Exclusive Charmonium Decays: The $J/\psi\ (\psi') \to \rho\pi,\ K^*\bar{K}$ Puzzle

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We propose a coherent explanation of the puzzle associated with $J/\psi\ (\psi')$ decays into vector plus pseudoscalar exclusive final states by assuming the general validity of the perturbative QCD hadron-helicity theorem, but supplemented by violation of this theorem when J/ψ decay to hadrons is mediated by an intermediate gluonium state $\mathcal{O}$. The mass $\mathcal{O}$ must be within 100 MeV of the mass of the J/ψ, and its total width must be less than 160 MeV. Comments are made about vector-scalar decays of J/ψ to ϕS^* and $\rho\delta$.

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Crisply defined experimental puzzles in high-energy physics have always been of intense interest to theorists ever since the θ-τ puzzle of 1956 which led to the parity revolution. One such well-defined puzzle appears in the offing in the exclusive decays of J/ψ and $\psi' \to \rho\pi,\ K^*\bar{K}$, and possibly other vector-pseudoscalar combinations. One expects $J/\psi\ (\psi')$ to decay to hadrons via three gluons or, occasionally, via a single direct photon. In either case the decay proceeds via $|\Psi(0)|^2$, where $\Psi(0)$ is the wave function at the origin in the nonrelativistic quark model for $c\bar{c}$. Thus it is reasonable to expect on the basis of perturbative QCD that for any final hadronic state h, we have

$$Q_h \equiv \frac{B(\psi' \to h)}{B(J/\psi \to h)} \cong \frac{B(\psi' \to e^+e^-)}{B(J/\psi \to e^+e^-)} = 0.135 \pm 0.023. \qquad (1)$$

Usually this is true, as is well documented by the works of Franklin, Franklin *et al.*, Trilling, and Bloom[1] for $p\bar{p}\pi^0$, $2\pi^+2\pi^-\pi^0$, $\pi^+\pi^-\omega$, and $3\pi^+3\pi^-\pi^0$ hadronic channels. The startling exceptions occur[1] for $\rho\pi$ and $K^*\bar{K}$, where the present experimental limits[2] are

$$Q_{\rho\pi} < 0.0063, \quad Q_{K^*\bar{K}} < 0.0027. \qquad (2)$$

Is this suppression due in some manner to an intermediate gluonium state?[3,4] Is it the effect of spins, as hinted in perturbative QCD?[5] Is it the effect of the node in the ψ' wave function? Could a sequential-fragmentation model[6] explain this puzzle? Clearly further examples of differences between J/ψ and ψ' hadronic decays would be useful[7]; examples of differences in exclusive hadronic decays *within* J/ψ and *within* ψ' could also shed important insight.

In this Letter we propose a coherent explanation of the puzzle by assuming (a) the general validity of the perturbative QCD theorem[5] that total hadron helicity is conserved in high-momentum-transfer exclusive processes, but supplemented by (b) violation of the QCD theorem when the J/ψ decay to hadrons via three hard gluons is modulated by the gluons forming an intermediate gluonium state $\mathcal{O}$ before transition to hadrons. In essence the model of Hou and Soni[3,4] takes over in this latter stage.

Le us first recollect some salient features of the QCD theorem.[5] Since the vector state V has to be produced with helicity $\lambda = \pm 1$, the vector-pseudoscalar decays should be suppressed by a factor $1/s$ in the rate. The ψ' seems to respect this rule. The J/ψ does *not* and that is the mystery. Put in more quantitative terms, we expect on the basis of perturbative QCD[1,5]

$$Q_{\rho\pi} \equiv \frac{B(\psi' \to \rho\pi)}{B(J/\psi \to \rho\pi)} \sim \left[\frac{M_{J/\psi}}{M_{\psi'}}\right]^6 \qquad (3)$$

assuming that quark helicity is conserved in strong interactions. This includes a form-factor suppression proportional to $[M_{J/\psi}/M_{\psi'}]^4$. The suppression (3) is not large enough, though, to account for the data given by (2) which is over a factor of 20 smaller than the benchmark prediction given by Eq. (1). To account for current data, the exponent in (3) would have to be greater than 23 to explain it.

