How to find η_c and a possible state $c\bar{c}c\bar{c}$

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In order to test the existence of $X(2.8)$ and the validity of interpreting it as a pseudoscalar $c\bar{c}$ meson, and also to test the existence of a possible state $c\bar{c}c\bar{c}$, it is proposed to measure the recoil-mass spectrum against $J/\psi(3.1)$ at the c.m. energy about 6 GeV in e^+e^- annihilation. This also serves to check the Okubo-Zweig-Iizuka rule.

The discovery of the charmed mesons makes it almost certain that it is valid to interpret $J/\psi(3.1)$ as a hidden charm state. The spectroscopy of these particles is well described by a picture that they are nonrelativistic quark-antiquark bound states. In this picture $J/\psi(3.1)$ is assigned to a $^3S_1$ state of $c\bar{c}$ and the pseudoscalar partner (to be called hereafter η_c) should exist near $J/\psi(3.1)$. The most plausible candidate for η_c is $X(2.8)$.[1] However, the existence of $X(2.8)$ itself is not completely established. Further, even if the existence is established, it is another problem whether $X(2.8)$ is really η_c. One of the puzzles that occurs in interpreting $X(2.8)$ as η_c is that the width for the decay $J/\psi(3.1) \rightarrow X(2.8)\gamma$ is too small compared with the theoretical expectations.[2] The $X(2.8)$ might be, for example, an exotic state made of ordinary quarks. It is therefore an urgent problem to make clear the existence of $X(2.8)$ and further to test the interpretation of $X(2.8)$ as η_c. One of the purposes of this note is to propose an experimental method which can give answers for these problems.

Before going into the experimental proposal, let us discuss another problem concerning the spectroscopy of the new particles: there seems to be too many resonances of vector mesons in e^+e^- annihilation at the energy about 3.9–4.4 GeV. Two years ago, the present author predicted[3,4] the exotic resonances $c\bar{c}q\bar{q}$, where q stands for u, d, or s, at about 3.7–4.1 GeV, much prior to the discovery of the resonances at 4.028 GeV and 4.4 GeV. After the discovery of them, some authors interpreted[5] them as exotic states. Further, recent data show that the resonance at 4.028 GeV couples strongly with $D^*\bar{D}^*$. This fact supports the interpretation that the resonance is an exotic state.[6]

In the article quoted above (Ref. 3), where the exotic states $c\bar{c}q\bar{q}$ were predicted, an exotic state $c\bar{c}c\bar{c}$ was also predicted at about 6.2 GeV (to be called hereafter ψ_ψ). If the exotic resonances $c\bar{c}q\bar{q}$ do really exist at about 4.0 GeV,

there is no reason *a priori* to reject the possibility' of the existence of ψ_ψ. Of course, the existence depends on the dynamics about which we unfortunately do not know much.

After the prediction, Eartly *et al.*[7] has an indication for a structure around 6 GeV in the muon-pair mass spectrum. Hom *et al.*[8] also reported clustering of events, which suggests a new resonance at 6 GeV in the electron-pair mass spectrum. However, in the muon-pair experiment by Hom *et al.*[9] data did not confirm a possible structure near $m_{e^+e^-} = 6$ GeV. Further, in the e^+e^- annihilation experiment at SLAC there are no indications for resonances at about 6 GeV.[10] The last experimental result apparently seems to be the most stringent against the existence of the resonance. However, as discussed in Ref. 4, we should say that it does not rule out the possibility of the existence of the resonance in question.

As new experimental results have been obtained since then, let us discuss here again, somewhat in detail, the last point stated in the preceding paragraph. The upper limit for the partial width Γ_{ee} of a possible resonance around 6.0 GeV was reported as[10]

$$\Gamma_{ee} \leq 100 \text{ eV}. \tag{1}$$

On the other hand, the experiment by Hom *et al.*[8] indicates that

$$B(\psi_\psi \rightarrow ee)\sigma(p+N \rightarrow \psi_\psi + X)$$
$$= \tfrac{1}{2000} B(J/\psi(3.1) \rightarrow ee)\sigma(p+N \rightarrow J/\psi(3.1)+X), \tag{2}$$

at the incident energy 400 GeV, whereas the experiment by Hom *et al.*[9] (in the electron-pair experiment) shows that even if the resonance should exist at all, the numerical factor in (2) should be smaller than $\tfrac{1}{2000}$. Since the estimate of the factor depends on some assumptions for acceptance and others, the number $\tfrac{1}{2000}$ itself may not be taken seriously, and this is also the case with the upper limit in Ref. 9. Since we need only rough

numbers in the subsequent discussions, we will use this number $\frac{1}{2000}$ for convenience.

