BABAR resonance as a new window of hadron physics

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Possible decays of four-quark mesons are studied by assigning the newly observed BABAR resonance to a four-quark meson, \( \hat{F}_1^+ \sim [cq][\bar{q}q] \) with \( q = u, d \). It is expected that some of them can be observed as narrow resonances. Implication of existence of four-quark mesons in hadronic weak interactions is also discussed.

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Recently the BABAR Collaboration [1] has observed a narrow \( D_1^+\pi^0 \) resonance with mass \( 2317.6 \pm 1.3 \text{ MeV} \) and width \( 8.8 \pm 1.1 \text{ MeV} \), and suggested that it is a scalar four-quark meson.

Four-quark mesons, \( \{qq\bar{q}q\} \), can be classified into four types [2].

\[
\{qq\bar{q}q\} = \{qq|\bar{q}q\} \oplus \{qq|(q\bar{q})\} \oplus \{(qq)(\bar{q}q)\} \pm (qq)(\bar{q}q), \tag{1}
\]

where () and [] denote symmetry and anti-symmetry, respectively. The first two on the right-hand-side of Eq. (1) can have \( J^{P(C)} = 0^{++}(0^+) \). Each of them is again classified into two classes because of two different ways to produce color singlet \( \{qq\bar{q}q\} \). Since these two can mix with each other, however, they are classified into heavier and lighter ones after all. We discriminate these two by putting * on the former as in Table 1 according to Ref. [2] in which the four-quark mesons were studied within the framework of \( q = u, d \) and \( s \). To explore hadronic weak decays of charm mesons, we have extended the above framework straightforwardly to \( q = u, d, s \) and \( c \), and studied a role of four-quark mesons [2, 4, 5, 6]. The heavier class of \( \{qq|\bar{q}q\} \) and \( \{qq|(q\bar{q})\} \) (with *) can play a dramatic role in charm decays while the lighter class of them (without *) can play an important role in hadronic weak interactions of \( K \) mesons [2]. Not only in hadron spectroscopy but also in hadronic weak interactions of \( K \) and charm mesons, therefore, it is very much important to confirm the existence of four-quark mesons.

In this short note, however, we will concentrate on the \( \{cq|\bar{q}q\} \) mesons (with \( q = u, d, s \)) since the other types of four-quark mesons will be massive enough to decay into two pseudoscalar mesons and therefore they will be broad and not very easy to observe. In Ref. [5], however, the mass of \( \hat{F}_1 \sim [cq][\bar{q}q] \) (with \( q = u, d \)) which was crudely estimated by using a simple quark counting and the result on the light four-quark meson masses in Ref. [2] was higher by \( \sim 100 \text{ MeV} \) than the measured one of the BABAR resonance since we took \( \Delta m_s = m_s - m_u = 0.2 \text{ GeV} \). We here revise the mass values of the \( \{cq|\bar{q}q\} \) mesons exchanging the old value of \( \Delta m_s \) by a new one, \( \Delta m_s \simeq m_{D_s} - m_D \simeq 0.1 \text{ GeV} \) at \( \sim 2 \text{ GeV} \) scale, and using the measured \( m_{\hat{F}_1} = 2.32 \text{ GeV} \) as the input data.

[We will assign the BABAR resonance to \( \hat{F}_1^+ \) later.] Their revised mass values are listed in Table 1. [The notations have been given in Ref. [2].] \( E^0 \sim [cs][\bar{u}d] \) was previously described by \( \hat{F}_0^0 \) but it seems to be misleading so that it is now revised. See also, for more details, Ref. [2]. To estimate more precisely the masses of \( \{cq|\bar{q}q\} \) mesons with *, we need additional input data.

As seen in Table 1, the four-quark mesons with * have large masses enough to decay into two pseudoscalar mesons so that they will be broad as mentioned before. On the contrary, the estimated masses of \( \{cq|\bar{q}q\} \) without * are close to the thresholds of two body decays through strong interactions. Therefore, some of them can decay through strong interactions but their rates will be rather small due to their small phase space, so that they will be observed as narrow resonances like the BABAR resonance. Since some of them are not enough massive to decay into two pseudoscalar mesons through strong interactions, their dominant decays may be \( I \)-spin non-conserving ones unless their masses are higher than the expected ones.

