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Hadronic Decay Puzzle in Charmonium Physics [1]

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Abstract

The status of the postulated existence of a trigluonia Omicron $\mathcal{O}[I = 0, J^{PC} = 1^{--}]$ as solution to the charmonium puzzle (absence of VP decay modes of ψ') is reviewed. Recent BES data has extended the puzzle to include the vector-tensor VT case of $\psi' \to \omega^o f_2(1270)$. The puzzle actually stimulated the discovery of the ZHAO Theorem which appears to be highly relevant to $\eta_c'(3600)$ search in ψ' dataset and future $p\bar{p}$ annihilation search for such a state.

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I will present this lecture by first outlining the situation with respect to the existence of a trigluonia (3g) state with the quantum numbers $I = 0$, and $J^{PC} = 1^{--}$ which we shall denote by $\mathcal{O}$ for Omicron. There is a large body of theoretical predictions during the 1984-1990 period[1] which predict the $\mathcal{O}(1^{--})$ at mass 2.4 to 2.5 GeV. However more recently there is a comprehensive lattice study of SU(3) glueballs by a British Collaboration[2] which places the $\mathcal{O}(1^{--})$ at 4 GeV! Hence S. J. Brodsky[3] was led to remark in the autumn of 1993 that "clearly the mass of the gluonium state has not been predicted definitely by lattice gauge theory, but having such a 1^{--} in the 3 GeV region seems reasonable". Indeed there is a body of theoretical literature[4] supporting this. Hence a preliminary conclusion one might draw, could well be that British pessimism aside, the ψ' group at BES (Beijing Electron Spectrometer) is in an unique position to search for the Omicron $\mathcal{O}(1^{--})$ glueball, scanning the complete mass range from 2.4 - 3.3 GeV - if theory gives correct outline!

For an $\mathcal{O}$ at say 2.4 GeV, Hou and Soni[1] have pointed out that such a state has the following distinguishing features: (a) Its mixing with quarkonia states is small of order $0(\alpha_s^3)$ to $0(\alpha_s^2)$ for those between quarkonia states; (b) the Omicron $\mathcal{O} \to e^+e^-$ decay width is of order 0.3 eV (hence very small) leading to a $BR(\mathcal{O} \to e^+e^-) \sim 10^{-8}$; (c) the cross section for $e^+e^- \to \gamma^* \to \mathcal{O}$ is of order or smaller than 20 pb, hence exceedingly small compared with the corresponding production of a quarkonium state. Thus interpretation of this gluonium 1^{--} state is likely to be far less difficult than that of $J^{PC} = 0^{\mp+}, 2^{++}$ glueball candidates, e.g. the $\eta(1440)[\iota(1440)]$ and the $f_o(1710)[\Theta(1690)]$.

Search Method. For the range of mass values 2.4 $GeV < M_{\mathcal{O}} <$ 2.7 GeV, there is enough phase space for $\mathcal{O}$ to be found from

$$J/\psi \to \pi^+\pi^-\mathcal{O}(\to \rho\pi) \tag{1}$$

though such a process might be inhibited if $\mathcal{O}$ is just a radially excited quarkonium state rather than the postulated Omicron. For the ψ' dataset, phase space allows the full range 2.4 $GeV < M_{\mathcal{O}} <$ 3.3 GeV to be explored from

$$\psi' \to \pi^+\pi^-\mathcal{O}(\to \rho\pi). \tag{2}$$

When $\mathcal{O}$ has been found, the following indirect tests of its properties can be applied. First, it is not being "produced" directly in e^+e^- annihilation; second, it seems "not to have" decay mode e^+e^-. With enough statistics we could do a spin-parity analysis to reassure us that $\mathcal{O}$ is indeed $J^{PC} = 1^{--}$, with no $(\rho\pi)^{\pm}-$ members - hence $I = 0$.

