The perspectives of decoding the nature of the $a_0(980)$ and $f_0(980)$ mesons and of defining the relative phase between the three-gluon and one-photon amplitudes in the $J/\psi$ decays *

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Abstract

It is argued that the search of the $J/\psi \to f_0(980)\omega$ and $J/\psi \to a_0(980)\rho$ decays and the more precise definition of $B(J/\psi \to f_0(980)\phi)$ are the urgent purposes in the $J/\psi$ spectroscopy.

It is shown that the study of the $\omega - \rho^0$ interference pattern in the $J/\psi \to (\rho^0 + \omega)\eta \to \pi^+\pi^-\eta$ decay provides evidence for the large (nearly 90°) relative phase between the isovector one-photon and three-gluon decay amplitudes.

1 Introduction

As is well known that the $J/\psi$ decays have played an outstanding role in creation of Standard Model, including creation QCD. But up to now potentialities the $J/\psi$ decays to give top level results, that is new physics, are far from to be exhausted as is clear from two topics considered below.

In Section 1 it is shown that there are good potentialities to clear the nature of the scalar $f_0(980)$ and $a_0(980)$- mesons studying the $J/\psi \to f_0(980)\omega$, $J/\psi \to a_0(980)\rho$ and $J/\psi \to f_0(980)\phi$ decays.

In Section 2 it is shown that that there good potentialities to get a relative phase between the isovector one-photon and three-gluon decay amplitudes in $J/\psi$ decays studying the $J/\psi \to (\rho^0 + \omega)\eta \to \pi^+\pi^-\eta$ and $J/\psi \to \omega\eta$ decays.

A brief summary is given in Section 3.

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The $J/\psi$ decays about the nature of the scalar $f_0(980)$ and $a_0(980)$ mesons

2.1 The $J/\psi$ decays about the nature of the scalar $a_0(980)$ meson

The following data is of very interest for our purposes:

\[ B(J/\psi \rightarrow a_0(980)\rho) < 4.4 \cdot 10^{-4} \quad [1] \] and

\[ B(J/\psi \rightarrow a_2(1320)\rho) = (109 \pm 22) \cdot 10^{-4} \quad [2]. \]  

The suppression

\[ B(J/\psi \rightarrow a_0(980)\rho)/B(J/\psi \rightarrow a_2(1320)\rho) < 0.04 \pm 0.008 \]  

seems strange, if one considers the $a_2(1320)$ and $a_0(980)$-states as the tensor and scalar two-quark states from the same P-wave multiplet with the quark structure\footnote{It cannot be too highly stressed that in $J/\psi$ decays there is no suppression of creation of isovector P-wave $q\bar{q}$ states in comparison with creation of isovector S-wave $q\bar{q}$ states. Please compare $B(J/\psi \rightarrow a_2(1320)\rho) = (109 \pm 22) \cdot 10^{-4}$ with $B(J/\psi \rightarrow \pi\rho) = (127 \pm 9) \cdot 10^{-4}$.}

\[ a_0^0 = (u\bar{u} - d\bar{d})/\sqrt{2} , \quad a_0^+ = u\bar{d} , \quad a_0^- = d\bar{u}. \]

While the four-quark nature of the $a_0(980)$-meson with the symbolic quark structure, similar (but not identical) the MIT-bag state \cite{3},

\[ a_0^+(980) = us\bar{d}s , \quad a_0^0(980) = \frac{(us\bar{s} - ds\bar{d}s)}{\sqrt{2}} , \quad a_0^-(980) = ds\bar{u}s. \]

is not contrary to the suppression in Eq. (3).

So, the improvement of the upper limit (1) and the search for the $J/\psi \rightarrow a_0(980)\rho$ decays are the urgent purposes in the study of the $J/\psi$ decays!

2.2 The $J/\psi$ decays about the nature of the scalar $f_0(980)$ meson

Let us discuss a possibility to treat the $f_0(980)$-meson as the quark-antiquark state.

