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CHARMONIUM POLARIZATION IN e^+e^- AND HEAVY-ION COLLISIONS

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In e^+e^- annihilation at $\sqrt{s} = 10.6$ GeV, Belle Collaboration found that J/ψ mesons are predominantly produced in association with an extra $\bar{c}c$ pair. The possible mechanisms of J/ψ production are discussed and the probability of the associate production of $\bar{c}c$ pair is estimated. The choice between these mechanisms can be done by measuring J/ψ polarization. It is suggested, that in case of heavy-ion collisions one may expect remarkable transverse polarization of produced J/ψ, if quark-gluon plasma if formed. The measurement of asymmetry of $e^+e^-(\mu^+\mu^-)$ angular distribution in $J/\psi \to e^+e^-(\mu^+\mu^-)$ decay is a useful tool for detection of quark-gluon plasma formation in heavy-ion collisions.

В e^+e^--аннигиляции при $\sqrt{s} = 10{,}6$ ГэВ коллаборация Belle обнаружила, что J/ψ-мезоны преимущественно образуются в сопровождении $\bar{c}c$-пары. Обсуждаются возможные механизмы образования J/ψ, оценивается вероятность образования $\bar{c}c$-пары. Выбор между этими механизмами может быть сделан путем измерения поляризации J/ψ. Предполагается, что в случае соударений тяжелых ионов можно ожидать значительную поперечную поляризацию J/ψ при образовании кварк-глюонной плазмы. Измерение асимметрии $e^+e^-(\mu^+\mu^-)$ углового распределения в распаде $J/\psi \to e^+e^-(\mu^+\mu^-)$ является полезным инструментом для поиска плазмы.

1. Recently, Belle Collaboration reported the measurement of J/ψ production in e^+e^- annihilation at $\sqrt{s} = 10.6$ GeV [1]. It was found that the cross section of J/ψ production significantly exceeds theoretical expectations based on the Color Singlet Model (CSM) [2] and nonrelativistic QCD (NRQCD) [3,4]. Even more surprisingly, it was found that most of the observed J/ψ's were accompanied by an extra $\bar{c}c$ pair, with $\sigma(e^+e^- \to J/\psi\bar{c}c)/\sigma(e^+e^- \to J/\psi X) = 0.59^{+0.15}_{-0.13} \pm 0.12$. This ratio exceeds the existing theoretical predictions by about an order of magnitude. The problem has recently attracted attention of many theorists (see, e.g., [5–12]).

Let us consider the diagrams of J/ψ production in e^+e^- annihilation. There are three types of such diagrams. In the diagrams of the first type (Fig. 1, *a*) J/ψ is formed by the fusion of $\bar{c}c$ pair produced by the initial virtual photon. This means that $\bar{c}c$ quarks, which initially were moving in the opposite directions, turn around and have almost equal and parallel momenta in the final state. The

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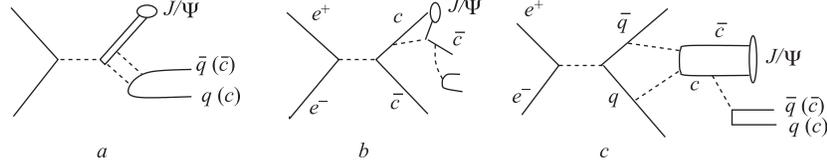
The production of J/ψ in e^+e^- annihilation

momentum conservation is ensured by the radiated gluons which may produce light ($q = u, d, s$) $\bar{q}q$ or charmed $\bar{c}c$ pairs. The diagrams of the second type (Fig. 1, *b*) correspond to the fragmentation of c (or $\bar{c}$) into J/ψ. This process requires the production of an additional $\bar{c}c$ pair by emission of at least one gluon by initial c or $\bar{c}$. Finally, the third type of processes is described by the diagrams in which the initial virtual photon creates a pair of light quarks and the J/ψ is formed from the $\bar{c}c$ pair produced by an exchange of gluons (Fig. 1, *c*). Evidently, the diagram of Fig. 1, *c* is suppressed in comparison to diagrams of Fig. 1, *a, b* by a factor of $\alpha_s(m_c)$ and will be disregarded in what follows.

