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New Challenges in Charmonium Physics

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Abstract

The puzzle of the absence of VP modes $\psi \to \rho\pi, K^*\bar{K} + c.c.$, is now extended to the VT mode $\psi' \to \omega^0 f_2(1270)$ from the recent BES run. This poses additional challenge to phenomenological theory. We study the new situation in terms of the Hadron Helicity Conservation (HHC) theorem and the postulated existence of a trigluonia Omicron $\mathcal{O}[I = 0, J^{PC} = 1^{--}]$.

Exciting news have emanated from the BES Collaboration[1] in recent months which pose new challenges in charmonium physics for theoretical understanding. In particular the hadronic decays $\psi(2S)(\psi') \to \omega^0\pi^+\pi^-$, $b_1^\pm(1230)\pi^\mp$, and $\omega^0 f_2(1270)$ have been measured in a sample of 1.27×10^6 produced $\psi(2S)$ at the BEPC e^+e^- Collider. Measurements of their branching fractions suggest that while $\psi(2S) \to b_1^\pm\pi^\mp$ obeys the "14%" rule (elucidated below) predicted by perturbative QCD (PQCD) theory, $\psi(2S) \to \omega^0 f_2$ is suppressed compared with the corresponding J/ψ decay. As a vector-tensor pair combination, the $\omega^0 f_2$ mode is the first example of a non-vector-pseudoscalar decay of charmonium which violates the above mentioned rule.

The "14%" rule is the statement that it is reasonable to expect on the basis of perturbative QCD that for any final hadronic state h, we have

$$Q_h \equiv \frac{B(\psi' \to h)}{B(J/\psi \to h)} \cong \frac{B(\psi' \to e^+e^-)}{B(J/\psi \to e^+e^-)} = (14 \pm 2)\% \qquad (1)$$

Usually this is true, and indeed is well documented[2, 3] for $h = p\bar{p}\pi^0, 2\pi^+2\pi^-\pi^0, 2(\pi^+\pi^-), \pi^+\pi^-p\bar{p}$, and $3\pi^+3\pi^-\pi^0$. Note the recent BES measurement[1] of $\psi' \to b_1^\pm(1230)\pi^\mp$ branching ratio of $(3.0 \pm 1.0 \pm 0.8) \times 10^{-4}$ taken in conjunction with that for $J/\psi \to b_1\pi$ of $(3.0 \pm 0.5) \times 10^{-3}$ from PDG[3], gives for $Q_h = 10\%$ and hence quite compatible with (1), within errors.

The charmonium hadronic puzzle in the past[2] has been centered on the astonishing absence of the vector-pseudoscalar (V-P) decays $\rho\pi, K^*\bar{K}$ of ψ' where[5] $Q_{\rho\pi} < 0.0048, Q_{K^{+*}K^{-}+c.c} < 0.0036$. Clearly the puzzle now extends beyond the (V-P) decays with the recent measurement by BES[1] that $B(\psi' \to \omega^0 f_2(1270)) < 1.1 \times 10^{-4}$ (90% C.L.) while PDG[3] for $B(J/\psi \to \omega^0 f_2(1270)) = (4.3 \pm 0.6) \times 10^{-3}$ quite a respectable value. Taking the central values above, we have

$$Q_{\omega^0 f_2} < 2.6\% \qquad (2)$$

This seems a clear violation of the "14%" rule (1), hence the charmonium puzzle manifestly extends beyond the vector-pseudoscalar decay hitherto known to include at least the vector-tensor (V-T) case as well.

In seeking a coherent explanation of the (V-P) case for $J/\psi(\psi') \to \rho\pi, K^*\bar{K}$ puzzle, one proposed solution[2] is to assume (a) the general validity of the perturbative QCD theorem[4] that total hadron helicity is conserved (HHC) 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 Omicron $\mathcal{O}$ before transition to hadrons. Such an $\mathcal{O}$ with $J^{PC} = 1^{--}$ needs to be nearly degenerate with J/ψ to explain the existing upper bounds on $Q_{\rho\pi}$ and Q_{K^*K}.

