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Some Theoretical Considerations on Heavy Quarkonium Systems

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ABSTRACT

There is a recent revival of experimental and theoretical interest in the heavy quarkonia systems with the experimental hint of a 1P_1 state in the charmonium system. Furthermore CESR is planning a possible $\Upsilon(3S)$ run to accumulate as much as $2.1 \times 10^6 \Upsilon(3S)$ decays in the near future. We discuss here the theoretical implications for these systems. Topics considered are the κ parameter and S-D mixing in heavy quarkonia, $\Upsilon(3S) \rightarrow \Upsilon(^1P_1)\pi\pi$ decay rate and spectrum, the predicted rate for $\Upsilon(1D) \rightarrow \Upsilon(1S)\pi\pi$, the problem of the production of spin-singlet states from hadronic transitions of charmonia and the puzzle of the missing $\psi(^1P_1) \rightarrow J/\psi\pi^+\pi^-$ decay.

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Recently there has been a revival of experimental and theoretical interest in the heavy quarkonia systems. First there is the experimental hint of a 1P_1 state at 3526 MeV in the isospin violating channel¹ $\psi' \rightarrow J/\psi + \pi^0$. Furthermore CESR is planning² to continue Υ physics with a possible (90% odds on) $\Upsilon(3S)$ run in the near future. CESR performance has now already reached a peak luminosity of order $2.3 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$, hence in a three months run (300pb^{-1}) an estimated 2.1×10^6 $\Upsilon(3S)$ can be accumulated, at their targeted magnetic field of 1.2 Tesla. Indeed even independent of the proposed future run, CLEO II has already in hand about 500,000 $\Upsilon(3S)$ decay events though the analysis will be somewhat difficult² because of the higher magnetic field of 1.5 Tesla currently in use. Theoretically the dominance of $\psi' \rightarrow J/\psi + \pi^0$ over the isospin allowed $\psi' \rightarrow J/\psi + \pi + \pi$ process (yet to be seen) poses a challenge for the Kuang-Yan theory³. Indeed, there have been of late several theoretical papers by Pyungwon Ko and collaborators⁴ endorsing the Voloshin approach⁵, and the Voloshin-Zakharov⁶ as well as Novikov- Shifman⁷ framework of discussion (where needed we shall refer to this collective body of literature as VZNS).

First Ko⁸ emphasized that the parameter $\lambda = \pi\alpha_s\rho_G$ in their published papers¹ enter in the amplitude for the $\pi\pi$ spectrum in $\psi' \rightarrow J/\psi\pi\pi$, (if one is willing to adopt the approach by Novikov and Shifman⁷), is determined from the data of this decay. He maintains that one can do the analogous thing in the Υ system, and a consistent result is obtained as discussed by S. Chakravarty, S. M. Kim, and Pyungwon Ko⁴, hence the claim is that the λ here is fixed through fitting the data, and not from theoretical calculations based on some models related with say the color octet $Q\bar{Q}$ system⁹. Indeed the question here has long been addressed by YAN in KUANG-TUAN-YAN³ (hence forth denoted as KTY) which needs to be re-emphasized. For instance, the gluon matrix element in VZNS is given by

$$\langle \pi^+ \pi^- | g^2 \mathbf{E}^a \mathbf{E}^a | 0 \rangle = \frac{8\pi^2}{9} [q^2 - \kappa(M_{\psi'} - M_{J/\psi})^2], \quad (1)$$

where $q^2 = (q_1 + q_2)^2$, $\kappa = (9/6\pi)\alpha_s \rho_G = (3/2\pi^2)\lambda$. This includes the correction term computed by Novikov and Shifman⁷. At that time KTY³ considered the ARGUS Collaboration data which had reported a detailed study of the hadronic transition $\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-$ (in the present context the argument could equally well be applied to $\psi' \rightarrow J/\psi\pi^+\pi^-$). In particular, the shape of the $\pi^+\pi^-$ mass spectrum was used to determine the parameters which appear in various theoretical models. At the time also the value of κ (or λ of Ko⁴ up to a numerical multiplicative constant) is consistent with the VZNS choice^{5,6,7} and with a small amount of D-wave $\pi^+\pi^-$. However KTY³ argued that such an agreement could be fortuitous, and indeed in general the use of κ parameter to fit data could be ambiguous. The important point is that the $\pi^+\pi^-$ mass spectrum can be fitted equally well by a $m_\pi^2 \neq 0$ correction as suggested by Voloshin and Zakharov⁶ in which one makes the substitution in Eq. (1):

$$q^2 - \kappa(M_{\psi'} - M_{J/\psi})^2 \rightarrow q^2 - \mu m_\pi^2. \quad (2)$$