By writing

$$R_B(\psi_\psi \to ee) = c/1000, \tag{3}$$

where c is a parameter, we obtain

$$\sigma(p+N \to \psi_\psi + X) = 0.03\frac{1}{c}\,\sigma(p+N \to J/\psi(3.1)+X) \tag{4}$$

and

$$\Gamma_{\psi_\psi} \lesssim 100/c \text{ keV} \tag{5}$$

from Eq. (2) and from Eq. (1), respectively. According to the estimate of Γ_{ψ_ψ} performed in Ref. 4, $\Gamma_{\psi_\psi} \sim 10^2$ keV. Thus, if c is of the order of unity, there is no contradiction between the limit, Eq. (1), and the existence of a narrow resonance.

The only problem is why the partial width Γ_{ee} is so small. If the ψ_ψ meson is a molecular state made of $J/\psi(3.1)$ and η_c, the electric charge of "atoms," $J/\psi(3.1)$ and η_c, are both neutral. Thus the coupling of the photon with the ψ_ψ meson takes place only through the substructures of the atom, and is therefore rather weak.[4] In view of these facts, it is also an urgent task to establish the existence (or nonexistence) of the ψ_ψ meson.

Let us now proceed to our experimental proposal. First in order to establish the existence of the η_c meson we propose to measure the recoil-mass spectrum against $J/\psi(3.1)$ at the c.m. energy about 6 GeV in e^+e^- annihilation. If there is a peak around 2.8 GeV, $X(2.8)$ will have to be η_c. If this is not the case, there will be peaks at different energies which correspond to η_c and to other states such as 0^{++}, 2^{++} mesons with the composition $c\bar{c}$.

It is of interest to see how the productions of $J/\psi(3.1)+\omega$, ρ, A_2, etc. are suppressed compared with that of $J/\psi(3.1)+\eta_c$. The quark diagram which corresponds to, e.g., $J/\psi(3.1)+\omega$, is of the same type as that corresponding to the decay $\psi(3.7) \to J/\psi(3.1)+\eta$. The experiment will tell us in what manner the Okubo-Zweig-Iizuka (OZI) rule[11] does work.

Let us now turn to the discussion of the search for the ψ_ψ meson. The experimental method we wish to propose is essentially the same as that discussed above. Measure the inclusive $J/\psi(3.1)$ production around 6 GeV in e^+e^- annihilation. If there is a peak in the cross section, it may correspond to the ψ_ψ meson. Further, if the recoil-mass spectrum shows a peak at some energy, e.g., at 2.8 GeV, then it indicates first that the peak in

the recoil-mass spectrum is the η_c meson and second that the resonance decays dominantly to $J/\psi(3.1)$ and η_c, that is, the resonance is the ψ_ψ meson.

Finally let us discuss further the motive of the prediction we made concerning the exotic mesons $c\bar{c}q\bar{q}$ and the ψ_ψ meson in Refs. 3 and 4. It was pointed out[3] that $\psi(3.7)$ may be an exotic state $c\bar{c}(u\bar{u}+d\bar{d})$ contrary to the usual assignment, the radial excitation of $J/\psi(3.1)$. Two phenomena were listed in Ref. 3 which can be explained more easily when $\psi(3.7)$ is assigned to the exotic state $c\bar{c}(u\bar{u}+d\bar{d})$ than to the radial excitation. Let us investigate the recent situation concerning the two phenomena.

(i) The ratios of $\psi(3.7)$ production to $J/\psi(3.1)$ production in pN collisions at various energies are as follows:

$$\sigma(\psi(3.7))/\sigma(J/\psi(3.1))$$

$$< 7\% \text{ at } p_L = 28 \text{ GeV (Ref. 12)}$$

$$\cong 1\% \text{ at } p_L = 225 \text{ GeV (Ref. 13)}$$

$$= 10\% \text{ at } p_L = 400 \text{ GeV (Ref. 14)}. \tag{6}$$

It should be noted that at 225 GeV the ratio is only 1%, which is significantly different from 10%, the ratio at 400 GeV. This smallness of the ratio and the strong energy dependence above 200 GeV suggest that the structure of $\psi(3.7)$ differs from that of $J/\psi(3.1)$. It was predicted in Ref. 3 that if $\psi(3.7)$ is an exotic meson, $c\bar{c}(u\bar{u}+d\bar{d})$, the yield of $\psi(3.7)$ will grow more slowly than that of $J/\psi(3.1)$ as the incident energy increases. The data are consistent with this prediction.

(ii) Although the decay $\psi(3.7) \to J/\psi(3.1)+\eta$ is forbidden by the OZI rule and SU(3) symmetry, the effective coupling constant turns out not to be so small as expected when we take into account the small phase space. In our model $\psi(3.7)$ belongs to $\underline{8}$ in the SU(3) symmetry, contrary to $\underline{1}$ in the usual assignment, and the decay $\psi(3.7) \to J/\psi(3.1)+\eta$ is not forbidden by the generalized OZI rule.[3] Thus our model accommodates this point.

Regarding the above two points (i) and (ii) the assignment of $\psi(3.7)$ to an exotic state $c\bar{c}(u\bar{u}+d\bar{d})$ is still consistent with the data. Some of the states with even charge conjugation which lie between 3.7 GeV and 3.1 GeV may be also exotic states.

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