OMICRON AND SUPPRESSION OF $\psi' \to \rho\pi, K^*\bar{K}$ PUZZLE

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

$$Q_h = \frac{B(\psi' \to h)}{B(J/\psi \to h)} \cong \frac{B(\psi' \to e^+e^-)}{B(J/\psi \to e^+e^-)} = (14 \pm 2)\% \tag{3}$$

Usually this is true, and indeed is well documented[5] for $h = p\bar{p}\pi^o, 2\pi^+2\pi^-\pi^o, \pi^+\pi^-\omega^o, 3\pi^+3\pi^-\pi^o$. However there is an astonishing absence of the vector-pseudoscalar VP decays $\rho\pi, K^*\bar{K}$ of ψ' where the present experimental limits for $\rho\pi$[6] and $K^*\bar{K}$ + c.c.[7] are

$$Q_{\rho\pi} < 0.0048, \;\; Q_{K^+K^-} + c.c. < 0.0036 \tag{4}$$

This strange behavior of ψ' for VP decay modes, is not followed by the corresponding decays of J/ψ where very respectable, unsuppressed branching ratios are seen, to wit[7]

$$\begin{aligned} BR(J/\psi \to \rho\pi) &= (1.28 \pm 0.10) \times 10^{-2} \\ BR(J/\psi \to K^*\bar{K}) &= (3.8 \pm 0.7) \times 10^{-3} \end{aligned} \tag{5}$$

and the anomaly here has since become known as the hadronic decay puzzle of charmonium physics.

In seeking a coherent explanation of the VP case for $J/\psi(\psi') \to \rho\pi, K^*\bar{K}$ puzzle, one proposed solution[5] is to assume (i) the general validity of the perturbative QCD theorem[8] that total hadron helicity is conserved (for short HHC) in high-momentum-transfer exclusive processes, but supplemented by (ii) 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 $\mathcal{O}$ of large transverse size, before transition to hadrons. Such an $\mathcal{O}$ with $J^{PC} = 1^{--}$ needs to be nearly degenerate with J/ψ to satisfy Eqs. (4) and (5). Back in 1987, Brodsky, Lepage, and I[5] found that we need the constraints

$$| \, M_{\mathcal{O}} - M_{J/\psi} \, | \; < \; 80 \; MeV, \; \Gamma_{tot}(\mathcal{O}) \; < \; 160 \; MeV \tag{6}$$

though a somewhat smaller width

$$\Gamma_{\mathcal{O}\to VP} \approx \frac{1}{10}\Gamma_{\mathcal{O}} \approx (1 - 10) \; MeV \tag{7}$$

has been suggested more recently by Anselmino et al.[9].

There are a number of problems associated with the B-L-T[5] solution towards understanding the hadronic puzzle of charmonium. First, an $\mathcal{O}$ at 3 GeV must have small mixing with J/ψ. Using the Hou-Soni model [10], the width $\Gamma(\mathcal{O} \to \rho\pi) \sim 22.2\ MeV$ when extrapolated to an $M_{\mathcal{O}}$ mass of order say 3.02 GeV. This corresponds to a mixing angle $\sin^2\theta \sim$ a few times $10^{-4} - 10^{-5}$ [11]. Furthermore, why should $\mathcal{O} \to VP$ dominate over other channels? After all an $\mathcal{O}$ at 3 GeV (unlike the ω^o say) has many decay channels. Let us remember that the original Freund-Nambu model[12] for $\mathcal{O} \to \rho\pi, K^*\bar{K}$ dominance, is probably outdated since the $\mathcal{O}$ is not at the relatively low mass 1.4 - 1.8 GeV but need to be at high mass 3 GeV to be relevant to the puzzle. Second, there is the mystery of the $J/\psi \to \omega^o\pi^o$ mode. This is expected to proceed via $J/\psi(c\bar{c}) \to \gamma^*(q^2) \to$ VP combination of h where γ^* is highly virtual with $q^2 >> 0$, and experimentally we have[7]

$$\Gamma(J/\psi \to \omega\pi^o) > 3\Gamma(J/\psi \to \pi^+\pi^-) \tag{8a}$$

$$BR(J/\psi \to \omega\pi^o) \sim (4-5)\times 10^{-4}. \tag{8b}$$

Here the $\mathcal{O}$ is not involved in the VP final state since this is an $I = 1$ electromagnetic transition. A contrived solution might consider replacing the Omicron by $q\bar{q}g$ states with both $I = 1$ and $I = 0$ components at the J/ψ mass scale or $qq\bar{g}$ for $I = 1$, and $\mathcal{O} \to ggg$ for $I = 0$ (which is even more contrived!). It is possible of course that HHC theorem[8] is not applicable at either J/ψ or ψ' mass scale, in which case the "14%" rule (3) would give us from (8b) that

$$BR(\psi' \to \omega\pi^o) \sim (0.56 - 0.70)\times 10^{-4} \tag{9}$$

which should be measured. As a third point, the schematic B-L-T diagram[5] for $e^+e^- \to J/\psi \to O \to \rho\pi$ can be regarded as a product of Breit-Wigner amplitudes[3]. For instance Brodsky[13] pointed out that the appropriate diagrams will involve the following chains:-

$$e^+e^- \to \gamma^* \to J/\psi(c\bar{c}) \to 3g \to \rho\pi \tag{10a}$$

$$e^+e^- \to \gamma^* \to J/\psi(c\bar{c}) \to 3g \to \mathcal{O} \to \rho\pi. \tag{10b}$$