The hypothesis that the $f_0(980)$-meson is the lowest two-quark P-wave scalar state with the quark structure

\[ f_0 = (u\bar{u} + d\bar{d})/\sqrt{2} \]  

contradicts the following facts:

i) the weak coupling with gluons \cite{4}

\[ B(J/\psi \rightarrow \gamma f_0(980) \rightarrow \gamma\pi\pi) < 1.4 \cdot 10^{-5} \]  

opposite the expected one \cite{5} for Eq. (6)

\[ B(J/\psi \rightarrow \gamma f_0(980)) \geq B(J/\psi \rightarrow \gamma f_2(1270))/4 \simeq (3.45 \pm 0.35) \cdot 10^{-4}; \]  

ii) the decays $J/\psi \rightarrow f_0(980)\omega$, $J/\psi \rightarrow f_0(980)\phi$, $J/\psi \rightarrow f_2(1270)\omega$ and $J/\psi \rightarrow f_2'(1525)\phi$ \cite{2}:

\[ B(J/\psi \rightarrow f_0(980)\omega) = (1.4 \pm 0.5) \cdot 10^{-4}, \]  

\[ B(J/\psi \rightarrow f_0(980)\phi) = (1.4 \pm 0.5) \cdot 10^{-4}, \]  

\[ B(J/\psi \rightarrow f_2(1270)\omega) = (1.4 \pm 0.5) \cdot 10^{-4}, \]  

\[ B(J/\psi \rightarrow f_2'(1525)\phi) = (1.4 \pm 0.5) \cdot 10^{-4}. \]
\[ B(J/\psi \to f_0(980)\phi) = (3.2 \pm 0.9) \cdot 10^{-4}, \]  
\( B(J/\psi \to f_2(1270)\omega) = (4.3 \pm 0.6) \cdot 10^{-3} \) and 
\[ B(J/\psi \to f'_2(1525)\phi) = (8 \pm 4) \cdot 10^{-4}. \]

The suppression
\[ B(J/\psi \to f_0(980)\omega)/B(J/\psi \to f_2(1270)\omega) = 0.033 \pm 0.013 \]
looks strange in the model under consideration as well as Eq. (3) in the model (4) \(^2\).

I would like to emphasize that from my point of view the DM2 Collaboration did not observe the \( J/\psi \to f_0(980)\omega \) decay and should give an upper limit instead of Eq. (9).

**So, the search for the \( J/\psi \to f_0(980)\omega \) decay is the urgent purpose in the study of the \( J/\psi \) decays!**

The existence of the \( J/\psi \to f_0(980)\phi \) decay of greater intensity than the \( J/\psi \to f_0(980)\omega \) decay (compare Eq. (9) and Eq. (10)) shuts down the model (6) for the case under discussion the \( J/\psi \to f_0(980)\phi \)-decay should be strongly suppressed in comparison with the \( J/\psi \to f_0(980)\omega \)-decay by the OZI-rule.

**So, Eq. (6) is excluded at a level of physical rigor.**

Can one consider the \( f_0(980) \)-meson as the near \( s\bar{s} \)-state?

It is impossible without a gluon component. Really, it is anticipated for the scalar \( s\bar{s} \)-state from the lowest P-wave multiplet that \([5]\)

\[ B(J/\psi \to \gamma f_0(980)) \geq B(J/\psi \to \gamma f'_2(1525))/4 \simeq 1.6 \cdot 10^{-4} \]
on the verge of conflict with experiment, compare Eq. (9) with Eq. (10). Here \( \lambda \) takes into account the strange sea suppression.

Equation (15) contradicts also the strong coupling with the \( K\bar{K} \)-channel \([6, 7]\)

\[ 1 < R = |g_{f_0 K+K-}/g_{f_0\pi\pi^-}|^2 \leq 10 \]
for the prediction
\[ R = |g_{f_0 K+K-}/g_{f_0\pi\pi^-}|^2 = (\sqrt{\lambda} - 2)^2/4 \simeq 0.4. \]

In addition, the mass degeneration \( m_{f_0} \approx m_{a_0} \) is coincidental in this case if to treat the \( a_0 \)-meson as the four-quark state or contradicts the light hypothesis (4).

\(^2\)It cannot be too highly stressed that in \( J/\psi \) decays there is also no suppression of creation of isoscalar P-wave \( q\bar{q} \) states in comparison with creation of isoscalar S-wave \( q\bar{q} \) states. Please compare \( B(J/\psi \to f_2(1270)\omega) = (4.3 \pm 0.6) \cdot 10^{-3} \) with \( B(J/\psi \to \eta\omega) = (1.58 \pm 0.16) \cdot 10^{-3} \) \([2]\).
The introduction of a gluon component, \( gg \), in the \( f_0(980) \)-meson structure allows the puzzle of weak coupling with two gluons (7) and with two photons but the strong coupling with the \( K \bar{K} \)-channel to be resolved easy [8]:

\[
\begin{align*}
f_0 &= gg \sin \alpha + \left[ \frac{1}{\sqrt{2}} (u\bar{u} + d\bar{d}) \sin \beta + s\bar{s} \cos \beta \right] \cos \alpha, \\
\tan \alpha &= -O(\alpha s) \left( \sqrt{2} \sin \beta + \cos \beta \right),
\end{align*}
\]

(19)

where \( \sin^2 \alpha \leq 0.08 \) and \( \cos^2 \beta > 0.8 \).

