

Possible four-quark isovector resonance in the family of Υ particles

M. B. Voloshin

Institute of Theoretical and Experimental Physics

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It is suggested, on the basis of data on the pion spectrum in the decay $\Upsilon'' \rightarrow \Upsilon \pi^+ \pi^-$, that there is an isovector resonance with a mass near the Υ'' mass.

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Data on the pion spectrum in the decay $\Upsilon'' \rightarrow \Upsilon \pi^+ \pi^-$ reported recently by the CLEO group¹ indicate that the distribution in the invariant mass m of the $\pi\pi$ system in this decay is more uniform than the corresponding distributions in the decays $\Upsilon'' \rightarrow \Upsilon \pi\pi$ and $\psi' \rightarrow \psi \pi\pi$, in which large values of m are significantly enhanced. If the decay amplitude in the c.m. frame is parametrized by

$$A(q_\mu^{(1)} q_\mu^{(2)}) + B q_0^{(1)} q_0^{(2)} \quad (1)$$

($q_\mu^{(1)}$ and $q_\mu^{(2)}$ are the 4-momenta of the pions), then the form factor A in the decay $\Upsilon'' \rightarrow \Upsilon \pi^+ \pi^-$ is relatively small according to the data of Ref. 1: $A/B = 0.12 \pm 0.15$. On the other hand, we know that precisely the opposite condition holds in the decays $\Upsilon' \rightarrow \Upsilon \pi\pi$ and $\psi' \rightarrow \psi \pi\pi$: $A \gg B$.

The hypothesis of partial conservation of axial current (PCAC) was originally used² to explain the nature of the amplitude (1) for the decay $\psi' \rightarrow \psi \pi \pi$. In quantum chromodynamics, these decays have been interpreted³ as stemming from the emission of soft gluons by heavy quarkonium, followed by the conversion of the gluons into π mesons. This conversion is determined^{4,5} by the triangle anomaly in the trace of the energy-momentum tensor, and, according to the analysis of Refs. 4 and 5, the first term in expression (1) should be dominant in the multipole expansion³ for the emission of gluons by heavy quarkonium in these decays.

Important to the applicability of the approach of Ref. 3, which has been used, in particular, in Refs. 4 and 5, is the assumption that the decay amplitude has no singularities near the physical decay region. Therefore, working from the data of Ref. 1 on the spectrum in the decay $\Upsilon'' \rightarrow \Upsilon \pi^+ \pi^-$ —data which are very obviously at odds with the conclusions of Refs. 4 and 5—we should take the approach that this assumption of no singularities does not hold in this case; i.e., we should assume that there is a singularity in the amplitude in the $(\Upsilon \pi)$ invariant mass. [The possibility that a singularity in the $(\pi \pi)$ invariant mass is having an effect can be eliminated easily since the m spectrum in the decay $\Upsilon'' \rightarrow \Upsilon \pi^+ \pi^-$ differs from the spectra in the decays $\Upsilon' \rightarrow \Upsilon \pi \pi$ and $\psi' \rightarrow \psi \pi \pi$ at the same values of m .] In other words, it should be assumed that there exists a resonant state Υ_1 which has an isospin $T = 1$ and a positive G -parity with a mass near the Υ'' mass and that this resonant state is the dominant intermediate state in the decay $\Upsilon'' \rightarrow \Upsilon \pi \pi$. The decay occurs in two steps,

$$\Upsilon'' \rightarrow \Upsilon_1 \pi \rightarrow \Upsilon \pi \pi, \quad (2)$$

and the ordinary gluon mechanism contributes only negligibly to the amplitude.

We can probably rule out values of the Υ_1 mass lower than $M(\Upsilon'') - \mu$ (μ is the mass of the π meson), i.e., the possibility of a real decay $\Upsilon'' \rightarrow \Upsilon_1 \pi$, since in this case it would be difficult to explain the extremely small width of the $\Upsilon'' \rightarrow \Upsilon \pi \pi$ decay, and the π mesons in the decay would be essentially monochromatic, and this circumstance would be noticeable experimentally. We might add that if the Υ_1 mass were approximately equal to the Υ' mass or smaller than $M(\Upsilon')$, this state might distort the spectrum of the decay $\Upsilon' \rightarrow \Upsilon \pi \pi$.

To find the amplitude for the decay which results from process (2) with a state Υ_1 off the mass shell, we should note that according to PCAC the amplitudes for the decays $\Upsilon'' \rightarrow \Upsilon_1 \pi$ and $\Upsilon_1 \rightarrow \Upsilon \pi$ are proportional to the pion energy if these are S -wave decays or proportional to the pion momentum if they are P -wave decays. In the former case the square amplitude for the decay $\Upsilon'' \rightarrow \Upsilon \pi \pi$ should be of the form

$$|C|^2 \left[\frac{(q_0^{(1)} q_0^{(2)})^2}{(q_0^{(1)} - W)^2 + \Gamma^2/4} + (q^{(1)} \rightleftharpoons q^{(2)}) \right],$$

where Γ is the total width of Υ_1 , and $W = M(\Upsilon'') - M(\Upsilon_1)$. In the latter case the square amplitude would be proportional to

$$\frac{[(q_0^{(1)})^2 - \mu^2][(q_0^{(2)})^2 - \mu^2]}{(q_0^{(1)} - W)^2 + \Gamma^2/4} + (q^{(1)} \rightleftharpoons q^{(2)}).$$

It is easy to see that the m spectra described by these expressions at values of W which

are not too close to μ (for $W \lesssim 100$ MeV, for example) are not distinguishable from each other or from the spectrum described by an amplitude of the form of the second term in (1) at the present level of experimental accuracy. As the accuracy improves, however, it may become possible to observe or rule out an Υ_1 resonance by studying the pion energy distribution.

Another possibility is to search for the proposed Υ_1 resonance in the decay of the Υ''' : $\Upsilon''' \rightarrow \Upsilon_1 \pi$. The signature of this decay is obviously the presence of a monochromatic pion. Estimates of the width of this decay are extremely indefinite. If we assume, for a ballpark estimate, that the Υ , Υ'' , and Υ''' resonances are coupled identically with the $\Upsilon_1 \pi$ channel, and if we assume $M(\Upsilon_1) \cong M(\Upsilon'')$, then we can expect values on the order of 0.1 MeV for the width of the decay $\Upsilon''' \rightarrow \Upsilon_1 \pi$.

The observation of an isovector resonance, in particular, a charged resonance, in the Υ family would represent the observation of an indisputable four-quark state (b, \bar{b}, q, \bar{q}) consisting of heavy and light quarks. Four-quark mesons have been discussed from time to time in the literature as states of light quarks exclusively and also as states of heavy and light quarks (see Refs. 6 and 7, for example). Up to now, however, all proposed candidates for such states could also be interpreted in the standard way, as quark-antiquark states. For the proposed Υ_1 resonance, in contrast, the standard interpretation can be ruled out. We note in conclusion that it is extremely likely that Υ_1 can be produced in hadron collisions,¹⁾ although it would be essentially impossible to calculate a cross section for this production at present, without an understanding of the structure of this state.

¹⁾This possibility was pointed out to the author by L. B. Okun'.

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