$\Upsilon(3S)\to\Upsilon(1S)\pi\pi$ decay: Is the $\pi\pi$ spectrum puzzle an indication of a $b\bar{b}q\bar{q}$ resonance?

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(Received 22 August 1994; revised manuscript received 2 February 1995)

The $\pi\pi$ mass spectrum in $\Upsilon(3S)\to\Upsilon(1S)\pi\pi$ has a peculiar double peak structure. This structure and the $\Upsilon(1S)\pi$ spectrum are reproduced by introducing a triangle singularity associated with a $b\bar{b}\pi$ resonance ($J^P=1^+$) in the mass range 10.4–10.8 GeV.

PACS number(s): 13.25.Gv, 14.40.Gx

The hadronic transitions $\Upsilon(nS)\to\Upsilon(mS)\pi\pi$ are of particular interest for exploring nonperturbative QCD interactions. The standard mechanism for these transitions is thought to be the emission of gluons, followed by their hadronization to two pions as shown by Figs. 1(a,b). It was calculated by various nonperturbative QCD multipole-expansion models [1–4]. All of them gave a single peak in the $\pi\pi$ mass spectra at high values. This is consistent with the data for $\Upsilon(2S)\to\Upsilon(1S)\pi\pi$ and $\Upsilon(3S)\to\Upsilon(2S)\pi\pi$ transitions, but disagrees with data for the $\Upsilon(3S)\to\Upsilon(1S)\pi\pi$ transition which shows a peculiar double peak in its $m_{\pi\pi}$ spectrum [5,6]. Several mechanisms have been suggested, such as including the known $\pi\pi$ final state interaction [4], or introducing $\pi\pi$ and/or $\Upsilon\pi$ resonances [4,7,8], or considering a $B\bar{B}^*$ intermediate state mechanism [9–11], etc., but all of them either could not explain the double peak puzzle or demanded very cumbersome assumptions [5].

In the present paper, following Voloshin's idea [8], we suggest the resolution of the $\Upsilon(3S)\to\Upsilon(1S)\pi\pi$ puzzle by introducing a resonance in the $\Upsilon(1S)\pi$ system — a four quark resonance $b\bar{b}q\bar{q}$ with isospin $I=1$, see Fig. 1(c). But contrary to Voloshin's proposal, we assume this resonance is outside the Dalitz plot of the produced particles $\Upsilon(1S)\pi\pi$, i.e., its mass $M_X>M_{\Upsilon(3S)}-\mu_\pi$. Therefore it does not produce a peak in the $\Upsilon(1S)\pi$ spectrum and only influences the $\pi\pi$ spectrum by the process with subsequent rescattering of pions as shown in Fig. 1(d). The qualitative feature of the spectrum for $\Upsilon(3S)\to\Upsilon(1S)\pi\pi$ is that an anomalous peak occurs in the $\pi\pi$ mass spectrum just where the mass of the $\Upsilon(1S)\pi$ system reaches its maximum, i.e., the top of the Dalitz plot [5]. If the triangle diagram of Fig. 1(d) plays a role, this is exactly where one expects such a band of events. The triangle diagram with a resonance in the intermediate state contains an anomalous logarithmic singularity close to the physical region for three-particle final states [12–14]. The closer the $b\bar{b}\pi$ system lies to the physical region, the stronger the anomalous band of events will be. This property has recently attracted attention to the triangle diagram in other processes [15–18].

In summary, two types of processes are assumed to be responsible for the decays $\Upsilon(nS)\to\Upsilon(mS)\pi\pi$: (i) the standard decay mode $\Upsilon(nS)\to gluons+\Upsilon(mS)\to\pi\pi\Upsilon(mS)$ with $\pi\pi$ final state interaction included [Figs. 1(a,b)]; (ii) the production of the pion and the virtual resonance $X(b\bar{b}q\bar{q})$ ($I=1$ and mass in the range 10.3–10.8 GeV) with subsequent decay $X\to\Upsilon(mS)\pi$ [Fig. 1(c)] and a further pion-pion interaction [Fig. 1(d)]. The process of Figs. 1(c,d) was considered in Ref. [4], but the approximation used there had the consequence of losing the triangle diagram singularity.