But Hou and Soni[1] have shown that e^+e^- production of gluonium $\mathcal{O}$ (by whatever means) is minuscule, hence amplitude diagram (10b) is likely to be negligible. Experimentally there is no sign of distortion of $J/\psi \to \rho\pi$ shape in (10a) due to Breit-Wigner interference[6] either.

An interesting theoretical question has been raised by Zhao[14], namely the mixing angle should be proportional to

$$\alpha_s^3 \mid \Psi(0) \mid /[M_{J/\psi} - M_{\mathcal{O}}],$$

but what happens when $M_{J/\psi} \sim M_{\mathcal{O}}$. Could there be substantial mixing? In the fall of 1993 I was encouraging Zhao, perhaps in collaboration with Hou, to look into this case.

To summarize, if nearly degenerate "$\mathcal{O}$" is component of J/ψ decaying into $\rho\pi, K^*\bar{K}$,....., then

$$\mid J/\psi > = \cos\theta \mid c\bar{c}, 1S > + \sin\theta \mid \mathcal{O} > \tag{11}$$

$$\Gamma(J/\psi \to \rho\pi) = \sin^2\theta\Gamma(\mathcal{O} \to \rho\pi) = (1.1 \pm 0.1)\ KeV.$$

Hence if "$\mathcal{O}$" has normal hadronic width $\Gamma(\mathcal{O} \to \rho\pi) \sim 22.2\ MeV$ as in the Hou-Soni model[10], then $\sin^2\theta = 5 \times 10^{-5}$ and $BR(\psi' \to \pi\pi\mathcal{O}) = 10^{-4} - 10^{-5}$. Thus folding in the efficiency for a non crystal calorimeter type detector, it remains marginal for BEPC/BES to find $\mathcal{O}$ from say 10^6 ψ' dataset. This result remains valid even if $M_{\mathcal{O}} \sim 2.4 - 2.5\ GeV$ as suggested by some authors[1, 10]. Here there is no sharp resonance with $J^{PC} = 0^{++}$ which couples to both $\pi\pi$ and gg below 1.5 GeV. For instance neither the $f_o(975)$ nor the $f_o(1300)$ have been observed in J/ψ radiative decay in the $\pi\pi$ channel. Thus in $\psi' \to \pi\pi J/\psi$ and $\psi' \to \pi\pi\mathcal{O}$ (via $\mathcal{O}-J/\psi$ mixing), the two pions probably come from the two gluon continuum, and therefore the smooth phase space enhancement should not be larger than say a factor of 10 - even for an $\mathcal{O}$ mass of 2.4 GeV. The conclusion we draw, from phenomenological type theoretical considerations, would not particularly favor a search for trigluonia $\mathcal{O}$ throughout the accessible range 2.4 - 3.3 GeV at BES.

However high energy physics is an experimental science, and we should not depend excessively on theorists (T. D. Lee remarked back in 1966 that 50% of theoretical physics is emotion[15]). I would therefore recommend that just go ahead and measure $\psi' \to \pi^+\pi^-\mathcal{O}(\to \rho\pi)$ for $\mathcal{O}$ in the whole range $2.4 < M_{\mathcal{O}} < 3.3\ GeV$. Good luck!

Remark. We have been accustomed to think of glueball widths as fairly large[16], as depicted in Eqs. (6) and (7). However historically, Robson[17] had suggested the $(OZI)^{1/2}$ suppression of glueball decay rule, where for the Omicron $\mathcal{O}$ we have

$$\Gamma_{\mathcal{O}} \approx \sqrt{\Gamma_{J/\psi} \times 500\ MeV} \approx 7\ MeV \tag{12}$$

and 500 MeV is the suggested width[9] for a normal light quark state with mass $\sim 3\ GeV/c^2$. The value (12) could still be consistent with existing BES limits, but will be stringently tested by the ongoing BES collaboration determination of (upper limit) $\Gamma_{\mathcal{O}}$ width through study of $\psi' \to \pi^+\pi^-\mathcal{O} \to \pi^+\pi^-(\rho\pi)$. However a total $\Gamma_{\mathcal{O}}$ width given by (12) would not be in good agreement with the expectations given by (6) and (7) for solution of the charmonium puzzle.

