Possible Mechanism for Non-$B\bar{B}$ Decays of the $\Upsilon(4S)$

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Recent observation of $\Upsilon(4S) \to \psi + X$ with the ψ too energetic to come from the decay of a B meson suggests that there could be a substantial rate of non-$B\bar{B}$ decay of $\Upsilon(4S)$. We attempt to explain this by conventional quarkonium spectroscopy and suggest that $\Upsilon(4S) \to h_b(1P) + \eta$ and $\Upsilon(4S) \to \eta_b + h_1(1170)$ with subsequent decays into ψ's are possible candidates. A crude estimate of the corresponding rates shows them to be of the correct order of magnitude. The model implies that h_b decays to $D\bar{D}$ are more frequent than into the ψ causing a potentially serious background to the sample used for determination of $|V_{ub}/V_{cb}|$.

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Recent analysis of data from the CLEO Collaboration[1] and confirmed by the ARGUS Collaboration[2] shows that $\Upsilon(4S) \to \psi + X$ has a branching fraction of about 2×10^{-3} with a cut in the ψ momentum such that the ψ cannot originate from B via $\Upsilon(4S) \to B\bar{B}$. This result is striking because the total branching ratio for Zweig-suppressed ($b\bar{b}$ annihilation) channels is only about 10^{-3}, assuming that the total annihilation width is similar to that of the other members of the Υ family. We postulate, therefore, that there must exist another Zweig-allowed decay of the $\Upsilon(4S)$ other than the supposedly dominant $\Upsilon(4S) \to B\bar{B}$.

In particular, such a decay must be of the form

$$\Upsilon(4S) \to R + Y, \tag{1}$$

where R is some $b\bar{b}$ state[3] such that the ψ is produced by $R \to \psi + X$. In order to explain the observed production of ψ mesons, the branching ratio of (1) should be at least 10^{-2}-10^{-1} as it is very difficult to see how a $b\bar{b}$ bound state (such as the R) could have a branching ratio into ψ any larger than a few percent. Let us now systematically consider what the possible states R and Y are.

We assume that R is a conventional quarkonium state although some of our later comments will also apply to more exotic interpretations. Clearly, such a conventional explanation needs to be ruled out before exotic possibilities are entertained. The possible choices for R are shown in Fig. 1 where the masses of unobserved states are calculated using a potential model.[4]

Consider first $Y = \gamma$. This case can be excluded since typical widths for γ emission by other Υ states is 2-5 keV and assuming the same holds true for $\Upsilon(4S)$, such a branching ratio would be about (5 keV)/(24 MeV) $\sim 10^{-4}$, much smaller than required.

Likewise, we note that the 2π emission by other Υ states is also[5] ~ 10 keV (probably because the phase space is so small) and hence Y cannot be a 2π state or, for that matter, any multimeson system. Thus Y is a single meson.

Referring to the $b\bar{b}$ spectrum in Fig. 1, as a quarkonium state below $\Upsilon(4S)$, R must be either an Υ, η_b, h_b, χ_b, or D-wave state. These possibilities are enumerated in Table I together with the appropriate choices of Y as a function of the decay orbital angular momentum. We systematically discuss these below.

First of all, suppose R is a $\Upsilon(nS)$ state, $n \le 3$.[6] The production of ψ would therefore proceed through the sequence $\Upsilon(4S) \to \Upsilon(nS) + Y \to \psi + X$. Since $\Upsilon(nS)$ decays through annihilation, we would expect the branching ratio of $\Upsilon(nS) \to \psi + X$ to be comparable to that for $\Upsilon(1S) \to \psi + X$ which is measured to be 10^{-3}.[7] Hence the total branching ratio for the cascade $\Upsilon(4S) \to \Upsilon(nS) \to \psi + X$ must be considerably smaller. Furthermore, $\Upsilon(4S) \to \Upsilon(nS) + Y$ is expected to occur at a rate comparable with $\Upsilon(4S) \to \Upsilon(1S) + Y$ and the results from the CLEO Collaboration[1] bound the branching ratio to $\Upsilon(4S) \to \Upsilon(1S) + Y$ to be $\le 4 \times 10^{-3}$. Therefore the branching ratio for the cascade $\Upsilon(4S) \to \Upsilon(nS) + Y \to \psi + X$ is expected to be less than 10^{-5}, too small to account for the recent observation.[1,2]

Next, we take R to be a χ_b state. Then the lightest Y with the correct quantum numbers is $Y = \omega(783)$. Since the difference in mass between $\Upsilon(4S)$ and the lightest χ_b state is 720 MeV, such decays are excluded.