Because of the centrifugal barrier effect, the quantum numbers for the X resonance are expected to be $J^P=1^+$, which gives an S-wave coupling of the $X\Upsilon\pi$ vertex. Then the following formula gives the amplitude of the decay $\Upsilon(nS)\to\Upsilon(mS)\pi\pi$ with all processes of Fig. 1 taken into account:

$$T=\epsilon^\mu(n)\epsilon^\nu(m)\left[g_{\mu\nu}\alpha_{nm}\frac{e^{i\delta_0}\sin\delta_0}{\rho_{\pi\pi}}+\Lambda_{nm}T^X_{\mu\nu}(s_{13},s_{23},s)\right]. \quad (1)$$

Here ϵ_μ is a polarization vector of Υ and $g_{\mu\nu}$ is the metric tensor. The first term in the square brackets describes the standard amplitude of Figs. 1(a,b): δ_0 is the $\pi\pi$ S-wave phase shift with $I=0$ and $\rho_{\pi\pi}=\sqrt{1-4\mu^2/s_{\pi\pi}}$ is the invariant $\pi\pi$ phase space volume. This is the standard gluon-multipole-plus-current-algebra model with pion final-state interactions [4]. The second term describes the process of

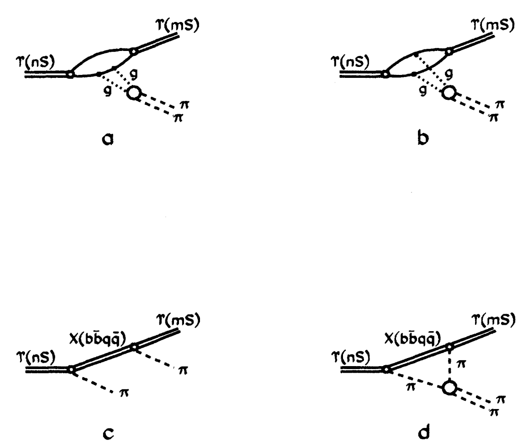

FIG. 1. Processes which are taken into account in the present model: (a,b) diagrams with gluon emission and their transition into $\pi\pi$; (c,d) production of the resonance X with subsequent rescattering of the produced pions.

resonance production and the subsequent rescattering of the pions, Figs. 1(c,d). For $\pi^+\pi^-$ production, $T^X_{\mu\nu}$ is

$$T^X_{\mu\nu}(s_{13},s_{23},s)=\frac{g_{\mu\nu}-p_{13\mu}p_{13\nu}/M_R^2}{M_R^2-s_{13}-iM_R\Gamma_R}+\frac{g_{\mu\nu}-p_{23\mu}p_{23\nu}/M_R^2}{M_R^2-s_{23}-iM_R\Gamma_R}+2\frac{e^{i\delta_0}\sin\delta_0}{\rho_{\pi\pi}}A^{\rm Tr}_{\mu\nu}(s) \qquad (2)$$

with

$$A^{\rm Tr}_{\mu\nu}(s)=\int_{4\mu^2}^{\infty}\frac{ds'}{\pi}\frac{\rho_{\pi\pi}}{s'-s-i\epsilon}\int\frac{d\Omega}{4\pi}\frac{g_{\mu\nu}-\tilde{p}_\mu\tilde{p}_\nu/\tilde{s}}{M_R^2-\tilde{s}}.$$

Here M_R and Γ_R are the mass and width of the resonance X, p_{i3} and $s_{i3}=p_{i3}^2$ are the total momentum and the energy squared of the system of outgoing Υ and pion i; $\tilde{p}$ and $\tilde{s}=\tilde{p}^2$ are the momentum and squared energy of the X resonance in the triangle diagram, and the integration over Ω means integration over angular distribution of intermediate pion, where z axis is defined by momentum of outgoing Υ. Here for the triangle diagram Fig. 1(d), we assume as usual [12–18] dominance of the triangle singularity contribution. The dispersion integral in Eq. (2) should not be taken literally because of the tensor factor $g_{\mu\nu}-\tilde{p}_\mu\tilde{p}_\nu/\tilde{s}$. First of all this factor must be expanded over external momenta and the dispersion integral taken for invariant functions. The details of such a procedure can be found in Refs. [19,20], but because of the large mass of Υ mesons this procedure can be simplified.

The term $\epsilon_\mu(n)\cdot(p_\mu p_\nu/M_R^2)\cdot\epsilon_\nu(m)$ is of the order of $\vec{k}^2/M_R^2$ where $\vec{k}$ is momentum of the Υ-π system. Therefore this term is small in the region considered and can be neglected for the calculation of the first two terms in the $T_{\mu\nu}$ and the imaginary part of $A^{\rm Tr}$. In the calculation of the real part of $A^{\rm Tr}$, such a term gives a divergence in the integral at large virtualities of the X resonance. To get rid of this divergence we apply a cutoff procedure assuming that the contribution from the large virtualities (that means small distances) is effectively taken into account by redefinition of the parameter a_{nm}. If a cutoff parameter Λ is much smaller then M_R the term proportional to $1/M_R^2$ can be also neglected for calculation of the real part of the $A^{\rm Tr}$. In that case the integral becomes convergent and a cutoff parameter can be spread to infinity $\Lambda\rightarrow\infty$. Thus we obtain the following expression for the amplitude T^X:

$$T^X_{\mu\nu}(s_{13},s_{23},s)=g_{\mu\nu}\left[\frac{1}{M_R^2-s_{13}-iM_R\Gamma_R}+\frac{1}{M_R^2-s_{23}-iM_R\Gamma_R}+2\frac{e^{i\delta_0}\sin\delta_0}{\rho_{\pi\pi}}A^{\rm Tr}(s)\right], \qquad (3)$$

where

$$A^{\rm Tr}(s)=\int_{4\mu^2}^{\infty}\frac{ds'}{\pi}\frac{\rho_{\pi\pi}}{s'-s-i\epsilon}\int\frac{dz}{4\pi}\frac{1}{M_R^2-\tilde{s}}.$$

Here z corresponds to the angle between an intermediate pion and outgoing Υ.