EXCITING NEWS FROM BES

This second part of the talk will concentrate on exciting news which have emanated from the BES collaboration [18], and communicated to me by my Chinese host at IHEP-Beijing (during my fall, 1993 sabbatical), Professor Yifan Gu, and cover the situation up to August 4 (1994). The new data pose new challenges in charmonium physics for theoretical understanding. In particular the hadronic decays $\psi(2S)[\psi'] \to \omega^o\pi^+\pi^-$, $b_1^{\pm}(1230)\pi^{\mp}$, and to the vector-tensor VT combination $\omega^o f_2(1270)$ have been measured in a data sample of 1.27×10^6 produced $\psi(2S)$ at the BEPC $e^+ - e^-$ collider. The branching ratio $BR(\psi' \to b_1^{\pm}(1230)\pi^{\mp}) = (3.0 \pm 0.7 \pm 0.7) \times 10^{-4}$ when combined with PDG value[7] for $BR(J/\psi \to b_1^{\pm}(1230)\pi^{\mp}) = (3.0 \pm 0.5) \times 10^{-3}$ give for the ratio $Q_{b_1\pi} \sim 10\%$ and hence within errors consistent with the "14%" rule (3). Note for this axial vector-pseudoscalar decay, there is conservation of the HHC theorem [8] and thus consistency with (3) is not surprising.

The big surprise is that BES[18] measured that $BR(\psi' \to \omega^o f_2(1270)) < 9.2\times10^{-5}(90\%\ C.L.)$, which when combined with PDG[7] value for the corresponding J/ψ case where $BR(J/\psi \to \omega^o f_2(1270)) = (4.3 \pm 0.6) \times 10^{-3}$ yield for $Q_{\omega^o f_2}$ (taking central values) that

$$Q_{\omega^o f_2(1270)} < 2.1\% \tag{13}$$

and there is a definite violation of Eq. (3). As a vector-tensor VT pair, the $\omega^o f_2$ mode is the first example of a non vector-pseudoscalar VP decay of charmonium which violates the "14%" rule (3). Hence the puzzle extends beyond the vector-pseudoscalar domain.

We might first ask as I did, why not check out the case $BR(\psi' \to \phi f_2)$ and $BR(J/\psi \to \phi f_2)$ where $\phi \to K^+K^-$ and $f_2(1270) \to \pi^+\pi^-$ are particularly good signatures for BES with all charged particles in the final leg? However in terms of OZI language[19], the decay $J/\psi \to \omega^o f_2(1270)$ is singly disconnected in the sense that $J/\psi(c\bar{c}) \to q\bar{q}(\text{with } q = u, d) \leftrightarrow \omega^* \to \omega^o f_2$ where ω^* denotes some excited $q\bar{q}$ state with the quantum numbers of the ω, but not necessarily a resonance, and this state decays by a normal OZI-allowed decay into $\omega^o f_2$. The decay $J/\psi \to \phi f_2(1270)$ is however doubly disconnected where the $3g \to s\bar{s} \to \phi$ creates only the ϕ; there is another disconnected piece needed in the diagram to create the f_2 from gluons. Hence study of $J/\psi(\psi') \to \phi f_2$ as another example of VT decay need possibly to await a future τ-charm factory, because of the much attenuated rates through being doubly-disconnected OZI processes. Note the current upper limit[7] for $J/\psi \to \phi f_2(1270)$ is $BR(J/\psi \to \phi f_2) < 3.7 \times 10^{-4}$, when contrasted with the singly-disconnected OZI process $J/\psi \to \omega^o f_2$ where a hefty $BR(J/\psi \to \omega^o f_2(1270)) = (4.3 \pm 0.6) \times 10^{-3}$ is observed[7].