The limit on the $\Upsilon(1S)$ signal in $\Upsilon(4S)$ decay may also be used to bound the branching ratio of $\Upsilon(4S) \to \chi_b + Y$. Experimentally the branching ratios of χ_b states decaying to $\Upsilon(1S)$ are about 10%.[5] Hence the limit on the branching ratio of $\Upsilon(4S) \to \Upsilon(1S) + X$ gives a bound of 4% on the branching ratio of $\Upsilon(4S) \to \chi_b + Y$. Now, since we expect

$$B(\chi_b \to \psi + X) \ll B(\chi_b \to \Upsilon(1S) + X), \tag{2}$$

the product branching ratio of $\Upsilon(4S)$ to χ_b followed by χ_b to ψ should be much less than 4×10^{-3}, and unlikely

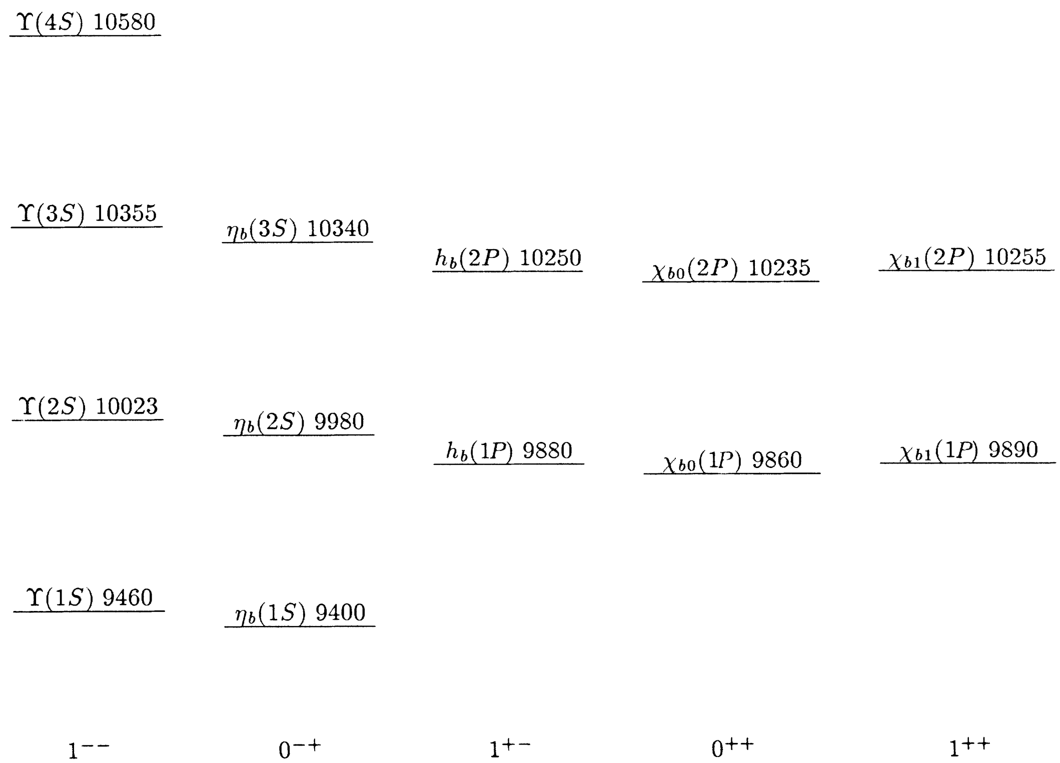

FIG. 1. The $b\bar{b}$ quarkonium spectrum with the observed masses indicated for the Υ and χ states and the estimates from the potential model of Ref. 4 for the η and h states. Mass splitting between triplet states is not shown.

to be enough for the experimental observation.[1,2]