The \( \hat{F}_1 \) mesons form an iso-triplet, \( \hat{F}_1^{++}, \hat{F}_1^+, \hat{F}_1^0 \) and \( \hat{F}_0^0 \), where iso\((I)\)-spin symmetry is always assumed in this note unless we note in particular. Then all of them can have the same type of kinematically allowed decays, \( \hat{F}_1 \sim D_s^+ \pi^0 \), with different charge states. The other decays, for example, \( \hat{F}_1 \sim D_s^+ (\pi\pi) \), are not allowed kinematically.

We have two iso-doublets \( \hat{D} \) and \( \hat{D}^* \). The former can decay into \( D \pi \) final states, \( \hat{D} \sim D \pi \), and the kinematical condition is similar to the one in the decay, \( \hat{F}_1 \sim D_s^+ \pi \), as long as the mass value of \( \hat{D} \) in Table 1 is taken. The

| \( S \) | \( I = 1 \) | \( I = \frac{1}{2} \) | \( I = 0 \) | Mass(GeV) |
|---|---|---|---|
| 1 | \( \hat{F}_1^+ \) | \( \hat{F}_0^0 \) | 2.32(1) |
| 0 | \( \hat{D} \) | \( \hat{D}^* \) | 2.22 |
| | | \( \hat{D}^{**} \) | 2.42 |
| -1 | \( \hat{E}^0 \) | \( \hat{E}^{0*} \) | 3.22 |

(\( \dagger \)): Input data
latter contains an $ss$ pair so that its decay mode is limited because of the OZI rule\cite{7}. One of possible decays would be $\hat{F}_1^+ \rightarrow D_s^* \rightarrow D_\eta$. Since this decay is approximately on the threshold, i.e., $m_{\hat{F}_1} \approx m_{D_s^n} + m_\eta$, however, it is not clear if such a decay is allowed kinematically, as long as the estimated value of $m_{D_s^n}$ in Table 1 is taken. Even if allowed, the rate would be very small because of small phase space.

$\hat{F}_0^0$ is an iso-singlet counterpart of $\hat{F}_1^+$ mesons. It cannot decay into $D_s^*\pi^0$ as long as the $I$-spin is conserved, so that it will decay dominantly through $I$-spin non-conserving interactions (like electromagnetic interactions). In this case, the width of $\hat{F}_0^0$ will be much narrower than the one of the BABAR resonance. If its mass should be higher (by $\gtrsim 50$ MeV) because of some $I$-spin dependent force, it could decay dominantly into the $D\bar{K}$ final states and its width might reproduce the measured one of the BABAR resonance.

$\hat{E}^0$ is exotic. It is an iso-singlet scalar meson with charm $C = 1$ and strangeness $S = -1$, i.e., $\hat{E}^0 \sim [c\bar{s}][u\bar{d}]$. It cannot decay into $D\bar{K}$ final states unless it is enough massive because of some extra force. If its mass is of almost the same as the one of $\hat{F}_0$, it cannot decay through strong interactions as well as electromagnetic interactions because of some ordinary meson with $C = 1$ and $S = -1$ exists. If it can be created, therefore, it will be of very long life.

Now we study numerically decays of the $[cq][\bar{q}\bar{q}]$ mesons by assigning the BABAR resonance to $\hat{F}_1^+$, although there exist many possibilities to assign it to the other hadron states like a $(D\bar{K})$ molecule \cite{10} (or atom \cite{11}), an excited $(c\bar{s})$ state \cite{12}, an iso-singlet four-quark meson \cite{13}, etc. Consider, as an example, a decay, $A(p) \rightarrow B(p') + \pi(q)$, where $A$, $B$ and $\pi$ are a parent, a daughter pseudoscalar and a $\pi$ meson, respectively. The rate for the decay is given by

$$\Gamma(A \rightarrow B \pi) = \frac{1}{2J_A + 1} \frac{q_c}{8\pi m_A} \sum_{\text{spin}} |M(A \rightarrow B \pi)|^2,$$  \hspace{1cm} (2)