The first obvious theoretical check is whether the VT decay of charmonium does or does not satisfy the Brodsky-Lepage[8] helicity theorem. Analogous to the constructions given in[8] for the VP case, we will have for the $\psi \to \omega^o f_2(1270)$ amplitude interaction form $(1^- \to 1^- 2^+)$

$$\epsilon_\mu^{(\psi)}(p)\epsilon_\nu^{(\omega)}(q)S_{\mu\nu}^{(f_2)}(p') \tag{14}$$

where ψ is generic for either J/ψ or ψ' and $q = p - p'$ the momentum transfer. For longitudinal component $\lambda_\omega = 0$, we substitute $\epsilon_\nu^{(\omega)}(q) \to q_\nu^{(\omega)} = (p - p')_\nu$ leading to the expression $\epsilon_\mu^{(\psi)}(p)(p-p')_\nu^{(\omega)} S_{\mu\nu}^{(f_2)}(p')$ which in general <u>does not vanish</u>. Hence $\psi \to \omega^o f_2(1270)$ is <u>allowed</u> by HHC and PQCD for both J/ψ and ψ'. We thus expect, 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:-

$$Q_{\omega^o f_2} \sim 14\%. \tag{15}$$

This is clearly not consistent with the recent BES findings given by (13). Hence suppression of $\psi' \to \omega^o f_2(1270)$ is in need of a new theoretical explanation.

There is a bonus in the study of the charmonium puzzle through the Omicron $\mathcal{O}$ gluonium approach, irrespective of whether such a trigluonia indeed solves the puzzle. For instance Anselmino et al.[20] <u>assume</u>, in order to suppress $\eta_c' \to \rho\rho, K^*\bar{K}^*, \phi\phi, p\bar{p}$, and $\omega\omega$ according to the Brodsky-Lepage helicity theorem[8], that for h an unforbidden hadronic channel

$$\frac{BR(\eta_c' \to h)}{BR(\eta_c \to h)} \sim \frac{BR(\psi' \to h)}{BR(J/\psi \to h)} \sim (14 \pm 2)\%. \tag{16}$$

This assumption is <u>wrong</u>. Unlike the $J/\psi, \psi'$ case, Zhao [11] proved the following theorem

$$BR(\eta_c' \to h) \sim BR(\eta_c \to h) \tag{17}$$

where h is an exclusive final state channel and $\eta_c' = \eta_c'(3600)$. The proof of (17) is given in ref.[11] and will not be repeated here. A key ingredient to the proof is due to the work of Taiwan born physicist T. M. Yan who showed[21] that $\Gamma(\eta_c' \to \eta_c\pi\pi) \sim \Gamma(\psi' \to J/\psi\pi\pi) = 140\ KeV$. Zhao estimated[11] that the total width for $\Gamma(\eta_c') \sim 4\ MeV$, hence the branching ratio $BR(\eta_c' \to \eta_c\pi\pi) \sim 3.5\%$ is substantially smaller than the corresponding situation for $\psi' \to J/\psi\pi\pi$.

IMPORTANCE OF THE ZHAO THEOREM

The importance of the Zhao theorem is in the search for the η_c' expected around 3600 MeV[22] from both the ψ' sample accumulated in e^+e^- collisions and from future $p\bar{p}$ annihilation experiments. Take the e^+e^- case first. We remember that Crystal-Ball [22] did give a result at 95% confidence level that $BR(\psi' \to \gamma + \eta_c') = [0.2 \text{ to } 1.3]\%$. However the Crystal Ball "discovery" of the $\eta_c'(3600)$ has not been confirmed by other experiments in the next 12 years! Let us now consider a search for $\eta_c'(3600)$ at BES without full use of the Zhao theorem, and with say a 10^6 accumulation of ψ' events. Using the most optimistic Crystal Ball value for $BR(\psi' \to \gamma\eta_c'(3600)) = 1.3\%$, and the largest PDG[7] branching ratio for $\eta_c \to K\bar{K}\pi \sim 6.6\%$, conventional wisdom dictates that the search be conducted via the chain

$$\psi' \to \gamma\eta_c' \to \gamma\eta_c\pi\pi \to \gamma(\eta_c \to K\bar{K}\pi)\pi\pi$$

and taking into account BES efficiency ϵ [conservatively $\sim 5\%$ because of soft photon with energy < 90 MeV in $\psi' \to \gamma\eta_c'$ of the first leg, we have for 10^6 ψ' only 1.5 events!