Next, we take $R=\eta_b$. Indeed, $R=\eta_b(1S)$ cannot be excluded by the above arguments, and, in fact, two possibilities must be considered: (1) the orbital angular momentum $L=1$ and $Y=\omega(783)$ or $\phi(1020)$; (2) $L=0$ and $Y=h_1(1170)$. In the case $Y=\omega$, $R=\eta_b$, the analogous decay $\Upsilon(3S)\to\omega+\eta_b(1S)$ is also possible energetically. However, since $\Upsilon(4S)\to\omega\eta_b$ and $\Upsilon(3S)\to\omega\eta_b$ should proceed at roughly the same rate, and since the total widths of $\Upsilon(4S)$ and $\Upsilon(3S)$ are 25 MeV and 25 keV, respectively, the branching ratio for $\Upsilon(4S)\to\omega\eta_b$ is $\leq 10^{-3}$, much smaller than re-

TABLE I. The possible states R and Y which contribute to ψ production via the decay $\Upsilon(4S)\to R+Y$. R is assumed to be a $b\bar{b}$ state, Y is taken to be a single meson (see text), and L is the relative angular momentum. Tabulated are the relevant arguments from the text for and against the various channels.

R	$L=0$	$L=1$
$\Upsilon(nS)$, $n\leq 3$	Ruled out by $B(\Upsilon(nS)\to\psi+X)\leq 2\times10^{-3}$ and/or $B(\Upsilon(4S)\to\Upsilon(1S)+X)\leq 4\times10^{-3}$	
χ_b	$PC(Y)=--$ The lightest such meson is $\omega(783)$, hence this is kinematically excluded.	$PC(Y)=+-$ The lightest such meson is $h(1170)$, hence this is kinematically excluded.
η_b	$J^{PC}(Y)=1^{+-}$ Thus $H=h(1170)$. This is possible.	$PC(Y)=--$ Thus $Y=\omega(783)$. This is excluded since $\Upsilon(3S)\to\omega\eta_b$ is also possible, thus indicating that $B(\Upsilon(4S)\to\omega\eta_b)\leq 10^{-3}$.
h_b	$J^{PC}(Y)=0^{-+}$ Thus $Y=\eta(548)$. This is possible.	$PC(Y)=++$ All such states are too massive to be kinematically allowed.

quired. In passing we note that this decay channel, which should occur at some level, is probably so small because it proceeds through a P wave. We also note that the ϕ coupling should be roughly comparable to that of the ω; therefore, the bound on $B(\Upsilon(4S) \to \omega + \eta_b)$ implies a similar bound on $B(\Upsilon(4S) \to \phi + \eta_b)$.

On the other hand, if $Y = h_1(1170)$ and $R = \eta_b(1S)$, $L = 0$ and there should be no suppression. Furthermore, $\Upsilon(3S)$ cannot decay in this way (due to kinematics) and thus this possibility is not bounded by existing data. Note, however, that in the potential model it is predicted to only have about 10 MeV of phase space available.[8]

Next, consider $R = h_b(1P)$. In this case the only possible $\Upsilon(4S)$ decay implies $Y = \eta$ which proceeds through an S wave. The $\Upsilon(3S)$ decay is energetically forbidden which makes this case a viable possibility.

Finally, if R is a D-wave state, there is only about 100–400 MeV of phase space, and hence there are no candidates for Y that do not violate isospin conservation and suffer additional suppression from being a P-wave emission. Thus, we are led to consider only the following two possibilities:

$$\Upsilon(4S) \to h_b(1P)\eta\,, \tag{3a}$$

$$\Upsilon(4S) \to \eta_b(1P) h_1(1170)\,. \tag{3b}$$

In order to estimate the rates of these decays, we form a crude model extrapolating from observed decay rates in the ψ system. Consider the decay $\psi' \to \psi\eta$ whose width is 6.5 keV. Let us suppose that the η-ψ-ψ' coupling is described by an effective Lagrangian of the form

$$a_c \eta F_{\mu\nu} \tilde{G}^{\mu\nu}\,, \tag{4}$$

where a_c is a constant and $F_{\mu\nu}, G_{\mu\nu}$ are the field strengths of ψ, ψ', respectively. $\tilde{G}^{\mu\nu}$ is the dual of G defined by $\tilde{G}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta} G_{\alpha\beta}$. In analogy, we take the effective Lagrangian for $\Upsilon(4S) \to h_b(1P)\eta$ to be

$$a_b \eta U^{\mu\nu} V_{\mu\nu}\,, \tag{5}$$

where U is the $\Upsilon(4S)$ field and V is the $h_b(1P)$ field. We thus arrive at

$$\Gamma(\Upsilon \to h_b \eta) \approx \frac{3 m_\Upsilon^2 P_\Upsilon}{2 P_\psi^3} \Gamma(\psi' \to \eta\psi) \left[\frac{a_b^2}{a_c^2} \right], \tag{6}$$

where P_Υ and P_ψ are the momentum of the η from the Υ, ψ' decays, respectively.