The $m_\pi^2 \neq 0$ corrections are not all calculable⁶; therefore such a term is likely to appear in addition to the κ term. Furthermore, the sign of μ in (2) cannot be predicted on general grounds. Thus $\Upsilon(2S) \rightarrow \Upsilon(1S)\pi\pi$ and $\psi' \rightarrow J/\psi\pi\pi$ data will not be able to determine the value of κ uniquely. We note that in VZNS the κ term is a small correction to the amplitude for $\Upsilon(2S) \rightarrow \Upsilon(1S)\pi\pi$ (and $\psi' \rightarrow J/\psi\pi\pi$), but the same parameter κ appears in the leading term for the transition amplitude of $\Upsilon(3S) \rightarrow \Upsilon(1P_1)\pi\pi$. Hence caution must be exercised in the interpretation of κ from bottomonium and charmonium dipion spectra, though such a determination has been made recently⁴ in the VZNS framework leading to a $\kappa = 0.32$ (for $\lambda = 2.1$).

A most perceptive and brilliant paper was submitted in July 1989 and published in January (1990) by KUANG and YAN³ [hence forth denoted as KY(1990)]. Amongst other significant observations, they noted that S-D mixing in the $\psi'(3686) - \psi''(3770)$ system needs to be small, $\theta = -10^\circ$, to understand the rate for $\psi''(3770) \rightarrow J/\psi \pi^+ \pi^-$ obtained by Crystal Ball and Mark II Collaborations and by Mark III. The small mixing solution is also affirmed by K. T. CHAO et al.¹⁰. There have been attempts by Chakravarty, Kim, and Ko⁴ to understand the twin peaks anomaly of $\Upsilon(3S) \rightarrow \Upsilon(1S)\pi\pi$ spectrum by regarding the " $\Upsilon(3S)$ " as a mixture of S and D contributions, but still within the general framework of the QCD multipole expansion model, to wit

$$| \Upsilon(3S) \rangle = \cos \phi | 3S \rangle + \sin \phi | D \rangle . \quad (3)$$

This ostensibly yields $\phi = 24^\circ$, however the authors argue^{4,8} that the determination¹¹ of ϕ is actually dependent on the matrix element of $| \langle 1S | r^2 | 3S \rangle |$ which Moxhay¹² pointed out can be much smaller than normal expectations because the $| 3S \rangle$ state has two nodes which may lead to total cancellation. Hence a much smaller value of ϕ can be expected. Apart from the conjectural nature of the cancellation, the determination¹¹ of the $\pi\pi$ spectrum fit is also dependent on the value of λ (or κ) whose relevance remains questionable as indicated above. We note that in the process $\Upsilon(3S) \rightarrow \Upsilon(1S)\pi\pi$, the dipion phase space is about 895 MeV and sufficiently large that a D-wave dipion component can reasonably be expected and indeed a mix of S-wave and D-wave dipion contributions give the best fit to the preliminary CLEO II data¹³ on the spectrum for $\Upsilon(3S) \rightarrow \Upsilon(1S)\pi\pi$. It must also be pointed out that the S-D of " $\Upsilon(3S)$ " discussed in recent literature⁴ is logically distinct from the S and D waves of the dipion system for which some evidence now exists¹³. The $\Upsilon(3S) \rightarrow \Upsilon(1S)\pi\pi$ does pose a problem for the application of QCD multipole methods, since because of the large phase space, typically $(kR) > 1$ where k is the

appropriate gluon momentum and R is the radius of $\Upsilon(3S)$ [we expect $(kR) < 1$ for multipole methods to be valid]. It is less clear that the breakdown of QCD multipole expansion is due to $\Upsilon(3S)$ lying too close to the $B\bar{B}$ threshold and thus to the importance of color octet intermediate states⁹. A thorough study in the coupled channels approach has been made by KUANG and ZHOU¹⁴ concerning the impact of $B\bar{B}$ threshold on $\Upsilon(3S)$. It appears that Chakravarty, Kim, and Ko⁴ needed 24° mixing angle ϕ in (3) to explain the two peaks structure in $\Upsilon(3S) \rightarrow \Upsilon(1S) + \pi + \pi$, and $4(\pm 6)$ degrees from the radiative data $\Upsilon(3S) \rightarrow \chi_{bJ}(2P) + \gamma$. This could mean that either their calculations of the two processes are unreliable or the $\Upsilon(3S) \rightarrow \Upsilon(1S) + \pi + \pi$ and the radiative decay data cannot be explained by the same mixing angle. Neither option appears appealing as explanation of the two peaks structure.