One can question the validity of the QCD helicity-conservation theorem at the charmonium mass scale. Helicity conservation has received important confirmation in $J/\psi \to p\bar{p}$, where the angular distribution is known experimentally to follow $1+\cos^2\theta$ rather than $\sin^2\theta$ for helicity flip. The helicity theorem also works[8] in $J/\psi \rightarrow \pi^0\omega^0$, where the three-gluon exchange is replaced by a highly virtual photon exchange $[\gamma(q^2), q^2 \gg 0]$ in this isospin-nonconserving process. The ψ' decays clearly respect hadron-helicity conservation. It is difficult to understand how the J/ψ could violate this rule since the J/ψ and ψ' masses are so close. Corrections from quark-mass terms, soft-gluon corrections, and finite-energy corrections would not be expected to lead to large J/ψ differences. It is hard to imagine anything other than a resonant or interference effect that could account for such dramatic energy dependence.

A relevant violation of the QCD theorem which does have significance to our problem is the recognition that the theorem is built on the underlying assumption of short-range "pointlike" interactions among the constituents throughout. For instance, $J/\psi(c\bar{c}) \rightarrow 3g$ has a short range $\cong 1/m_c$ associated with the short time scale of interaction. If, however, subsequently the three gluons were to resonate forming a gluonium state $\mathcal{O}$ which has large transverse size $\cong 1/M_H$ covering an extended (long) time period (see Fig. 1), then the theorem would be invalid. Note that even if the gluonium state $\mathcal{O}$ has large mass, close to $M_{J/\psi}$, its size could still be the standard hadronic scale of 1 fm, just as is the case for the D meson and B mesons.

We thus propose, following Hou and Soni,[3,4] that the enhancement of $J/\psi \rightarrow K^*\bar{K}$ and $J/\psi \rightarrow \rho\pi$ decay modes is caused by a quantum mechanical mixing of the J/ψ with a $J^{PC}=1^{--}$ vector gluonium state $\mathcal{O}$ which causes the breakdown of the QCD helicity theorem. The decay width for $J/\psi \rightarrow \rho\pi$ $(K^*\bar{K})$ via the sequence $J/\psi \rightarrow \mathcal{O} \rightarrow \rho\pi$ $(K^*\bar{K})$ must be substantially larger than the decay width for the (nonpole) continuum process $J/\psi \rightarrow 3$ gluons $\rightarrow \rho\pi$ $(K^*\bar{K})$. In the other channels (such as $p\bar{p}, p\bar{p}\pi^0, 2\pi^+2\pi^-\pi^0$, etc.), the branching ratios of the $\mathcal{O}$ must be so small that the continuum contribution governed by the QCD theorem dominates over that of the $\mathcal{O}$ pole. For the case of the ψ', the contribution of the $\mathcal{O}$ pole must always be inappreciable in comparison with the continuum process where the QCD theorem holds. The experimental limits on $Q_{\rho\pi}$ and $Q_{K_*\bar{K}}$ given by (2) are now substantially more stringent than when Hou and Soni[3] made their estimates of $M_{\mathcal{O}}$, $\Gamma_{\mathcal{O}\rightarrow\rho\pi}$, and $\Gamma_{\mathcal{O}\rightarrow K^*\bar{K}}$ back in 1982.

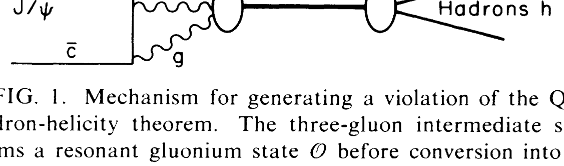

FIG. 1. Mechanism for generating a violation of the QCD hadron-helicity theorem. The three-gluon intermediate state forms a resonant gluonium state $\mathcal{O}$ before conversion into the final hadronic state h.

It is interesting, indeed, that the existence of such a gluonium state $\mathcal{O}$ was first postulated by Freund and Nambu[4] on the basis of Okubo-Zweig-Iizuka dynamics soon after the discovery of the J/ψ and ψ' mesons. In fact Freund and Nambu predicted that the $\mathcal{O}$ would decay copiously precisely into $\rho\pi$ and $K^*\bar{K}$ with severe suppression of decays into other modes like e^+e^- as required for the solution of the puzzle.