where $J_A$, $q_c$, and $M(A \rightarrow B \pi)$ denote the spin of $A$, the center-of-mass momentum of the final mesons and the decay amplitude, respectively. To calculate the amplitude, we here use the PCAC (partially conserved axial-vector current) hypothesis and a hard pion approximation in the infinite momentum frame (IMF), i.e., $p \rightarrow \infty$ \cite{14}. In this approximation, the amplitude is evaluated at a little unphysical point, i.e., $m_{\pi}^2 \rightarrow 0$. In this way, the amplitude is given approximately by

$$M(A \rightarrow B \pi) = \frac{m_A^2 - m_B^2}{f_\pi} \langle B|A_\pi|A\rangle,$$  \hspace{1cm} (3)

where $A_\pi$ is the axial counterpart of $I$-spin. Asymptotic matrix elements (matrix elements taken between single hadron states with infinite momentum) of $A_\pi$ can be parameterized by using asymptotic flavor symmetry (flavor symmetry of the asymptotic matrix elements). Asymptotic symmetry and its fruitful results were reviewed in Table 2. Assumed dominant decays of scalar $[cq][\bar{q}\bar{q}]$ mesons and their estimated widths.

<table>
<thead>
<tr>
<th>Parent (Mass in GeV)</th>
<th>Final State</th>
<th>Width (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\hat{F}_1^+(2.32)$</td>
<td>$D_s^+\pi^+$</td>
<td>8.8</td>
</tr>
<tr>
<td>$\hat{F}_1^+(2.32)$</td>
<td>$D_s^+\pi^0$</td>
<td></td>
</tr>
<tr>
<td>$\hat{F}_0^0(2.32)$</td>
<td>$D_s^+\pi^-$</td>
<td></td>
</tr>
<tr>
<td>$\hat{D}^+(2.22)$</td>
<td>$D_s^0\pi^+$</td>
<td>9.0</td>
</tr>
<tr>
<td>$\hat{D}^+(2.22)$</td>
<td>$D_s^0\pi^0$</td>
<td>4.5</td>
</tr>
<tr>
<td>$\hat{D}^+(2.22)$</td>
<td>$D_s^0\pi^-$</td>
<td>9.0</td>
</tr>
<tr>
<td>$&lt;\hat{D}_s^0K&gt;$</td>
<td>$D_s^0\pi^0$</td>
<td>(I-spin viol.)</td>
</tr>
</tbody>
</table>

Ref. \cite{14}. Asymptotic matrix elements including four-quark states have been parameterized previously \cite{13,14}. We here list the related ones,

$$\langle D_s^+|A_\pi|\hat{F}_1^+\rangle = \sqrt{2}\langle D_s^+|A_\pi|\hat{F}_1^+\rangle = \langle D_s^+|A_\pi|\hat{F}_1^+\rangle = \langle D_s^+|A_\pi|\hat{F}_1^+\rangle = \langle D_s^+|A_\pi|\hat{F}_1^+\rangle = \langle D_s^+|A_\pi|\hat{F}_1^+\rangle = \langle D_s^+|A_\pi|\hat{F}_1^+\rangle$$

Inserting Eq.(3) with Eq.(4) into Eq.\hspace{1cm} (4).

\begin{align*}
\Gamma(\hat{F}_1^+ \rightarrow D_s^*\pi^0) &\simeq 8.8 \text{ MeV,} \\
\end{align*}

since we do not find any other decays which can have large rates, and use it as the input data when we estimate the rates for the other decays. The result is listed in Table 2. All the calculated widths of $\hat{F}_1$ and $D_s$ are lying in the region, 4.5 – 9.0 MeV, so that they will be observed as narrow resonances in the $D_s^*\pi$ and $D\pi$ channels, respectively. The $D_s^* \rightarrow D\eta$ decays are approximately on the threshold, $m_{\rho_s} \approx m_{D_s^n} + m_\eta$, so that it is not clear if they are kinematically allowed. Besides, the decay is sensitive to the $\eta\eta'$ mixing scheme which is still model dependent\cite{15}. Therefore, we need more precise and reliable values of $m_{\rho_s}$, $\eta\eta'$ mixing parameters and decay constants in the $\eta\eta'$ system to obtain a definite result.