An heuristic explanation of $\Upsilon(3S) \rightarrow \Upsilon(1S)\pi\pi$ spectrum in terms of S and D waves dipion contributions, but without a commitment to QCD multipole expansion here, nevertheless makes it easier to accept the validity of multipole expansion prediction for $\Upsilon(3S) \rightarrow \Upsilon(^1P_1)\pi\pi$ spectrum in KTY³. Here the dipion phase space is only about 455 MeV, hence S-wave dominant with $(kR) < 1$. Thus ultimately CESR could check this prediction, taking advantage of the need¹⁵ to strengthen the $\Upsilon(^1P_1)$ signal by selecting low mass dipion as experimental signature. Taking into account $m_\pi \neq 0$ corrections, important when $\alpha_M = \alpha_E$, KUANG-YAN theory¹⁶ predicts the LOWER bound

$$BR[\Upsilon(3S) \rightarrow \Upsilon(^1P_1)\pi^+\pi^-] > 0.022\%. \quad (4)$$

Hence with a planned 2.1×10^6 $\Upsilon(3S)$ decays, CESR can expect (depending on efficiency) NO LESS than 462 $\Upsilon(3S) \rightarrow \Upsilon(^1P_1)\pi^+\pi^-$ events, making for quite a feasible experiment. It would be interesting to see even a rough dipion plot since KTY³ predicts a rather unique spectrum - peaked at the lower dipion mass end.

A particularly attractive and immediate test of the KUANG-YAN theory is in the D-states of the Υ system. For the $b\bar{b}$ system¹⁷, two D-wave states are predicted, $\Upsilon(1D)$ at 10.16 GeV and $\Upsilon(2D)$ at 10.43 GeV. The presently published upper limit¹⁸ based on $237,000 \pm 6800$ $\Upsilon(3S)$ decays is

$$B(\Upsilon(3S) \rightarrow \Upsilon(1D) + X)B(\Upsilon(1D) \rightarrow \Upsilon(1S)\pi\pi) < 0.6\%. \quad (5)$$

KUANG-YAN³ in 1981 (and reaffirmed in KY(1990)³) predicts a partial width for $\Upsilon(1D) \rightarrow \Upsilon(1S)\pi\pi$ of 24 KeV. This leads to

$$B(\Upsilon(3S) \rightarrow \Upsilon(1D) + X)B(\Upsilon(1D) \rightarrow \Upsilon(1S)\pi\pi) = 0.43\%. \quad (6)$$

Hence even without reference to the future planned $\Upsilon(3S)$ run, the existing CLEO II accumulation of about 500,000 $\Upsilon(3S)$ decays could well be decisive in affirming the non-local (color octet intermediate state) method of KY (1981)³ as contrasted to the $G_8(E) \approx \text{constant}$ local interaction approach⁸ of VZNS which leads¹⁷ to 0.01% for r.h.s. of (6). If combined with the analysed 237,000 CLEO I events (5) there are now close to 3/4 of a million $\Upsilon(3S)$ decays already in hand! The calculated value for $\Gamma(\psi''(3770) \rightarrow J/\psi\pi\pi)$ width by KY(1990)³ is about a factor of 2-3 higher than the observed rate. Since $\psi''(3770)$ is above the $D\bar{D}$ threshold, coupled-channel effects are likely to be significant. Experience with the electromagnetic E1 transitions from $\psi'(3686)$ suggests that these coupled-channel effects could reduce the rate for $\psi''(3770) \rightarrow J/\psi\pi\pi$ by as much as 50%. However the $\Upsilon(1D)$ is estimated to be at 10.16 GeV, and hence substantially below the $\Upsilon(4S)$ state at 10.580 GeV which is just above the corresponding $B\bar{B}$ threshold. Hence the KUANG-YAN³ calculated width for $\Upsilon(1D) \rightarrow \Upsilon(1S)\pi\pi$ of 24 KeV should then be quite reliable in contrast to only a factor of 2-3 agreement in the charmonium case.

