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Is a State $c\bar{c}c\bar{c}$ Found at 6.0 GeV?

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It is pointed out that the newly discovered particle at 6 GeV may correspond to the $c\bar{c}c\bar{c}$ state which was previously predicted to exist around 6 GeV by the present author. It will decay dominantly to $J/\psi\,(3.1)+\eta_c\,(2.8)$.

One year ago, the present author[1] predicted a $c\bar{c}c\bar{c}$ resonance state at about 6.2 GeV based on a model of charm and exotics. Recently a new resonance[2] at about 6.0 GeV was reported. It is quite natural to consider that the newly discovered resonance corresponds to what was predicted in Ref. 1.[3] In this Letter this possibility will be examined in detail and possible tests of the model will be given.

In the present model the $J/\psi(3.1)$ meson is assigned to a vector meson $c\bar{c}$, as is usual in the charm scheme, while the $\psi(3.7)$ meson is assigned to an exotic meson $c\bar{c}(u\bar{u}+d\bar{d})$. Two resonances, $c\bar{c}(u\bar{u}-d\bar{d})$ $(I=1)$ and $c\bar{c}s\bar{s}$ $(I=0)$, were predicted in Ref. 1 between ~ 3.7 and ~ 4.1 GeV, as well as another resonance $c\bar{c}c\bar{c}$ at 6.2 GeV. As a rough estimate for the masses of these resonances, I used the sum of the quark masses, assuming $m_u = m_d = 300\text{–}400$ MeV, $m_s \sim 500$ MeV, and $m_c \sim 1550$ MeV.

The states $q\bar{q}q\bar{q}$ belong to $\underline{84}\oplus\underline{15}\oplus\underline{1}$ in the SU(4) symmetry if two quarks and two antiquarks are symmetric (symmetric states), respectively, in the SU(4) indices, while they belong to $\underline{20}\oplus\underline{15}\oplus\underline{1}$ if two quarks and two antiquarks are antisymmetric (antisymmetric states). The other states belong to $\underline{45}\oplus\underline{45}^*\oplus\underline{15}\oplus\underline{15}$ where two quarks are symmetric and two antiquarks are antisymmetric or vice versa (mixed-symmetry states). The model in Ref. 1 corresponds to the symmetric case (Model I).

An alternative model (Model II) is the one where both the symmetric and antisymmetric states exist. In this model there are six exotic vector mesons $c\bar{c}q'\bar{q}'$ (two $I=1$ and four $I=0$ states), where q' stands for u, d, or s. Note that there are three states in Model I. These states correspond to resonances between 3.7 and 4.4 GeV. I assume that the mixed-symmetry states exist at the higher mass region or do not exist as resonances at all.

I do not discuss here the complications due to spin and orbital angular momenta and just assume that there is a vector meson corresponding to each unitary spin state. I shall discuss the details of the models which depend on dynamics, as well as the justification of the assumptions made here and above, in a separate paper.

The choice between the two models is reserved for future investigation when more experimental data are available. (There are also other variations than Model I and Model II.) I refer to $c\bar{c}(u\bar{u}+d\bar{d})$, $c\bar{c}(u\bar{u}-d\bar{d})$, $c\bar{c}s\bar{s}$, and $c\bar{c}c\bar{c}$ as ψ_ω, ψ_ρ, ψ_φ, and ψ_ψ, respectively. (Note that there are two ψ_ω,

ψ_ρ, and ψ_φ mesons in Model II.) The physical states are mixtures of these states. In Model II, in particular, mixing effects will be significant.

$\psi_\psi \to J/\psi(3.1) + \eta_c(2.8)$.—If the new resonance at 6 GeV is the ψ_ψ meson in the present model, it will decay dominantly to $J/\psi(3.1)$ and $\eta_c(2.8)$. The mechanism of this decay is essentially the same as that of the decay $\psi(3.7) \to J/\psi(3.1) + \eta$. We can roughly estimate the width of the decay $\psi_\psi \to J/\psi(3.1) + \eta_c(2.8)$, using the experimental value $\Gamma(J/\psi(3.7) \to \psi(3.1) + \eta) \sim 9$ keV as an input. Assuming that the width depends on q^3/M_i^2 (M_i is the mass of the parent particle) and taking into account the mixing effect of η and η', we obtain

$$\Gamma(\psi_\psi \to J/\psi(3.1) + \eta_c(2.8)) \sim 140 \text{ keV}. \tag{1}$$

It should be noted that this is a rough number, since the coupling constant may depend on the masses of relevant particles.