On general grounds one may expect that the diagrams of Fig. 1, *b* dominate at very high energies of the colliding e^+e^-, when the ladder of $\bar{c}c$ pairs is formed and the process may be described by Regge theory (such a process was considered by Kaidalov [12]). It is easy to estimate the energies starting from which one may expect the dominance of the diagrams of Fig. 1, *b*. Let p_c be the momentum of the c-quark (in the e^+e^- c.m.s.) fragmenting into J/ψ. Then the minimal value of the recoil momentum q, corresponding to the forward production, is equal to

$$q \simeq \frac{M_{J/\psi}^2 - m_c^2}{2p_c}. \tag{1}$$

By requiring q to be at least as small as $q \simeq 0.5$ GeV (typical for Regge asymptotics), we get $p_c > 10$ GeV, i.e., $\sqrt{s} > 20$ GeV. In fact one may expect that the energy should be $\sqrt{s} > 50$ GeV.

Probably, the mechanism of Fig. 1, *b* cannot be the dominating one at $\sqrt{s} = 10.6$ GeV. The more suitable candidate for description of J/ψ production in e^+e^- annihilation at this energy is Fig. 1, *a* mechanism.

Belle Collaboration [1] measured the distribution of events as a function of the mass of the system recoiling against the J/ψ. The recoil mass was defined as

$$M_{\mathrm{recoil}} = \sqrt{(\sqrt{s} - E_{J/\psi}^*)^2 - p_{J/\psi}^{*2}}, \tag{2}$$

where $E_{J/\psi}^*$ and $p_{J/\psi}^*$ are the energy and momentum of J/ψ in the c.m. frame. It was found that M_{recoil} concentrates in the domain $M_{\mathrm{recoil}} \geqslant 5$ GeV, with almost no events below 2.8 GeV [3]. This invariant mass is sufficiently larger than the

threshold for the production of an additional $\bar{c}c$ pair. At such a large M_{recoil} one can expect, that the perturbative theory is valid in the production of additional to J/ψ hadrons and the mass of c quarks may be neglected. If all additional quarks are produced incoherently, then one would expect

$$R \equiv \frac{\sigma(J/\psi\bar{c}c)}{\sigma(J/\psi X)} \approx \frac{1}{4} \qquad (3)$$

for $X = \bar{c}c + \bar{q}q$, $(q = u, d, s)$. If they are produced coherently, then light quarks are in the $SU(3)$ singlet state $|X_{\text{light}}\rangle = |\bar{u}u + \bar{d}d + \bar{s}s\rangle\sqrt{3}$. Therefore, light and charm quarks should be produced in association with the J/ψ with equal probabilities, and we find

$$\sigma(e^+e^- \to J/\psi\ \bar{c}c)/\sigma(e^+e^- \to J/\psi\ X) = \frac{1}{2}. \qquad (4)$$

Probably, the true answer is somewhere between estimations (3) and (4).

In fragmentation mechanism (Fig. 1, *b*) we have evidently $R = 1$.

Let us now turn to the discussion of J/ψ polarization. Since the photon in e^+e^- annihilation is mostly transverse, it has helicity $\lambda = \pm 1$. Therefore the $\bar{c}c$ produced by the photon should have opposite helicities of $\lambda_c = +1/2, \lambda_{\bar{c}} = -1/2$ or $\lambda_c = -1/2, \lambda_{\bar{c}} = +1/2$. Initially, heavy quark and antiquark move in the opposite directions in the c.m.s. of e^+e^- annihilation with the velocities $v = \sqrt{1 - 4m_c^2/s}$ which are close to $v \simeq 1$ at $\sqrt{s} = 10.6$ GeV. However, to become bound in the J/ψ (or any other bound state of charmonium), at least one of the quarks has to change the direction of its momentum by radiating gluons (and extra quark–antiquark pair(s)) since the relative velocity of heavy quarks in a bound state should be small. Since in QCD the helicity of the quark is conserved, a change in the direction of its momentum should be accompanied by the spin flip. We thus come to the conclusion that in the case of J/ψ produced at high momentum, the total spin of J/ψ should have zero projection on its direction of motion, which corresponds to the longitudinal polarization.

This is in agreement with the experimental result of the BaBar Collaboration [13], which states that the angular distribution of positively charged lepton decay product with respect to the direction of J/ψ measured in the c.m. frame is $W(\theta) \sim 1 + \alpha \cos^2 \theta$ with $\alpha = -0.46 \pm 0.21$ for c.m. momentum $p^* < 3.5$ GeV, and $\alpha = -0.80 \pm 0.09$ for c.m. momentum $p^* > 3.5$ GeV. (In this distribution, $\alpha = -1$ corresponds to longitudinal polarization, $\alpha = +1$ to transverse, and $\alpha = 0$ indicates no polarization.)

