$Y(4260)$ as an $\omega \chi_{c1}$ molecular state

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Outline

Introduction
$Y(4260)$ as $\omega \chi_{c1}$ molecular state
Decays of $Y(4260)$
Production of $Y(4260)$
Discussion
Recently, in studying the initial-state radiation events,
\[ e^+ e^- \rightarrow \gamma_{\text{ISR}} \pi^+ \pi^- J/\psi \] (\( \gamma_{\text{ISR}} \): initial state radiation photon) with 233 fb\(^{-1} \) data collected around \( \sqrt{s} = 10.58 \) GeV, BaBar collaboration observed an accumulation of events near 4.26 GeV/c\(^2 \) in the invariant-mass spectrum of \( \pi^+ \pi^- J/\psi \).
Introduction

The fit to the mass distribution yields 125 ± 23 events with a mass of $4259 \pm 8_{-6}^{+2}$ MeV/$c^2$ and a width of $88 \pm 23_{-4}^{+6}$ MeV/$c^2$. 
Introduction

Since the resonance is produced in initial state radiation from $e^+e^-$ collision, its quantum number $J^{PC} = 1^{--}$. However, this new resonance seems rather different from the known charmonium states with $J^{PC} = 1^{--}$ in the same mass scale, such as $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$. Being well above the $D\overline{D}$ threshold, the $Y(4260)$ shows strong coupling to $\pi^+\pi^- J/\psi$ final state. So this new resonance does not seem to be a usual charmonium state but rather an exotic. The strange properties exhibited by the $Y(4260)$ have trigged many theoretical discussions.
In the paper C.Z.Yuan, P.Wang and X.H.Mo, Physics Letter B 634 (2006) 399-402 we proposed the $Y(4260)$ as a bound state composed of the vector meson $\omega(783)$ and the $P$-wave charmonium state $\chi_{c1}(3510)$.

In this scenario, $Y(4260)$ decays into $\pi\pi J/\psi$, and it is expected that it decays into $\pi^+\pi^-\pi^0\chi_{c1}$ with considerably large rate. The search for the latter is experimentally reachable using the available data from the $B$-factories. In addition, this scenario could give some predictions which are distinctive from those of other models.
Since the $Y(4260)$ decays into $\psi(3770)$, it is very natural to consider that there is $c\bar{c}$ content in its wave function. We try to find a narrow charmonium state and a narrow light meson to form a $J^{PC} = 1^{--}$ state, with the sum of their masses slightly above the mass of the $Y(4260)$. There are not many such combinations, and we find that the one consisting of a $1^{--}$ state $\omega$ (mass 782.59 MeV/$c^2$) and a $1^{++}$ state $\chi_{c1}$ (mass 3510.59 MeV/$c^2$) satisfy the criteria. The sum of the masses, 4293 MeV/$c^2$, is higher than the mass of the $Y(4260)$ by 34 MeV/$c^2$, which is considered as the binding energy between the two constituents to form the bound state. The orbital angular momentum between $\omega$ and $\chi_{c1}$ can be zero to get the quantum number $J^{PC} = 1^{--}$. Here the $Y(4260)$ is an iso-scalar particle and so has no isospin-partner.
Decays of the $Y(4260)$

The decays of $Y(4260)$ to the observed $\pi^+\pi^- J/\psi$ is illustrated

$Y(4260) \xrightarrow{\omega} \chi_{c1} \xrightarrow{\omega} \sigma \xrightarrow{\omega} J/\psi$
Decays of the $Y(4260)$

This decay mechanism can be seen from the $\pi^+\pi^-$ invariant mass distribution in the BaBar data.
Decays of the $Y(4260)$

In this scenario, according to the isospin symmetry, we expect

$$\frac{\Gamma[Y(4260) \to \pi^0 \pi^0 J/\psi]}{\Gamma[Y(4260) \to \pi^+ \pi^- J/\psi]} \approx 0.5,$$

(1)

which is different from the predictions of being 1 in in the scenario of $Y(4260)$ as a $\Lambda_c - \bar{\Lambda}_c$ and being 0 in scenario that $Y(4260)$ is $\chi_c - \rho$ molecular. This provides a proof to our scenario.
The $Y(4260)$ also decays via the exchange of a scalar particle as illustrated in

$$
\begin{array}{cc}
\omega & \omega^* \\
\sigma & \\
\end{array}
$$

So a search for the $Y(4260)$ decays into $\gamma\chi_{c1} \rightarrow \gamma\gamma J/\psi$, or $\omega^*\chi_{c1} \rightarrow \pi^+\pi^- \pi^0 \gamma J/\psi$, provides another test of our scenario.
Decays of the $Y(4260)$