Using Zhao's theorem[11] we proceed directly via $\psi' \to \gamma\eta_c' \to \gamma h$ where $\eta_c' \to h$ (light hadrons) are governed by Eq. (17) where the $\eta_c(2980)$ branching ratios are well measured[7]. We have

$$\begin{aligned}
BR(\eta_c' \to K\bar{K}\pi) &\sim BR(\eta_c \to K\bar{K}\pi) = 6.6 \pm 1.8\% \\
BR(\eta_c' \to \eta\pi\pi) &\sim BR(\eta_c \to \eta\pi\pi) = 4.9 \pm 1.8\% \\
BR(\eta_c' \to \eta'\pi\pi) &\sim BR(\eta_c \to \eta'\pi\pi) = 4.1 \pm 1.7\% \\
BR(\eta_c' \to \rho\rho) &\sim BR(\eta_c \to \rho\rho) = 2.6 \pm 0.9\% \\
BR(\eta_c' \to \phi\phi) &\sim BR(\eta_c \to \phi\phi) = 0.71 \pm 0.28\%.
\end{aligned} \tag{18}$$

Around July 12 (1994) BES decided that the coming run, after their summer shutdown, will be at ψ' energy for data taking at BEPC. For three months running and including the 1.27×10^6 ψ' already accumulated, one can optimistically work with 5×10^6 $\psi(2S)$ events soon. I will be optimistic and illustrate the expectations for η_c' but choose a conservative value, that $BR(\psi' \to \gamma\eta_c')$ =0.4% and hence at the lower end of the range of Crystal Ball values [22] of (0.2 - 1.3)% for this branching ratio. For 5×10^6 ψ' events, we will have 20,000 η_c' events. The detailed breakdown of $BR(\psi' \to \gamma\eta_c' \to \gamma h)$, using Eq. (17) give the following entries

η_c' channel	BR	N events in 2×10^4 η_c'
$K\bar{K}\pi \to K^{\pm}\pi^{\mp}K_s^0(\to \pi^+\pi^-)$	0.018	365
$\to K^{\pm}K^{\mp}\pi^0(\to \gamma\gamma)$	0.013	260
$\eta^0\pi\pi \to \eta^0(\to \gamma\gamma)\pi^+\pi^-$	0.013	260
$\to \eta^0(\to \pi^+\pi^-\pi^0)\pi^+\pi^-$	0.008	160
$\eta'\pi\pi \to \pi^+\pi^-\gamma\gamma\pi^+\pi^-$	0.005	100
$\to \pi^+\pi^-\gamma\pi^+\pi^-$	0.008	160
$\rho\rho \to \pi^+\pi^-\pi^+\pi^-$	0.009	180
$\pi^+\pi^-K^+K^-$	0.020	400
$\phi\phi \to K^+K^-K^+K^-$	0.002	40
$p\bar{p}$	0.0012	25

(19)

If average efficiency for detection is 5% for the non-crystal calorimeter detector at BES, we will have conservatively about 98 events for a 5×10^6 ψ' dataset. We must point out however that at BES, there is a potentially serious background from $\psi' \to \gamma\chi_{c2}$ where χ_{c2} subsequently decays into light hadrons h with the same exclusive hadronic channels as ψ'. BES should therefore measure accurately the χ_c branching ratios, and consequences for η_c' detection need careful study by Monte-Carlo methods.

Search for $\eta_c'(3600)$ formation from $\bar{p}p$ annihilation is another area for the application of Zhao's theorem[11]. We now know of the great success of the cooling ring for anti-proton bunches from the SPS at CERN and their counterparts at FERMILAB, it has proved possible to inject these antiproton bunches into $\bar{p}p$ colliders, providing a circulating antiproton beam of considerable intensity and accurately known momentum. With such a circulating antiproton beam, experimenters by providing a hydrogen gas jet target within the vacuum chamber of the said $p\bar{p}$ collider are able to study $\bar{p}p$ interactions in the c.m.energy range of interest for charmonium physics, with unprecedented energy resolution. E760 at FERMILAB is such a group deploying the above method[23], and actually made a search for the $\eta_c'(3600)$ via $\eta_c' \to 2\gamma$ (photon detection appears to be a particular strength in their apparatus setup). Use of the relationship (17) for the process $p\bar{p} \to \eta_c' \to h$ where h is a light hadron exclusive channel appears to be much more promising. For instance the peak production cross section is given by[9] as

$$\sigma(p\bar{p} \to \eta_c' \to h) = \frac{\pi}{k_{c.m.}^2}\ BR(\eta_c' \to h)\ BR(\eta_c' \to p\bar{p}) \tag{20}$$

where $k_{c.m.}$ is the center-of-mass momentum of the initial hadrons, and for charmonium energy $\pi/k_{c.m.}^2$ is about 1mb (actually 0.52 mb at η_c' mass 3600 MeV). Invoking again