The other decays of the ψ_ψ meson will be suppressed by the Okubo-Zweig-Iizuka (OZI) rule.[4] The next favorable decay modes are J/ψ + (ordinary mesons) or $\eta_c(2.8)$ + (ordinary mesons). The decay to ordinary mesons only is doubly suppressed by the OZI rule. Thus the total width will be in the range several times 10 keV to several times 100 keV.

$\psi(3.7) \to \psi(3.1) + 2\pi$ and $\psi(3.7) \to \psi(3.1) + \eta$.—The present model accommodates the large branching ratios of the decays $\psi(3.7) \to J/\psi(3.1) + 2\pi$ and $J/\psi(3.1) + \eta$. In the model these decays are allowed ones, while the decay $\psi(3.7) \to n\pi$ is forbidden by a generalized OZI rule.[1] One comment is in order here. Sometimes an exotic meson (M_4) is assumed not to decay to ordinary mesons.[5] In a string model, however, the decay is not forbidden.[1] Accordingly I assume here that the decay is is not forbidden.

In the model the mechanism of the decay $\psi(3.7) \to \eta_c(2.8) + \omega$ is the same as that of the decay $\psi(3.7) \to J/\psi(3.1) + \eta$. In a similar way as used to derive Eq. (1), we obtain the branching ratio

$$R(\psi(3.7) \to \eta(2.8) + \omega) \sim 30\%. \tag{2}$$

We understand that there are about 30% unknown decay modes of $\psi(3.7)$. The decay to $\eta_c(2.8) + \omega$ may resolve this situation.

If we assign $\psi(3.7)$ to a radially excited state of $J/\psi(3.1)$, the decays $\psi(3.7) \to J/\psi(3.1) + 2\pi$ and $\psi(3.7) \to J/\psi(3.1) + \eta$ are forbidden under the OZI rule and, further, the latter is SU(3) forbidden. The decay $\psi(3.7) \to \eta_c(2.8) + \omega$ also should be suppressed and consequently the branching ratio should be much less than in Eq. (2).

Small yield of $\psi(3.7)$ in hadronic reactions.—The upper bound for the $\psi(3.7)$ production cross section in $p + N$ scattering at Fermi National Accelerator Laboratory[6] is

$$\sigma(p + N \to \underset{\llcorner\!\to l\bar{l}}{\psi(3.7)} + X) \lesssim \tfrac{1}{200}\,\sigma(p + N \to \underset{\llcorner\!\to l\bar{l}}{J/\psi(3.1)} + X). \tag{3}$$

Taking into account the factor $\frac{1}{5}$ of the ratio of the branching ratios to lepton pairs, we find

$$\sigma(p + N \to \psi(3.7) + X) \lesssim \tfrac{1}{40}\,\sigma(p + N \to J/\psi(3.1) + X). \tag{4}$$

The small cross section of the $\psi(3.7)$ production might suggest a difference in structure between $J/\psi(3.1)$ and $\psi(3.7)$. The present model naturally explains this difference.

Coupling with the photon.—Since the electromagnetic current transforms as $\underline{15} \oplus \underline{1}$ in the SU(4) symmetry, the exotic states $\underline{84}$ and $\underline{20}$ cannot couple with the photon in the SU(4)-symmetry limit. However, they can couple with the photon through a large symmetry breaking, $T_4{}^4$. In view of this, I discuss the coupling of the exotic meson with the photon in the SU(3)-symmetry limit.