The invariant energy squared of the X resonance is equal to

$$\tilde{s}=\mu^2+m^2+2k_{30}k'_{10}-2zk_3k'_1$$

where μ,k'_{10},k'_1 are the mass, energy component, and absolute value of space components of the intermediate pion, while m,k_{30},k_3 are the corresponding characteristics of the outgoing Υ. Performing the integration over z we obtain the following expression for the amplitude $A^{\rm Tr}$:

$$A^{\rm Tr}(s)=\int_{4\mu^2}^{\infty}\frac{ds'}{\pi}\frac{\rho_{\pi\pi}}{s'-s-i\epsilon}\frac{1}{4k_3k'_1}\times\ln\frac{M_R^2-\mu^2+m^2-2k_{30}k'_{10}+2k_3k'_1}{M_R^2-\mu^2+m^2-2k_{30}k'_{10}-2k_3k'_1}. \qquad (4)$$

We calculate this integral with use of the dispersion relation integral over $\pi\pi$ invariant energy s'. Then

$$k_{30}=\frac{W^2-m^2-s'}{2\sqrt{s'}},\quad k_3=\sqrt{k_{30}^2-m^2},$$

$$k'_{10}=\frac{\sqrt{s'}}{2},\quad k'_1=\sqrt{k'^2_{10}-\mu^2},$$

where W is the mass of the initial Υ. The integration over s' near the square root singularities should be performed with the shift $W\rightarrow W+i\epsilon$. In Eq. (2) the isotopic structure of the amplitudes is taken into account as well as the production of $\pi^0\pi^0$ in the intermediate state of the triangle diagram. For the pion final-state interaction amplitude $T_{\pi\pi}\equiv e^{i\delta_0}\sin\delta_0/\rho_{\pi\pi}$, we take the form of Ref. [17].

Using Eqs. (1), (3), and (4) with eight parameters (M_R, Γ_R, three α_{nm}, and three $\lambda_{nm}\equiv\Lambda_{nm}/\alpha_{nm}$) we fit the invariant mass spectra of the three reactions $\Upsilon(3S)\rightarrow\Upsilon(1S)\pi^+\pi^-$, $\Upsilon(3S)\rightarrow\Upsilon(2S)\pi^+\pi^-$, $\Upsilon(2S)\rightarrow\Upsilon(1S)\pi^+\pi^-$ simultaneously. The data in our fit are taken from the CLEO Collaboration [5] (circle) and the CUSB Collaboration [6] (square). A typical fit is shown by solid curves in Fig. 2 with $M_R=10.5$ GeV, $\Gamma=0.15$ GeV, $\lambda_{31}=-3.78$, $\lambda_{32}=-0.76$, and $\lambda_{21}=-2.02$. The α_{nm} constants are absorbed into the normalization factors which are normalized to the number of events measured. The solution has $\chi^2=164$ for 104 degrees of freedom. A big contribution to the χ^2 arises from the older data of CLEO for the $\Upsilon\pi$ invariant mass spectra [open circles in Figs. 2(b,d)]. The χ^2 for the newer data for the $\Upsilon(1S)\pi$ spectrum [block squares in Fig. 2(b)] is good. Further data on the $\Upsilon(2S)\pi$ spectrum to update Fig. 2(d) would be helpful. As a comparison, we also show the case without resonance production (i.e., $\lambda_{nm}=0$) by the dashed curves in Fig. 2; these have $\chi^2=640$. The virtual production of the X resonance improves the fit to the pion-pion invariant mass spectra for all three reactions and at the same time does not disturb the $\Upsilon(1S)\pi^\pm$ spectra very much since the resonance is located outside the Dalitz plot. In Fig. 2(e), we also show the more precise data of the ARGUS Collaboration [21] (triangles). They are compatible with our solution.