The production of spin singlet states from hadronic transitions of heavy quarkonia is evidently a problem area for KUANG-YAN model. The weakness was evident in

the original KY paper in 1981³ where the calculated rate (without apparent use of anomaly constraint) for $\Gamma(\psi'(3686) \rightarrow J/\psi + \eta^0)$ requires $\alpha_M \gg \alpha_E$ for agreement with data. The approximation of η by two gluons is obviously quite poor since the two gluons do not even have a definite mass. [We mean here that η is regarded as two gluons projected to $J^P = 0^-$ state. However, the kinematics is $\psi' \rightarrow J/\psi + g + g$ which is a three-body decay in which the invariant mass of the two-gluon system is diversely distributed, not simply peaked at mass of the η meson.] The success of KUANG-YAN is most clearly demonstrated in KY(1990)³ in hadronic transitions of heavy quarkonia to final states involving dipions, where $\alpha_M = \alpha_E$. One could argue that the discrepancy between α_M and α_E in the two cases is due to the DIFFERENCE in the hadronization process $gg \rightarrow \eta$ and $gg \rightarrow \pi\pi$. However in the absence of a plausible argument to implement this suggestion, the situation remains an uneasy one. For the neutral single pion emission, KTY³ did estimate the rates from the axial anomaly, taking into account the difference that we expect the coupling constants in the pion emission is proportional to $g_E g_M$ while the anomaly is proportional to g_s^2 since it is a short distance behavior. For instance in Eq. (31) of KTY (where factor α_M/α_E appears), g_E originates from E1 and g_M originates from M1 and we have identified the single coupling constant g_s with g_E (this is because usually one assumes $\alpha_s(600 \text{ MeV}) = 0.5 - 0.7$, and α_E in the Cornell model is gratifyingly 0.54. Hence introducing the $\alpha_E = \alpha_s$ approximation, one can reduce one free parameter in making predictions). Thus in the decay $\psi' \rightarrow \psi(^1P_1) + \pi^0$ of current interest, the (α_M/α_E) ratio in $\text{BR}(\psi' \rightarrow \psi(^1P_1) + \pi^0)$ [Eq. (36) in KTY] must be given to us by experiment and is discussed elsewhere¹⁹. A theoretical uncertainty of $\alpha_M = (1-3)\alpha_E$ is inherent in our predictions. The ratio

$$\text{BR}(\psi(^1P_1) \rightarrow J/\psi + \pi^0) / \text{BR}(\psi(^1P_1) \rightarrow J/\psi + \pi + \pi) = (0.07)(\alpha_M/\alpha_E) \quad (7)$$

hence even for $\alpha_M = 10\alpha_E$, the single pion emission can be at best only comparable to the dipion emission. Unlike the result for $\psi' \rightarrow \psi(^1P_1) + \pi^0$, the result for $\psi(^1P_1) \rightarrow J/\psi + \pi^0$ in Eq. (7) may suffer from a substantial hard-pion correction and hence to that extent, it is not reliably calculated. Again the two gluon approximation inherent in $\psi(^1P_1) \rightarrow J/\psi + \pi + \pi$ is likely to be only order of magnitude correct; indeed the calculation of KY(1990)³ for $\psi''(3770) \rightarrow J/\psi + \pi + \pi$ is a factor of 3 larger than data. Such factor can accentuate two pion dominance in (7). Nevertheless even taken into account refinements¹⁶, the branching ratio for $\psi(^1P_1) \rightarrow J/\psi + \pi + \pi$ is expected to be comparable or somewhat larger than that for the single pion emission. Hence the E760 result T. A. Armstrong et al.¹ that the l.h.s. of (7) is > 5.5 at 90% confidence level would be accomodated only if the $\psi(^1P_1)$ spin-flip transition to $\pi\pi J/\psi$ prove to be not an efficient marker for this state, as suggested by Dalitz²⁰. Further experimentation, perhaps deploying the two photon physics program at LEP/L3 are needed to clarify the situation as discussed elsewhere¹⁹.

