ψ is produced through the $\chi_2 \to J/\psi + \gamma$ decay, the coefficient α in Eq. (1) is determined unambiguously (at small p_t): $\alpha = 1$ [16]. This comes from the fact that χ_2 is produced by two-gluon fusion $gg \to \chi_2$, for which the effective interaction is $f_{\mu\nu}\Theta_{\mu\nu}$, where $\Theta_{\mu\nu}$ is the energy-momentum tensor of the gluon field and $f_{\mu\nu}$ is the wave function of χ_2. Since $\Theta_{\mu\nu}$ has only $J_z = \pm 2$ spin projections on the direction of gluon momenta (indeed, $\Theta_{\mu\nu}$ may be considered as a source of the graviton field), the same spin projections have the χ_2. As a result, J/ψ produced via χ_2 decay is transversely polarized, $J_z = \pm 1$ and thus $\alpha = 1$.

This conclusion is somewhat modified when the initial transverse momenta of the gluons are taken into account. This reduces the value of α to [16]

$$\alpha \to \alpha' = \alpha \frac{\left(1 - \frac{3}{2}\theta_0^2\right)}{1 + \alpha\theta_0^2/2}, \tag{2}$$

where $\theta_0^2 \sim 4\langle p_t^2 \rangle / M_\chi^2$. The average transverse momentum of gluons is expected to increase with energy and the atomic number of the colliding systems. For example, in the gluon saturation scenario $p_t \sim Q_s \sim A^{1/3} s^{\lambda/2}$, with $\lambda \simeq 0.25$; at RHIC energies in central Au-Au collisions $Q_s \sim 1$ GeV [9]. For $p_t \sim 1$ GeV, the formula, Eq. (2), yields a reduction of polarization down to $\alpha \simeq 0.5$; still, this value corresponds to a significant transverse polarization.

The asymmetry coefficient α was also computed for the directly produced J/ψ and for the production via the χ_1 decay [13]. The results are $\alpha_{dir} \simeq 0.25$ for direct production and $\alpha_{\chi_1} \simeq -0.15$ for the production via χ_1 decay (except the forward region of $x_F > 0.8$, where both α_{dir} and α_{χ_1} begin to increase). After summing all channels of J/ψ production it was found [13] that $\alpha_{tot}^{pert} \simeq 0.5$. Experimentally [17], no sizable polarization in the entire range of x_F was observed, $\alpha \simeq 0$ (there is however an indication that at very large x_F α becomes negative). This disagreement between theory and experiment demonstrates again that the production mechanism of J/ψ and possibly χ_1 and χ_2 in hadronic collisions is essentially nonperturbative. (Even though we have discussed only πN data, there is no reason to believe that in pN collisions the situation will be very different, apart from a relatively smaller contribution of the $\bar{q}q$ annihilation in the latter case.) It is also interesting to note that for the case of Υ production, the data from E866 Collaboration [18] show transverse polarization for $\Upsilon(2S+3S)$, in qualitative agreement with the predictions of perturbation theory. This of course is to be expected if the validity of perturbation theory were to improve between the scales fixed by the masses of charm and bottom quarks.

Let us now dwell upon the J/ψ production in heavy ion collisions. Let us assume that at sufficiently high collision energy the quark-gluon plasma is formed. Due to the arguments presented above, the formation of quarkonia will thus take place in the plasma. This will of course result in the suppression of the formation probability [1]; moreover, the presence of the plasma is likely to affect the excited states more significantly, and the contribution of the excited quarkonium states to the observed yield of J/ψ will thus change, which also can result in the change of the J/ψ polarization [19]. If quarkonium is produced in the plasma, the nonperturbative effects should be absent (or small), and we are left only with the perturbative mechanism. Then, according to Ref. [13] about one-half of J/ψ's will be produced directly and another one-half via $\chi_2 \rightarrow J/\psi + \gamma$. (The approximate equality of these contributions stems from the fact that the extra power of α_s in the direct production cross section is compensated by a relatively small branching ratio—about 20%—of the $\chi_2 \rightarrow J/\psi + \gamma$ decay; note also that $\chi/J/\psi$ ratio has been found to be independent of the collision energy—see Ref. [12].) We thus expect that the asymmetry coefficient of the electron (muon) angular distribution in the $J/\psi \rightarrow e^+e^-(\mu^+\mu^-)$ decay in the case of quark-gluon plasma formation will increase from zero to about (at $p_t = 0$) $\alpha \simeq 0.6$. The account of the initial transverse momentum distribution of gluons as discussed above reduces asymmetry coefficient to

$$\alpha \simeq 0.35 - 0.4. \tag{3}$$

Still, we expect a remarkable increase in the asymmetry coefficient when going from hadron to heavy ion collisions.

Of course, there are effects which may result in some decrease of α in comparison with Eq. (3), notably a more accurate account of the transverse momentum distributions of gluons and, as also discussed above, the interactions of J/ψ with the constituents of hadronic and/or quark-gluon fireball.

However, we do expect an increase of J/ψ polarization in heavy ion collisions if the quark-gluon plasma is formed there.

To summarize, the test of quark-gluon plasma formation in heavy ion collisions can be performed by measuring the asymmetry of $e^+e^-(\mu^+\mu^-)$ angular distribution of $J/\psi \rightarrow e^+e^-(\mu^+\mu^-)$ decay (at small p_t of the produced J/ψ). In the case of plasma formation the asymmetry parameter $\alpha \simeq 0.3$–0.4 is expected [α is defined by the angular distribution $W(\theta) \sim 1 + \alpha \cos^2\theta$].

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