Hence in any attempt to incorporate the vector-tensor case for $J/\psi(\psi') \to \omega^0 f_2$ into the same framework of discussion as for the vector-pseudoscalar channels, we need to examine again these hypotheses (a) and (b).

Concerning (a), the suppression of $J/\psi(\psi') \to \rho\pi, K^*\bar{K}$ and other V-P channels in $e^+e^- \to J/\psi(\psi') \to \pi\rho, \bar{K}K^*$ etc. occurs[4] because the $\psi - \pi - \rho$ can couple through only a single form factor- $\epsilon^{\mu\nu\tau\rho}\epsilon_\mu^{(\psi)}\epsilon_\nu^{(\rho)}p_\tau^{(\pi)}p_\sigma^{(\rho)}\ F_{\pi\rho}(s)$ - and this requires $|\ \lambda_\rho\ | = 1$ in e^+e^- collision (note for $\lambda_\rho = 0$ longitudinal component $\epsilon_\nu^{(\rho)} \propto p_\nu^{(\rho)}$ and hence the amplitude vanishes). Here ψ denotes generically either J/ψ or ψ'. Hadronic-helicity conservation requires $\lambda = 0$ for mesons, and thus these amplitudes are suppressed in QCD. For the vector-tensor (V-T) channel $\psi \to \omega^0 f_2(1270)$, the analogous interaction form is

$$\epsilon_\mu^{(\psi)}(p)\ \epsilon_\nu^{(\omega)}\ S_{\mu\nu}^{(f_2)}\ (p') \tag{3}$$

where the longitudinal $\lambda_\omega = 0$ contribution is obtained by setting $\epsilon_\nu^{(\omega)} \to q_\nu^{(\omega)} = (p - p')_\nu$, and Eq. (3) is of form $\epsilon_\mu^{(\psi)}(p)(p-p')_\nu^{(\omega)}S_{\mu\nu}^{(f_2)}(p')$ which in general does not vanish. Hence $\psi \to \omega^0 f_2(1270)$ is <u>allowed</u> by (HHC) and PQCD. We expect that in the absence of a theoretical principle for suppression (e.g. HHC violation), $J/\psi(\psi')$ decay branching ratios should follow the "14%" rule, viz:-

$$Q_{\omega^0 f_2}\ \sim 14\% \tag{4}$$

This is clearly not consistent with the recent BES findings given by Eq. (2).

Irrespective of hypothesis (a), the existence of an Omicron nearly degenerate with J/ψ to account for the substantial[3] $B(J/\psi \to \rho\pi) = (1.28 \pm 0.10) \times 10^{-2}$, $B(J/\psi \to K^+\bar{K}^* + c.c.) = (5.0 \pm 0.4) \times 10^{-3}$, and $B(J/\psi \to K^0\bar{K}^{*0} + c.c.) = (4.2 \pm 0.4) \times 10^{-3}$ in hypothesis (b) is now questionable. For instance the $\rho\pi$ channel has been carefully scanned across the J/ψ region in e^+e^- annihilation at BEPC (Beijing Electron-Positron Collider), but no hints of trigluonia $\mathcal{O}$ are found[5]. Though the $\sqrt{OZI}$ suppression of the glueball decay rule[6], which suggests the (total) width of a trigluonium to be in between the one for a light quark state with a mass around 3 GeV/c^2 and the J/ψ one: namely,

$$\Gamma_{\mathcal{O}} \approx \sqrt{\Gamma_{J/\psi}\ 500\ MeV}\ \approx 7\ MeV, \tag{5}$$

even such a minimal width prediction for the Omicron is likely to be stringently tested by the ongoing BES Collaboration determination of (upper limit on) $\Gamma_{\mathcal{O}}$ width through study of $\psi' \to \pi^+\pi^-\mathcal{O} \to \pi^+\pi^-(\rho\pi)$. Note Anselmino et al.[7] have suggested that an acceptable scenario for implementing assumptions (a) and (b) as solution to the charmonium puzzle[2] is for <u>larger</u> $\Gamma_{\mathcal{O}\to VP}$ and $\Gamma_{\mathcal{O}}$ *s.t.*

$$\Gamma_{\mathcal{O}\to VP} \approx \frac{1}{10}\Gamma_{\mathcal{O}} \approx (1-10)\ MeV. \tag{6}$$