The exchanges of light hadrons between the $\omega$ and $\chi_{c1}$ inside the molecular state require the exchange of at least two or three gluons in the quark level and thus the processes are OZI suppressed, which in principle, will be smaller than the final states produced by changing quarks in the two constituents in the initial states directly, as shown by

$$
\begin{array}{c}
\omega \\
\text{u,d} \\
\bar{u},d \\
\bar{c} \\
\chi_{c1} \\
\bar{c} \\
\text{u,d} \\
c \\
c
\end{array}
\begin{array}{c}
D^{(*)} \\
\text{u,d} \\
\bar{c} \\
\bar{u},d \\
D^{(*)} \\
c \\
c
\end{array}
$$

However, in these decays of the $Y(4260)$ into $D^{(*)}\overline{D}^{(*)}$ which indicates possible combinations such as $D\overline{D}$, $D^{*}\overline{D}$, $DD^{*}$, and $D^{*}\overline{D}^{*}$, the rate is suppressed due to color reconnection.
Decays of the $Y(4260)$

From these discussions, we see that the two decay mechanisms may have comparable decay rates. The decays of the $Y(4260)$ into a charmonium state together with a photon or some light mesons like pions will be better tagging modes due to the clear signature and clean environment; while the decays of the $Y(4260)$ to the charmed mesons have not been discovered experimentally by now because of the small branching fractions of the $D$ decay modes.

The decays of the $Y(4260)$ into charmed meson-pair with strange quarks have even lower rates since a strange quark pair must be created.
Production of the $Y(4260)$

The production of the $Y(4260)$ in $e^+e^-$ collision occurs via the so-called hairpin mechanism.

$e^+e^- \rightarrow \omega \chi_{c1}^*$

$Y(4260)$ as an $\omega \chi_{c1}$ molecular state
The $Y(4260)$ was also found in $B$ decays in association with a $K$ meson. It may be produced via a spectator diagram,
Production of the $Y(4260)$

It may also be produced a hairpin diagram, as shown in
Production of the $Y(4260)$

Although in the hairpin mechanism, the $\omega$ is produced from the gluons emitted by the quarks, so its amplitude is thought to be suppressed, but there is indication from the weak decays of charmed mesons that such suppression is not severe: the experiments measured $\mathcal{B}(D^0 \to \phi \overline{K}^0) = (9.4 \pm 1.1) \times 10^{-3}$ and $\mathcal{B}(D_s^+ \to \omega \pi^+) = (2.8 \pm 1.1) \times 10^{-3}$ can be explained by

If this is extended to the weak decays of $B$ mesons, one may expect that the hairpin diagrams could be important in the production of the $Y(4260)$ in $B$ decays.
Although the above discussions are limited to the $\omega \chi_{c1}$ bound state, the scenario can be naturally extended to other bound states consisting of a light meson and a charmonium state. If the bound state of $\chi_{c1}$ and $\omega$ exists, by the same mechanism, a $\chi_{c0}$ or a $\chi_{c2}$ can also form a bound state with an $\omega$.

At the same time, besides $\omega$, other $SU(3)$ singlet light hadrons, like $\phi$, $\eta$, and $\eta'$, can also form bound states with charmonia, such as $J/\psi$, $\psi'$, $\chi_{c0}$, $\chi_{c1}$, $\chi_{c2}$ and $h_c$. 
Table 1: The sum of the masses (in MeV/$c^2$) of a light meson and a charmonium state. A bound state of each possible combination could be produced by emitting a few or a few ten MeV binding energy. The numbers underlined may correspond to the states which have been observed experimentally.

<table>
<thead>
<tr>
<th></th>
<th>$J/\psi$</th>
<th>$\chi_{c0}$</th>
<th>$\chi_{c1}$</th>
<th>$\chi_{c2}$</th>
<th>$h_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta$</td>
<td>3645</td>
<td>3963</td>
<td>4058</td>
<td>4104</td>
<td>4073</td>
</tr>
<tr>
<td>$\eta'$</td>
<td>4055</td>
<td>4373</td>
<td>4468</td>
<td>4514</td>
<td>4483</td>
</tr>
<tr>
<td>$\omega$</td>
<td>3880</td>
<td>4198</td>
<td>4293</td>
<td>4339</td>
<td>4308</td>
</tr>
<tr>
<td>$\phi$</td>
<td>4116</td>
<td>4435</td>
<td>4530</td>
<td>4576</td>
<td>4544</td>
</tr>
</tbody>
</table>

Considering a binding energy of a few to a few ten MeV in forming the bound state, we can see the newly observed states $X(3872)$ could be interpreted as an $\omega J/\psi$ bound state, the $Y(3940)$ could be an $\eta \chi_{c0}$ bound state.
Discussions

Furthermore, there are many other possible combinations which have no experimental evidence yet. Their decay properties can be analyzed in the same way as in this Letter, and the production of these bound states in $e^+e^-$ collision (if it is a $J^{PC} = 1^{--}$ state) and in $B$ decays follows the similar mechanisms described in previous sections. These bound states should be searched for by the $B$-factories both in ISR data and in $B$ decays.