Now we compare the decay of $\hat{F}_1^+ \rightarrow D_s^*\pi^0$ with the ordinary scalar meson decay, $K_0^*(1430) \rightarrow K\pi$, which has been confirmed well\cite{14}. From Eq.\hspace{1cm} (5), we can obtain $|\langle D_s^+|A_\pi|\hat{F}_1^+\rangle| \simeq 0.12$ as a typical coupling strength.
of $\hat{F}_I$ to $D^+_s \pi$ using Eqs. (2) and (3). In the same way, we can estimate $\langle (K_s^+)_{A_{\pi}} |K_s^{0*}(1430)\rangle$ from the experimental data on the $K_s^0(1430) \rightarrow K\pi$ decay, i.e., from $\Gamma(K_s^0(1430) \rightarrow all) = 294 \pm 23$ MeV and $Br(K_s^0(1430) \rightarrow K\pi) = 93 \pm 10\%$, we obtain $\langle (K_s^+)_{A_{\pi}} |K_s^{0*}(1430)\rangle \approx 0.29$. Since the sizes of the above matrix elements of axial charges will be controlled by overlappings of wave-functions, the order of their sizes are quite natural, i.e., axial charges will be controlled by overlappings of wave-functions. 

In summary we have studied decays of scalar $[cq][\bar{q}\bar{q}]$ mesons into two pseudoscalar mesons by assigning the BABAR resonance to $F_1^+$ (in our notation) and assuming the $I$-spin conservation. All the allowed decays are not very far from the corresponding thresholds so that their rates have been expected to saturate approximately their total widths. Therefore, we have used the measured width as the input data, $\Gamma(\hat{F}_1^+ \rightarrow D_0^{+*} \pi^0) \simeq 8.8$ MeV. $\hat{F}_1$ and $\hat{D}$ will be observed as narrow resonances like the BABAR one. It is very much different from the results in Ref. [12] in which $\hat{F}_0^0$ (in our notation) was assigned to the BABAR resonance and all the other $[cq\bar{q}q]$ mesons were predicted to be much broader ($\sim 100$ MeV or more). To distinguish the present assignment from the other models and to confirm it, therefore, it is important to observe these narrow resonances. 

We have not studied numerically the $\hat{D}^0 \rightarrow D\eta$. Since the decay is approximately on the threshold and sensitive to model dependent $\eta$-$\eta'$ mixing, it is hard to obtain a definite result on this decay at the present stage, although we can qualitatively expect that $D^0$ will be much narrower than $\hat{F}_I$ and $\hat{D}$.

$\hat{E}^0$ will decay through weak interactions if it is created as long as its mass is below the $\hat{E}^0 \rightarrow D\bar{K}$ threshold. We have studied, so far, strong decay properties of a part of the four-quark mesons. If their existence is confirmed, it will be very much helpful to understand hadronic weak decays of $K$ and charm mesons. The existence of $[qq][\bar{q}\bar{q}]$ and $(qq)(\bar{q}\bar{q})$ mesons (with $*$) immediately leads to a solution to the long standing puzzle in charm decays [12],

$$\frac{\Gamma(D^0 \rightarrow K^+ K^-)}{\Gamma(D^0 \rightarrow \pi^+ \pi^-)} \simeq 3,$$

in consistency with the other two-body decays of charm mesons [3, 4, 5]. Besides, the lighter $(qq)(\bar{q}\bar{q})$ (without $*$) mesons are useful to understand the $\Delta I = 1/2$ rule and its violation in $K \rightarrow \pi\pi$ decays in consistency with the $K_L-K_S$ mass difference, the $K_L \rightarrow \gamma\gamma$ and the Dalitz decays of $K_L$.

Confirmation of the BABAR resonance as a four-quark meson will open a new window of hadron physics.

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[1] B. Aubert et al., the BABAR Collaboration, hep-ex/0304021