In principle, there should be some prior relationship between Γ_R and the values of Λ_{nm}, and also between the values of Λ_{nm} themselves. But due to lack of knowledge of these relationships, we take all of them as free parameters in

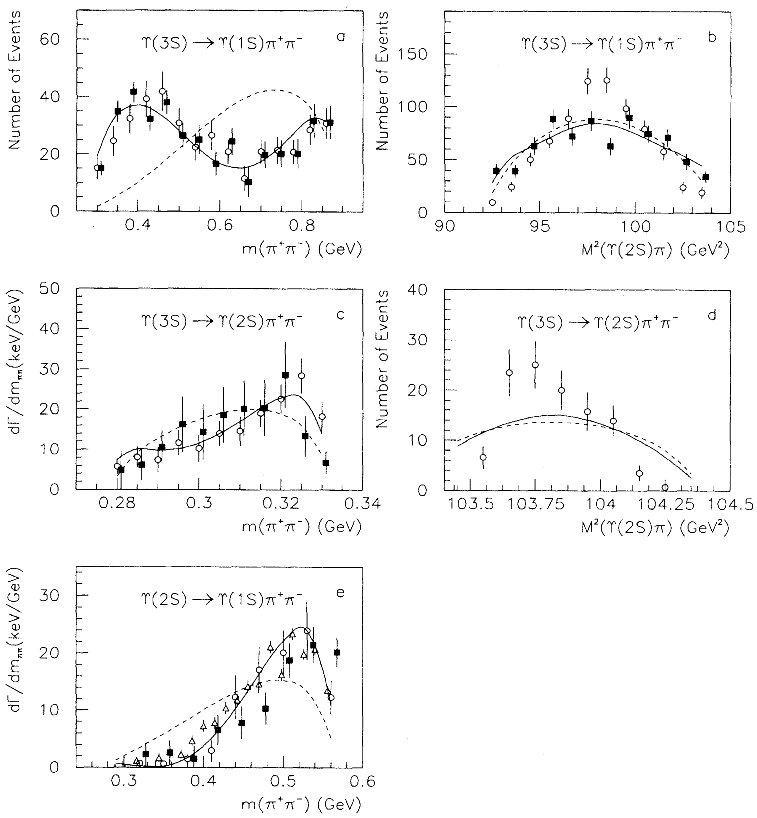

FIG. 2. Typical fit with $M_R=10.5$ GeV and $\Gamma_R=150$ MeV. The data are taken from Ref. [5] (circle) and Ref. [6] (square). The dashed curves are with the standard mechanism [Figs. 1(a,b)] only; the solid curves are with both the standard mechanism and the $X(b\bar{b}q\bar{q})$ resonance production mechanism [Figs. 1(c,d)].

our fit. It may be worthwhile in the future to study microscopically whether the values we fit here are reasonable. The fit is not very sensitive to the width of the resonance. For $M_R=10.5$ GeV, if we change the width from 150 MeV to 0 or 300 MeV, the χ^2 increases by 26 for 104 degrees of freedom. As for the mass of the resonance, if we change it from 10.5 to 10.4 GeV, χ^2 increases by 25; if we increase the mass above 10.5 GeV, we can get an equally good fit by increasing the values of λ_{nm}, i.e., increasing the coupling of the resonance with $\Upsilon\pi$ and therefore also its width. Its strong effect on $\Upsilon(3S)$ suggests its mass is close to $\Upsilon(3S)$, so we limit its mass value below 10.8 GeV.

With our model, the angular distribution for the pion decay angle $\cos\theta^*_\pi$ in the pion-pion rest system is quite flat, close to the result of the conventional mechanism, since pion-pion S wave dominates in both models. So our model cannot explain the slight slope downward from $\cos\theta^*_\pi=0$ to $\cos\theta^*_\pi=1$ reported by the CLEO Collaboration recently [5]. But the discrepancy is small and may be explained by a little mixture of D-wave component in $\Upsilon(3S)$ [22].

A place to check our mechanism is to measure the invariant mass spectra of $\Upsilon(4S)\rightarrow\Upsilon\pi\pi$. We expect a similar double peak would appear for pion-pion invariant mass spectra unless the coupling of the resonance to $\Upsilon(4S)$-π is very small due to some peculiar reason.

We conclude that the existence of an $I=1$ $J^P=1^+$ resonance in the $\Upsilon(1S)\pi$ system is a possible solution of the $\Upsilon(3S)\rightarrow\Upsilon(1S)\pi^+\pi^-$ decay puzzle. It explains naturally all the invariant mass spectra in $\Upsilon(nS)\rightarrow\Upsilon(mS)\pi\pi$. According to our estimation the mass of this resonance is in the region 10.4–10.8 GeV. To find this resonance is important since a resonance with $I=1$ and hidden b flavor would indicate definitely the existence of resonances in the four-quark system, $b\bar{b}q\bar{q}$. Four-quark resonances have been widely discussed but as yet there is no definite indication for their existence.

We thank N. Achasov, I. J. R. Aitchison, S. Stone, and S. F. Tuan for helpful comments and discussions. V.V.A. and A.V.S. are grateful to the Royal Society for financial support for their visit to QMWC.

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