So, the \( f_0(980) \)-meson is near the \( s\bar{s} \)-state, as in [9].

It gives

\[
0.1 < \frac{B(J/\psi \to f_0(980)\omega)}{B(J/\psi \to f_0(980)\phi)} = \frac{1}{\lambda} \tan^2 \beta < 0.54.
\]

(20)

As for the experimental value,

\[
B(J/\psi \to f_0(980)\omega)/B(J/\psi \to f_0(980)\phi) = 0.44 \pm 0.2,
\]

(21)

it needs refinement.

**Remind that in my opinion the \( J/\psi \to f_0(980)\omega \) was not observed!**

The scenario with the \( f_0(980) \) meson as in Eq. (19) and with the \( a_0(980) \) meson as the two-quark state (4) runs into following difficulties:

i) it is impossible to explain the \( f_0 \) and \( a_0 \)-meson mass degeneration in a natural way;

ii) it is possible to get only [7]

\[
\begin{align*}
B(\phi \to \gamma f_0 \to \gamma \pi^0 \pi^0) &\simeq 1.7 \cdot 10^{-5}, \\
B(\phi \to \gamma a_0 \to \gamma \pi^0 \eta) &\simeq 10^{-5}.
\end{align*}
\]

(22)

iii) it is also predicted

\[
B(J/\psi \to a_0(980)\rho) = (3/\lambda \approx 6) \cdot B(J/\psi \to f_0(980)\phi),
\]

(23)

that has almost no chance, compare Eqs. (1) and (10).

Note that the \( \lambda \) independent prediction

\[
B(J/\psi \to f_0(980)\phi)/B(J/\psi \to f_1^0(1525)&\phi) = \\
= B(J/\psi \to a_0(980)\rho)/B(J/\psi \to a_2(1320)\rho)
\]

(24)

is excluded by the central figure in

\[
B(J/\psi \to f_0(980)\phi)/B(J/\psi \to f_2^0(1525)\phi) = 0.4 \pm 0.23,
\]

(25)

obtained from Eqs. (10) and (12), compare with Eq. (3). But, certainly, experimental error is too large.

**Even twofold increase in accuracy of measurement of Eq. (25) could be crucial in the fate of the scenario under discussion.**

The prospects for the model of the \( f_0(980) \)-meson as the almost pure \( s\bar{s} \)-state (19) and the \( a_0(980) \)-meson as the four-quark state (5) with the coincidental mass degeneration is rather poor especially as the mechanism without creation and annihilation of the additional \( u\bar{u} \) pair, i.e. the OZI-superallowed \((N_C)^0\) order transition \( \phi = s\bar{s} \to \gamma s\bar{s} = \gamma f_0(980) \)

\(^3\)In this regard the \((N_C)^0\) order mechanism is similar to the principal mechanism of the \( \phi \to \gamma \eta'(958) \) decay \( (\phi = s\bar{s} \to \gamma s\bar{s} = \gamma \eta'(958)) \).
the photon spectrum in $\phi \rightarrow \gamma f_0(980) \rightarrow \gamma \pi^0 \pi^0$, which requires the domination of the $K^+K^-$ intermediate state in the $\phi \rightarrow \gamma f_0(980)$ amplitude: $\phi \rightarrow K^+K^- \rightarrow \gamma f_0(980)$, as is shown in Refs. [10, 11]! The $(N_C)^0$ order transition is bound to have a small weight in the large $N_C$ expansion of the $\phi = s\bar{s} \rightarrow \gamma f_0(980)$ amplitude, because this term does not contain the $K^+K^-$ intermediate state, which emerges only in the next to leading term of the $1/N_C$ order, i.e., in the OZI forbidden transition [11].

While the four-quark model with the symbolic structure

$$f_0(980) = \frac{(us\bar{s} + ds\bar{d})}{\sqrt{2}} \cos \theta + ud\bar{u} \sin \theta,$$

similar (but not indentically) the MIT-bag state [3], reasonably justifies all unusual features of the $f_0(980)$-meson [6, 12, 8, 11].