If we take $a_b = a_c$, then the width for (3a) is about 46 MeV, which is clearly too large because the total width $\Gamma(\Upsilon(4S)) = 24$ MeV. However, on dimensional grounds a more reasonable choice is $a_b \sim 1/m_b$, $a_c \sim 1/m_c$. Equation (6) then yields a width of about 5 MeV, i.e., $B(\Upsilon(4S) \to h_b \eta) \sim 20\%$. In any case, the point of this exercise is merely to suggest that it is plausible that this mode forms a substantial fraction of the $\Upsilon(4S)$ decays.

For case (3b) we will use the same effective Lagrangian as Eq. (5) except that this time $V_{\mu\nu}$ stands for the h_1 field and η for the η_b field. In this case (with $a_b/a_c = m_c/m_b$) we get a width of 2 MeV. Thus, this is also a candidate provided there is sufficient phase space.[8]

If reaction (3a) takes place, it could be confirmed by observing the $\eta \to \gamma\gamma$ decay mode. The invariant mass and total energy of the γ pair is fixed by kinematics giving a possible signature. An analogous signature for (3b) is problematic since little is known about the decay properties of the $h_1(1170)$ except that it decays into $\rho + \pi$.

Consider now the properties of the h_b state more closely. By charge conjugation, its annihilation decay channel requires it to couple to at least three gluons, as is the case for the Υ states. The h_b, however, is a P state so we expect the annihilation to be somewhat suppressed with respect to the S-wave Υ. Consequently, we guess the annihilation width of h_b to be in the range of a few tens of keV's. The radiative transition allowed by charge conjugation is $h_b \to \eta_b \gamma$. Using the effective Lagrangian approach as above we note that this decay is of the same form as the observed process $\Upsilon(2S) \to \chi_{b0}\gamma$ which has a width of 2 keV. Since both proceed through an S wave, the rate is proportional to the final-state momentum which gives us an estimate of the decay rate for $h_b \to \eta_b \gamma$ of about 6 keV. Also, the 2π transitions from the h_b involve $L \neq 0$ and hence should be suppressed. This leads to a picture where the radiative decays of h have a branching ratio of somewhat more than 10% of the annihilation width.

Another interesting decay of the h_b is the isospin-violating reaction h_b to $\Upsilon(1S) + \pi^0$.[9] This may be estimated using the same analysis which led to Eq. (6). We obtain

$$\Gamma(h_b \to \Upsilon\pi^0) \approx \frac{3 m_h^2 P_h}{2 P_\psi^3} \Gamma(\psi' \to \pi^0 \psi) \left[\frac{a_b^2}{a_c^2} \right], \tag{7}$$

where P_h, P_ψ are the momentum of the π^0 from the h_b and ψ' decays, respectively. From the observed rate of $\Gamma(\psi' \to \pi^0 \psi)$ and again using $a_b/a_c = m_c/m_b$ we obtain $\Gamma(h_b \to \Upsilon\pi^0) \approx 8$ keV. This channel may therefore be an appreciable fraction of the annihilation channel and may well have a branching ratio of over 10%. This could serve as an experimental tag for the presence of the h_b. Indeed, if (3a) is the origin of the ψ production, $\Upsilon(4S) \to \eta + h_b \to \eta + \pi^0 + \Upsilon(1S)$ should have a branching fraction of at least a few percent of $\Upsilon(4S)$ decays.