In the SU(3) symmetry, the ψ_ω, ψ_ρ, and ψ_φ mesons belong to $\underline{8} \oplus \underline{1}$. In the ideal mixing case

$$\Gamma(\psi_\omega \to e^+e^-) : \Gamma(\psi_\rho \to e^+e^-) : \Gamma(\psi_\varphi \to e^+e^-) = |1 + 2a|^2 : 9 : |\sqrt{2}(-1 + a)|^2, \tag{5}$$

where a is a parameter which corresponds to the contribution from the $\underline{1}$ component of the current.

I discuss the two cases $a = \pm 2$ in detail. The choice $a = +2$ corresponds to the case where an exotic meson $c\bar{c}q\bar{q}$ is produced as $(cq) + (\bar{c}\bar{q})$, while the choice $a = -2$ corresponds to the case $(c\bar{q}) + (\bar{c}q)$. That is, in the former case the photons couple with the sum of the charges of c and q, while in the latter with the sum of the charges of c and $\bar{q}$. In other words in the former case the "molecular" structure in an exotic meson is diquark, while in the latter case the molecular structure is a quark-antiquark pair.

In the quark-parton approach, it is generally assumed that the photon couples with a quark, but does not couple with a molecular structure of quark. One should note, however, that at $q^2 = 0$ the photons couple with any state which has a charge. The point is how fast the form factor does decrease.

According to the report by Schwitters,[7] an upper limit (90% confidence level) for the radiatively corrected integrated cross section of a possible narrow resonance is 450 nb MeV in the mass region 5.90 to 7.60 GeV. This number corresponds to

$$\Gamma_{ee} \leq 700 \text{ eV}. \tag{6}$$

It should be noted that if the new resonance is a pair state of a new quark with $Q=\frac{2}{3}$ (or $Q=\frac{1}{3}$), the particle width to an electron pair is naively $\Gamma_{ee}=4$ keV (or $\Gamma_{ee}=1$ keV), which the author regards as being in contradiction to (6). Although we cannot predict the partial width in the present model, we can stay within the experimental limit.

Let us assume, just as an example, that $\Gamma_{ee}=300$ eV, $\Gamma_{\text{tot}}=150$ keV, and $\sigma(p+N\to\psi_\psi+X)=\frac{1}{50}\sigma(p+N\to J/\psi(3.1)+X)$. Then we obtain

$$\sigma(p+N\to \underset{\hookrightarrow l\bar{l}}{\psi_\psi}+X) \simeq \frac{1}{2000}\sigma(p+N\to \underset{\hookrightarrow l\bar{l}}{J/\psi(3.1)}+X), \tag{7}$$

which is consistent with the experiment.[2] These numbers are not predictions and are given just to show that the present model is consistent with the experiment.

Exotics without charmed quarks.—The model predicts a lot of exotic mesons without the charmed quark in the mass region between about 1.5 and 2.2 GeV. Although there are several candidates,[8] none of the hadrons are identified definitely as exotics. This may seem to be a difficulty in the model. I do not, however, consider it as a difficulty for the following reasons:

(i) The spectroscopy above 1.5 GeV is not satisfactory except for the leading trajectories. For example, the ψ' meson which is an SU(3) partner of the $\rho'(1600)$ meson has not been discovered and the ω' meson has not been observed, at least in e^+e^- annihilation, although I do not necessarily assume that these mesons are exotics. I hope that more extensive searches for exotic mesons will reveal their existence. For example, an exotic meson such as $(u\bar{u}+d\bar{d})(u\bar{u}-d\bar{d})$ will decay to $\rho 2\pi$ with a width of several MeV.

(ii) The possible existence of exotics does not make invalid the success of the duality without exotics, since the trajectory of the exotic meson will lie much below the leading trajectory, at the position which corresponds to the second daughter.

(iii) The model predicts a doubly charged meson such as $u\bar{d}u\bar{d}$ around 1600 MeV. The decay to $\pi^+\pi^+$ might be suppressed compared with many-body decays such as $\rho^+\pi^+\pi^0$.

(iv) The production of exotic mesons in hadronic reactions (such as πN or NN reaction) may be suppressed compared with ordinary mesons.[1]

In conclusion, the present model is consistent with the experiment. A crucial test for the model is whether the new resonance at 6 GeV does decay dominantly to $J/\psi(3.1)+\eta_c(2.8)$.

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