### 3 The $\omega - \rho^0$ interference pattern in the $J/\psi \rightarrow (\rho^0 + \omega)\eta \rightarrow \pi^+ \pi^- \eta$ decay about the relative phase between the three-gluon and one-photon amplitudes in the $J/\psi$ decays

In the last few years it has been noted that the single-photon and three-gluon amplitudes in the two-body $J/\psi \rightarrow 1^-0^-$ and $J/\psi \rightarrow 0^+0^-$ [13, 14, 15] decays appear to have relative phases nearly $90^\circ$.

This unexpected result is very important to the observability of CP violating decays as well as to the nature of the $J/\psi \rightarrow 1^-0^-$ and $J/\psi \rightarrow 0^-0^-$ decays [13, 14, 15, 16, 17, 18, 19]. In particular, it points to a non-adequacy of their description built upon the perturbative QCD, the hypothesis of the factorization of short and long distances, and specified wave functions of final hadrons. Some peculiarities of electromagnetic form factors in the $J/\psi$ mass region were discussed in Ref. [20].

The analysis [13, 14, 15] involved theoretical assumptions relying on the strong interaction $SU_f(3)$-symmetry, the strong interaction $SU_f(3)$-symmetry breaking and the $SU_f(3)$ transformation properties of the one-photon annihilation amplitudes. Besides, effects of the $\rho - \omega$ mixing in the $J/\psi \rightarrow 1^-0^-$ decays were not taken into account in Ref. [13] while in Ref. [14] the $\rho - \omega$ mixing was taken into account incorrectly, see the discussion in Ref. [21]. Because of this, the model independent determination of these phases are required.

Fortunately, it is possible to check the conclusion of Refs. [13, 14] at least in one case [21, 22]. We mean the relative phase between the amplitudes of the one-photon $J/\psi \rightarrow \rho^0\eta$ and three-gluon $J/\psi \rightarrow \omega\eta$ decays.

The point is that the $\rho^0 - \omega$ mixing amplitude is reasonably well studied [23, 24, 25, 26, 27, 28, 29]. Its module and phase are known. The module of the ratio of the amplitudes of the $\rho$ and $\omega$ production can be obtained from the data on the branching ratios of the $J/\psi$-decays. So, the investigation of the $\omega - \rho$ interference in the $J/\psi \rightarrow (\rho^0 + \omega)\eta \rightarrow \rho^0\eta \rightarrow \pi^+ \pi^- \eta$ decay provides a way of measuring the relative phase of the $\rho^0$ and $\omega$ production amplitudes.

Indeed, the $\omega - \rho$ interference pattern in the $J/\psi \rightarrow (\rho^0 + \omega)\eta \rightarrow \rho^0\eta \rightarrow \pi^+ \pi^- \eta$ decay is conditioned by the $\rho^0 - \omega$ mixing and the ratio of the amplitudes of the $\rho^0$ and $\omega$ production:

$$\frac{dN}{dm} = N_{\rho}(m)\frac{2}{\pi}m\Gamma(\rho \rightarrow \pi\pi, m) \times$$

$$\left| \frac{1}{D_{\rho}(m)} \left(1 - \varepsilon(m) \left[ N_{\omega}(m) \right]^\frac{1}{2} \right) \right|^2 \exp \{i(\delta_{\omega} - \delta_{\rho})\} +$$
latter is a small correction. Really, it follows from the structure of the electromagnetic current of the three-gluon amplitude and the isoscalar one-photon amplitude. But luckily for us the modules of the \(\rho\) amplitude of the polynomial background term.

The branching ratio of the \(\omega \rightarrow \pi \pi\) decay

\[ B(\omega \rightarrow \pi \pi) = \frac{\Gamma(\omega \rightarrow \pi \pi, m_\omega)}{\Gamma_\omega(m_\omega)} \cdot |\varepsilon(m_\omega) + g_{\omega \pi \pi}/g_{\rho \pi \pi}|^2. \]  

The results are

\[ \phi = (46 \pm 15)^\circ, \quad N_\omega(m_\omega)/N_\rho = 8.86 \pm 1.83 \ [30], \]
\[ \phi = -0.08 \pm 0.17 = (-4.58 \pm 9.74)^\circ, \quad N_\omega(m_\omega)/N_\rho = 7.37 \pm 1.72 \ [31]. \]  