Eq. (17), we have the following tabulation for $p\bar{p}$ production cross section of η_c' in various exclusive channels from Eq. (20):-

η_c' channel h	$\sigma(p\bar{p} \to \eta_c' \to h)$ in μb
$K\bar{K}\pi \to K^{\pm}\pi^{\mp}K_s^0(\to \pi^+\pi^-)$	0.011
$\to K^{\pm}K^{\mp}\pi^0(\to \gamma\gamma)$	0.008
$\eta^0\pi\pi \to \eta^0(\to \gamma\gamma)\pi^+\pi^-$	0.008
$\to \eta^0(\to \pi^+\pi^-\pi^0)\pi^+\pi^-$	0.005
$\eta'\pi\pi \to \pi^+\pi^-\gamma\gamma\pi^+\pi^-$	0.003
$\to \pi^+\pi^-\gamma\pi^+\pi^-$	0.005
$\rho\rho \to \pi^+\pi^-\pi^+\pi^-$	0.0056
$\pi^+\pi^-K^+K^-$	0.012
$\phi\phi \to K^+K^-K^+K^-$	0.001
$p\bar{p}$	0.0007

(21)

E760[23] did not find η_c' via $p\bar{p} \to \eta_c' \to 2\gamma$, however they were handicapped by lack of knowledge of the product $BR \to BR(\eta_c' \to p\bar{p})BR(\eta_c' \to \gamma\gamma)$. For instance current knowledge of even the well known $\eta_c(2980)$, the radiative decay $BR(\eta_c \to \gamma\gamma)$, is listed as $(6\pm5)\times10^{-4}$, hence given the errors consistent with zero. If one took a theory derived value[23] $BR(\eta_c \to \gamma\gamma) = 3.0\times10^{-4}$, the corresponding $\sigma(p\bar{p} \to \eta_c \to \gamma\gamma) \simeq 0.0004$ μb is still smaller (in some cases substantially smaller) then the entries in (21). It has been pointed out to us[24] that the design of the E835 (formerly E760) detector for the 1996-1997 fixed target run is fixed. It is basically the same detector (emphasizing on photon detection), with improvements in tracking and data acquisition capability. Looking towards the 21st Century, it is possible to consider a detector with a magnetic spectrometer. Such a detector would allow clean detection of $K\bar{K}\pi$ final states (from η_c' (3600) say) and other exclusive modes despite the severe backgrounds in $\bar{p}p$ experiments.

Remark: Tornqvist and Chaichian[25] argue on the basis of overlap integral between initial/final state wavefunctions extrapolated from OZI allowed vertices, that since 2S state wavefunction of charmonium has a node, while 1S state does not, therefore "all light hadron h channels in charmonium 2S decays should be suppressed relative to those of charmonium 1S decays". In particular $BR(\eta_c' \to h) << BR(\eta_c \to h)$ which contradicts Eq. (17). However the data[7] suggest that (I) $\psi' \to \pi^+\pi^-$ and (II) $\psi' \to K^+K^-$ are not suppressed at all, while (III) $\psi' \to p\bar{p}$ obeys the normal "14%" suppression law. It has been suggested that (I) is electromagnetic and (II) is SU(3) forbidden since K^+K^- with $J^{PC} = 1^{--}$ has no singlet component. Since broken SU(3) is not large here, we expect $\psi' \to K^+K^-$ to be also dominated by one photon transition. Hence pseudoscalar PP pairs like $(\pi^+\pi^-, K^+K^-)$ do not necessarily vitiate the Tornqvist-Chaichian proposal. However it must also be pointed out [3] that time-like form factors enter (I) and (II) amplitudes above, they involve the same type of meson wavefunction overlap integrals as in the multi-gluon mediated decays. Hence $\psi' \to PP$ should be the same as $\psi' \to PV$ in the Tornqvist-Chaichian approach in terms of suppression. Besides the unambiguous case (III) for $\psi' \to p\bar{p}$ clearly rules out the Finnish model. Thus the Zhao theorem appears to have survived this challenge to its validity.

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