As is clear from Fig. 1, *b* one of the c quarks has helicity, say, $\lambda = +1/2$; the helicity of the other quark created from the vacuum is uniformly distributed. Therefore the mean value of α is equal to zero (it is easy to see that the cases of $\alpha = +1$ and $\alpha = -1$ have equal probabilities), and the produced J/ψ is

unpolarized. The conclusion is that the precise measurement of J/ψ polarization can distinguish among two mentioned above production mechanisms.

2. 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 [14] 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 impossible the binding of heavy quarks into the bound states 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 [15] and NA50 Collaborations [16]. The results on J/ψ production at RHIC have recently been presented by the PHENIX Collaboration [17]. The observations of quarkonium suppression have been interpreted as a signal of quark–gluon plasma formation [18]. However, different conclusions were reached in [19], 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.

I would like to present here the idea: to use the polarization of J/ψ, produced in heavy-ion collisions for diagnostics of quark–gluon plasma.

Let me first formulate what I mean by the quark–gluon plasma, since different definitions sometimes may result in misunderstanding. I 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. It is no need to specify the properties of this state of matter in more detail to develop the idea.

It is well known that the description of the data on heavy quarkonium production within the framework of perturbative QCD (pQCD) meets with significant 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 [20], which allows certain nonperturbative physics, does not allow one to explain the polarization measurements [21].

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 Ref. 22 J/ψ-production cross section in πN interactions was calculated in perturbation theory. The contributions from various sources to the J/ψ production in $\pi^- N$ collisions at the incident energy of 185 and 300 GeV are shown in the Table (the data are from [23]).

	$\sigma(\chi_2)$, nb	$\dfrac{\sigma_{\mathrm{dir}}(J/\psi)}{\sigma(\chi_2 \to J/\psi)}$	$\dfrac{\sigma(\chi_1)}{\sigma(\chi_2)}$	$\sigma(J/\psi)$, nb			
				Dir.	$\chi_2 \to J/\psi\gamma$	$\chi_1 \to J/\psi\gamma$	Total
Exper.	$188 \pm 30 \pm 21$	$0.54 \pm 0.1 \pm 0.1$	0.70 ± 0.15	102	35	42	180
Theory	78	0.17	0.067	13.2	14.7	1.6	29.5

As is clear from the Table the perturbative calculations of J/ψ production in πN collisions disagree with the data by a factor of 6: the nonperturbative effects are dominant.

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

$$W(\theta) \sim 1 + \alpha \cos^2 \theta, \tag{5}$$

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. (5) is determined unambiguously (at small p_t): $\alpha = 1$ [24]. 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-mometum 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 has 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 [24]

$$\alpha \longrightarrow \alpha' = \alpha \frac{\left(1 - \frac{3}{2}\,\theta_0^2\right)}{1 + \alpha\,\theta_0^2/2},\tag{6}$$

where $\theta_0^2 \sim 4\langle p_t^2\rangle/M_\chi^2$. For $p_t \sim 1$ GeV, Eq. (6) 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 [22]. The results are $\alpha_{\rm dir} \simeq 0.25$ 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 $\alpha_{\rm dir}$ and α_{χ_1} begin to increase). After summing all channels of J/ψ production it was found [22] that $\alpha_{\rm tot}^{\rm pert} \simeq 0.5$. Experimentally [25], 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.

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 [14]). The nonperturbative effects should thus be absent (or small), and we are left only with the perturbative mechanism. Then, according to the third row of the Table, about one half of J/ψ's will be produced directly and another one half via $\chi_2 \to J/\psi + \gamma$. (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 $\chi_2 \to J/\psi + \gamma$ decay.) We thus expect that the asymmetry coefficient of the electron (muon) angular distribution in the $J/\psi \to e^+e^-(\mu^+\mu^-)$ 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

$$\alpha \simeq 0.35 \div 0.4.\tag{7}$$

In conclusion it is pointed out that in case of quark–gluon plasma formation in heavy-ion collisions, one may expect an essential increase of $J\psi$ polarization in comparison with that in hadronic collisions. Therefore, the measurement of electron (muon) angular asymmetry of $J/\psi \to e^+e^-(\mu^+\mu^-)$ decay is an effective tool of detection of quark–gluon plasma formation in heavy-ion collisions.

The content of this article is based on the papers by D. Kharzeev and myself [26, 27].

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