Of course for the VT case where $\psi \to \omega^0 f_2$ <u>satisfies</u> HHC, the existence of the $\mathcal{O}$ [for instance to "explain" $B(J/\psi \to \omega^0 f_2(1270) = (4.3 \pm 0.6) \times 10^{-3}]$ is in any case a moot point. To summarize, suppression of $\psi' \to \rho\pi, K^*\bar{K}$ in V-P channels and $\psi' \to \omega^0 f_2$ in V-T channel remains an open problem for theorists.

Remarks

(i) There is general belief in the validity of QCD for $J/\psi(\psi') \to 3g$ leg. However the details of handling this $c\bar{c} \to 3g$ leg involve additional assumptions. For instance in the hadron helicity conservation theorem of Brodsky and Lepage[2, 4], the underlying assumption of short-range "point like" interaction among the constituents is made throughout. For instance, $J/\psi(c\bar{c}) \to 3g$ and $\psi'(c\bar{c}) \to 3g$ have a short range $\cong 1/m_c$ associated with the short time scale of interaction. However it is entirely possible that the $3g \to h$ leg is governed by the QCD parameter $1/\Lambda_{MS}$ and thus relatively long-ranged[8]. Hence details of the not well known hadronization process $3g \to h$ could have significance towards the understanding of the charmonium puzzle. Also as a test of the QCD picture of charmonium decays, Mark Wise[9] suggested the precise measurement of the inclusive ratio.

$$B(\psi' \to 3g)\ /\ B(J/\psi) \to 3g). \tag{7}$$

Using current PDG values, (7) is about 0.22, and some 1.5σ deviation from the ratio $B(\psi' \to \mu^+\mu^-)/B(J/\psi \to \mu^+\mu^-)$ though the error is big[10]. Clearly new measurements are needed here.

(ii) If however perturbative QCD and HHC are applicable to ψ decays, then the decay angular distributions for $J/\psi(\psi') \to \omega^0 f_2$ as hadron helicity conserving decays should have the usual $\sin^2\theta$ distribution. The general argument is given by Brodsky-Lepage[4], but it is instructive[11] to see this result for VT case emerge in an elementary way as follows: From e^+e^- the virtual photon γ and $J/\psi(\psi')$ have $J_z = 1$ along e^+e^- direction. HHC requires $S_z = 0$ for the $q\bar{q}$ in each decay meson. If these mesons decay along the the $z-$direction then the ω^0 can have $J_z = S_z = 0$ [note for ω^0 with $L = 0$, $L_z = 0$ is a necessity] and the $f_2(q\bar{q}$ with $L = 1)$ can have $J_z = L_z = 1$ with $S_z = 0$. However the transverse space wavefunctions for $L_z = 1$ vanishes at the origin, so this amplitude will vanish for small sources (where "small source" refers to the idea that source of 3g which hadronizes to h, has annihilation scale $\sim 1/m_c$ for charmonium decay rather than the typical hadronic size $\sim 1/\Lambda_{MS}$). It is clearly of critical importance for the helicity theorem[4] to measure the angular distribution of $J/\psi(\psi') \to \omega^0 f_2$ (1270) and confirm whether the PQCD prediction of $\sin^2\theta$ is valid. One can also measure the polarization of ω^0 through its leptonic decay. It should have $J_z = 0$ since as shown above ω^0 has $J_z = 0$ in z-direction, i.e. longitudinal polarization. Note the above argument does not apply to photon-tensor final states, e.g. $J/\psi(\psi') \to \gamma f_2(1270)$. The photon can couple directly to the light q or charm c quarks in the $\gamma + f_2(1270)$ decay, thus HHC does not involve the photon.

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