From Eqs. (27), (30), and (31) it follows

\[ N_\rho = N_\rho(m_\rho) \left| 1 - \varepsilon(m_\rho) \left[ N_\omega(m_\rho)/N_\rho(m_\rho) \right]^{1/2} \exp \{i (\delta_\omega - \delta_\rho) \} \right|^2, \]
\[ N_\omega = B(\omega \rightarrow \pi \pi) N_\omega(m_\omega), \]
\[ \phi = \delta_\omega - \delta_\rho + \arg \left[ \varepsilon(m_\omega) + g_{\omega \pi \pi}/g_{\rho \pi \pi} \right] - \arg \left\{ 1 - \varepsilon(m_\rho) \left[ N_\omega(m_\rho)/N_\rho(m_\rho) \right]^{1/2} \exp \{i (\delta_\omega - \delta_\rho) \} \right\} \]
\[ \approx \delta_\omega - \delta_\rho + \arg \left[ \varepsilon(m_\omega) + g_{\omega \pi \pi}/g_{\rho \pi \pi} \right] - \arg \left\{ 1 - \varepsilon(m_\omega) \left[ N_\omega(m_\omega)/N_\rho \right]^{1/2} \exp \{i \phi \} \right\}. \]  

From Eqs. (29), (32) and (35) we get that

\[ \delta_\rho - \delta_\omega = (60 \pm 15)^\circ \ [30] \text{ and } \]
\[ \delta_\rho - \delta_\omega = (106 \pm 10)^\circ \ [31]. \]  

Whereas \(\delta_\rho\) is the phase of the isovector one-photon amplitude, \(\delta_\omega\) is the phase of the sum of the three-gluon amplitude and the isoscalar one-photon amplitude. But luckily for us the latter is a small correction. Really, it follows from the structure of the electromagnetic current

\[ j_\mu(x) = \frac{2}{3} \bar{u}(x)\gamma_\mu u(x) - \frac{1}{3} \bar{d}(x)\gamma_\mu d(x) - \frac{1}{3} \bar{s}(x)\gamma_\mu s(x) + \ldots \]  

\(4\)If we use Ref. [2] we shall obtain \(\varepsilon(m_\omega) + g_{\omega \pi \pi}/g_{\rho \pi \pi} = (2.99 \pm 0.25) \cdot 10^{-2} \exp \{i (102 \pm 1)^\circ\}. \)
and the Okubo-Zweig-Iizuka rule the ratio for the amplitudes under consideration (please image all possible diagrams!):

\[
\frac{A(J/\psi \to \text{the isoscalar photon } \to \omega \eta)}{A(J/\psi \to \text{the isovector photon } \to \rho \eta) \equiv A(J/\psi \to \rho \eta)} = \frac{1}{3}.
\]

(39)

Taking into account Eqs. (32) and (33) one gets

\[
\frac{|A(J/\psi \to \text{the isoscalar photon } \to \omega \eta)|}{|A(J/\psi \to \text{the three-gluon } \to \omega \eta)|} \approx \frac{1}{9}.
\]

(40)

From Eqs. (36), (37) and (40) one gets easily for the relative phase (\(\delta\)) between the isovector one-photon and three-gluon decay amplitudes

\[
\delta = (60 \pm 15)^\circ - 4^\circ \quad [30] \quad \text{and}
\]

\[
\delta = (106 \pm 10)^\circ - 6^\circ \quad [31],
\]

(41)

(42)

if the isovector and isoscalar one-photon decay amplitudes have the same phase. In case the isoscalar one-photon and three-gluon (isoscalar also!) decay amplitudes have the same phase

\[
\delta = (60 \pm 15)^\circ \quad [30] \quad \text{and}
\]

\[
\delta = (106 \pm 10)^\circ \quad [31].
\]

(43)

(44)

So, both the MARK III Collaboration [30] and the DM2 Collaboration [31], see Eqs. (41), (43) and (42), (44), provide support for the large (nearly 90\(^\circ\)) relative phase between the isovector one-photon and three-gluon decay amplitudes.

The DM2 Collaboration used statistics only half as high as the MARK III Collaboration, but, in contrast to the MARK III Collaboration, which fitted \(N_\omega\) as a free parameter, the DM2 Collaboration calculated it from the branching ratio of \(J/\psi \to \omega \eta\) using Eq. (34).

In summary I should emphasize that it is urgent to study this fundamental problem once again with KEDR in Novosibirsk and with BES II in Beijing.

But I am afraid that only the \(\tau\)-CHARM factory could solve this problem in the exhaustive way.

4 Conclusion

So, the search for the \(J/\psi \to a_0(980)\rho\) and \(J/\psi \to f_0(980)\omega\) decays, the more precise definition of \(B(J/\psi \to f_0(980)\phi)\), and the study of the \(\omega - \rho^0\) interference pattern in the \(J/\psi \to (\rho^0 + \omega)\eta \to \pi^+\pi^-\eta\) decay are the urgent purposes in the \(J/\psi\) spectroscopy!

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