We close with the following additional remarks:

(1) Regardless of what the state R is, it is very likely that its decays to $c\bar{c}$ are dominated by final states such as $D\bar{D}$, $D_S\bar{D}^*, \ldots$ rather than ψ. The observed $B(\Upsilon(4S) \to \psi + X)$ of 2×10^{-3} implies that the branching ratio to $D\bar{D}$-like final states could easily be 10^{-2} leading to electron final states from decays of such D states at the level of 10^{-3}. This is comparable to the sample of electrons used in the determination of V_{ub}. As

a consequence, it might be necessary to reexamine[10] the background to semileptonic charmless B decays before a definite value of V_{ub}/V_{cb} can be deduced.[11]

(2) One obvious question is why the state R should produce many ψ mesons while the $\Upsilon(1S)$ yields them at such a low rate.[7] In the case of η_b perhaps there is some helicity suppression of low mass quark pairs so that more charm is produced in its decays than the corresponding $\Upsilon(1S)$ case. For example, in the $c\bar{c}$ system, $B(\eta_c \to K^+K^-\pi^+\pi^-)$ is 2.0% while $B(\eta_c \to \pi^+\pi^-\pi^+\pi^-)$ is 1.2%. A simple explanation for this is that the η_c, being a pseudoscalar, likes to couple to fermions of opposite helicity and since QCD is a helicity-preserving theory, such a coupling will of necessity be proportional to the mass of the fermion.[12] If this explanation is in fact correct, one would expect η_b to produce many more $c\bar{c}$ pairs than other $q\bar{q}$ pairs. This may, at least in part, be the cause for the lack of signal into inclusive ϕ final states.[1]

(3) A similar argument can be made for the h_b. Its J^{PC} quantum numbers of 1^{+-} can only couple to a fermion pair of opposite helicity. Hence a similar mass enhancement of $c\bar{c}$ pairs is possible. χ and Υ states, on the other hand, couple to fermion pairs of the same helicity and so no such effects should be present. It is not clear how well this argument holds in the presence of hadronization and the associated production of gluons although the η_c example suggests that it may work to some extent.

(4) Needless to say, both η_b and h_b may be contributing to the observed non-$B\bar{B}$ decays of the $\Upsilon(4S)$.

(5) Whether or not our explanation for the observed non-$B\bar{B}$ decays of $\Upsilon(4S)$ holds, reactions (3a) and (3b) may still have reasonable branching ratios to be viable methods for searching h_b and η_b.

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[1]CLEO Collaboration, J. Alexander *et al.*, Phys. Rev. Lett. **64**, 2226 (1990).

[2]A similar observation has been made by the ARGUS Collaboration (private communication).

[3]Or possibly an exotic $b\bar{b}g$ or $b\bar{b}q\bar{q}$ state.

[4]See, e.g., W. Buchmüller and S. Cooper, in *Electron-Positron High Energy Physics,* edited by A. Ali and P. Söding (World Scientific, Singapore, 1988), pp. 412–487; S. Godfrey and N. Isgur, Phys. Rev. D **32**, 189 (1985), and references therein.

[5]Particle Data Group, G. P. Yost *et al.*, Phys. Lett. B **204**, 29 (1988).

[6]From now on, in this paper the n in $\Upsilon(nS)$ will always mean $n \leq 3$.

[7]CLEO Collaboration, R. Fulton *et al.*, Phys. Lett. B **224**, 445 (1989).

[8]The fact that reaction (3b) has only a marginal phase space available need not be a very serious problem as $h_1(1170)$ has a broad width $\sim$300 MeV; see Ref. 5.

[9]Our model Lagrangian also implies the reverse decay $h \to \Upsilon(1S) + \eta$, but there is not enough phase space.

[10]That the observation of $\Upsilon(4S)$ decays to non-$B\bar{B}$ states could affect the deduced value of V_{ub}/V_{cb} was emphasized to one of us (A.S.) by Bruce Winstein.

[11]CLEO Collaboration, R. Fulton *et al.*, Phys. Rev. Lett. **64**, 16 (1990); ARGUS Collaboration, H. Albrecht *et al.*, Phys. Lett. B **241**, 270 (1990).

[12]Indeed, the enhancement in η_c decays to inclusive $K\bar{K}$ states could even be larger when we include final states such as $K\bar{K}\pi$, $K^*\bar{K}^*$, and $K^*\bar{K}\pi$. However, helicity arguments in hadronic decays are fraught with danger and are definitely not as clean as in the classic example of pure leptonic decays of the charged pion.