Final states h which can proceed only through the intermediate gluonium state satisfy the ratio

$$Q_h = \frac{B(\psi' \rightarrow e^+e^-)}{B(J/\psi \rightarrow e^+e^-)} \frac{(M_{J/\psi}-M_{\mathcal{O}})^2+\Gamma_{\mathcal{O}}^2/4}{(M_{\psi'}-M_{\mathcal{O}})^2+\Gamma_{\mathcal{O}}^2/4}. \tag{4}$$

We have assumed that the coupling of the J/ψ and ψ' to the gluonium state scales as the e^+e^- coupling. The value of Q_h is small if the $\mathcal{O}$ is close in mass to the J/ψ. Thus we require

$$(M_{J/\psi}-M_{\mathcal{O}})^2+\tfrac{1}{4}\Gamma_{\mathcal{O}}^2 \lesssim 2.6 Q_h \text{ GeV}^2.$$

The experimental limit (2) for $Q_{K^*\bar{K}}$ then implies

$$[(M_{J/\psi}-M_{\mathcal{O}})^2+\tfrac{1}{4}\Gamma_{\mathcal{O}}^2]^{1/2} \lesssim 80 \text{ MeV}. \tag{5}$$

This implies $|M_{J/\psi}-M_{\mathcal{O}}| < 80$ MeV and $\Gamma_{\mathcal{O}} < 160$ MeV. Typical allowed values compatible with (5) are

$$M_{\mathcal{O}} = 3.0 \text{ GeV}, \quad \Gamma_{\mathcal{O}} = 140 \text{ MeV}$$

or

$$M_{\mathcal{O}} = 3.15 \text{ GeV}, \quad \Gamma_{\mathcal{O}} = 140 \text{ MeV}.$$

Notice that the gluonium state could be either lighter or heavier than the J/ψ. The branching ratio of the $\mathcal{O}$ into a given channel must exceed that of the J/ψ.

It is not necessarily obvious that a $J^{PC}=1^{--}$ gluonium state with these parameters would necessarily have been found in experiments to date. One must remember that though $\mathcal{O} \rightarrow \rho\pi$ and $\mathcal{O} \rightarrow K^*\bar{K}$ are important modes of decay, at a mass of order 3.1 GeV many other modes (albeit less important) are available. Hence a total width $\Gamma_{\mathcal{O}} \cong 100-150$ MeV is quite conceivable while satisfying the constraint (5). Because of the proximity of $M_{\mathcal{O}}$ to $M_{J/\psi}$, the most important signatures for an $\mathcal{O}$ search via exclusive modes $J/\psi \rightarrow K^*\bar{K}h$, $J/\psi \rightarrow \rho\pi h$, $h=\pi\pi, \eta, \eta'$, are no longer available by phase-space considerations. However, the search could still be carried out by use of $\psi' \rightarrow K^*\bar{K}h$, $\psi' \rightarrow \rho\pi h$, with $h=\pi\pi$ and η. As already pointed out,[3] another way to search for $\mathcal{O}$ in particular, and the three-gluon bound states in general, is via the inclusive reaction $\psi' \rightarrow (\pi\pi)+X$, where the $\pi\pi$ pair is an isosinglet. The three-gluon bound states such as $\mathcal{O}$ should show up as peaks in the missing mass (i.e., mass of X) distribution.

Perhaps the most direct way to search for the $\mathcal{O}$ is to scan $\bar{p}p$ or e^+e^- annihilation at $\sqrt{s}$ within $\simeq 100$ MeV of the J/ψ, triggering on vector/pseudoscalar decays such as $\pi\rho$ or $\bar{K}K^*$.

The data from the Mark III collaboration[9] which show the J/ψ decaying to ϕS^* but not to $\rho\delta$ are especially intriguing. Note that these are vector-scalar final-state decays of the same parent J/ψ. Freund and Nambu[4] have allowed for the possibility that the $\mathcal{O}$ meson might have strengthened decay into vector-scalar combinations such as $\omega\epsilon$ through violation of the Okubo-Zweig-Iizuka rule due to mixing of the SU(3)-singlet vector meson $\mathcal{O}$ with ω, ϕ, and J/ψ mesons (including their radial excitations and daughter members at higher mass). Hence $\mathcal{O}$-ϕ transitions can be important, but of course $\mathcal{O}$-ρ transitions would be forbidden by isospin conservation. Perhaps this is part of the explanation for the suppression of $\rho\delta$ decay over ϕS^* decay from J/ψ. Clearly more experimental information concerning the nature and degree of this suppression will be most interesting.

The fact that the $\rho\pi$ and $K^*\bar{K}$ channels are strongly suppressed in ψ' decays but not in J/ψ decays clearly implies dynamics beyond the standard charmonium analysis. As we have shown, the hypothesis of a three-gluon state $\mathcal{O}$ with mass within $\cong 100$ MeV of the J/ψ mass provides a natural, perhaps even compelling, explanation of this anomaly. If this description is correct, then the ψ' and J/ψ hadronic decays are not only confirming hadron-helicity conservation (at the ψ' momentum scale) but are also providing a signal for bound gluonic matter in QCD.

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