Finally, we comment on the spectrum of $\Upsilon(3S) \rightarrow \Upsilon(2S)\pi\pi$. Here the phase space is quite small, only 332 MeV, hence $(kR) < 1$ for validity of the multipole method is likely to be well satisfied with the dipions in a relative S-wave. The existing CLEO II data¹³ support the multipole expectations, though the statistics remain limited and analysis must contend with the very small $\Upsilon(3S) - \Upsilon(2S)$ phase space. In particular there is little evidence of the two peaks in dipion spectrum seen in the much larger phase space case of $\Upsilon(3S) \rightarrow \Upsilon(1S)\pi\pi$. The fact that $\Upsilon(3S) \rightarrow \Upsilon(2S)\pi\pi$ tends to confirm the standard picture, would also argue that $B\bar{B}$ threshold effects^{9,14} near $\Upsilon(3S)$ may not be the explanation for the twin peaks anomaly in $\Upsilon(3S) \rightarrow \Upsilon(1S)\pi\pi$. In analogy with the charmonium $\psi'(3686) - \psi''(3770)$ S-D mixing, one could consider here the mixing between $\Upsilon(3S)$ at 10.355 GeV with a nearby $\Upsilon(2D)$ estimated to be at 10.43 GeV¹⁷. Using the E1 transition formula¹⁰ of earlier charmonium work,

CHAO²¹ estimates from $\Upsilon(3S) \rightarrow \chi_{bJ}(2P) + \gamma$ data, that the mixing angle for 3S-2D must be small perhaps in the range of 0 to -5 degrees. The large angle solution from (3) with $\phi = \pm 26^\circ$ is in substantial disagreement with the experimental widths for $\chi_{bJ}(2P)$ for $J=0$ and $J=1$.

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REFERENCES AND FOOTNOTES

1. T. A. Armstrong et al., Phys. Rev. Lett. **69**, 2337 (1992); also E705 (Brad. Cox et al.).
2. E. Shibata, private communication.
3. Y. P. KUANG and T. M. YAN, Phys. Rev. **D41**, 155 (1990); Y. P. KUANG, S. F. TUAN, and T. M. YAN, Phys. Rev. **D37**, 1210 (1988); Y. P. KUANG and T. M. YAN, Phys. Rev. **D24**, 2874 (1981).
4. P. Ko, Phys. Rev. **D47**, 2837 (1993); S. Chakravarty and Pyungwon Ko, Phys. Rev. **D48**, 1205 (1993); S. Chakravarty, S. M. Kim, and Pyungwon Ko, Phys. Rev. **D48**, 1212 (1993).
5. M. B. Voloshin, Yad. Fiz. **43**, 1571 (1986) [Sov. J. Nucl. Phys. **43**, 1011 (1986)].
6. M. B. Voloshin and V. I. Zakharov, Phys. Rev. Lett. **45**, 688 (1980).
7. V. A. Novikov and M. A. Shifman, Z. Phys. **C8**, 43 (1981).

8. Pyungwon Ko, private communication.
9. M. B. Voloshin, Nucl. Phys. **B154**, 365 (1979).
10. K. T. CHAO et al., Phys. Rev. **D44**, 3562 (1991).
11. See Eq. (18) of Phys. Rev. **D48**, 1212 (1993) in Ref. 4 above.
12. P. Moxhay, Phys. Rev. **D37**, 2557 (1988).
13. J. Matthew Dominick, Ph.D Thesis [PU-92-667], Purdue University, May (1993).
14. H. Y. ZHOU and Y. P. KUANG, Phys. Rev. **D44**, 756 (1991).
15. J. L. Rosner, in PROC. OF HADRON '87, KEK, Tsukuba, Japan, p.221.
16. S. F. TUAN, Mod. Phys. Lett. **A**, Vol. 7, No. 38, 3527 (1992).
17. P. Ko, Phys. Rev. **D47**, 208 (1993).
18. I. C. Brock et al., Phys. Rev. **D43**, 1448 (1991).
19. K. T. CHAO, Y. F. GU, and S. F. TUAN, "Search for η'_c and $\psi(^1P_1)$ in ψ' decay", to be published.
20. R. H. Dalitz and S. F. TUAN, in PROCEEDINGS OF THE TENTH HAWAII CONFERENCE ON HIGH ENERGY PHYSICS, Honolulu, Hawaii, 1985, edited by F. A. Harris, S. Pakvasa, and S. F. TUAN (University of Hawaii Press, Honolulu, 1986), p. 707.
21. K. T. CHAO, private communication, and to be published.