Possible candidate of $0^+ sar{s}sar{s}$ state

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Abstract

The possibility of the $0^+ \eta\eta$ resonance $f_0(2100)$ as a candidate of the $Q^2\bar{Q}^2$ state $C^{ss}(36)$ is explored. The $\eta\eta$ channel of $f_0(2100)$ is the dominant decay mode, $\eta\eta'$ channel has less decay rate, the decay rate of the $\eta'\eta'$ channel is very small. The $\pi\pi$, $K\bar{K}$, $4\pi$ modes are at next leading order in $N_C$ expansion. Other possible decay modes are discussed.
Among many $I^G(J^{PC}) = 0^+(0^{++})$ resonances discovered [1] around 2 GeV there are $f_0(2100)$ and $f_0(2020)$ two scalar mesons [1]. The parameters of the $f_0(2100)$ are determined to be [1]

$$M = 2103 \pm 8\text{MeV}, \quad \Gamma = 209 \pm 19\text{MeV}.$$ 

The $f_0(2020)$ is a broad scalar meson whose decay width is about 400 MeV and it has many decay modes: $\rho\pi\pi$, $\pi^0\pi^0$, $\rho\rho$, $\omega\omega$, $\eta\eta$, ... [1]. The $f_0(2100)$ is different from the $f_0(2020)$. In this paper the possible nature of the $f_0(2100)$ is investigated. In 1993 $\eta\eta$ resonances have been reported in following processes [2]

$$\bar{p} + p \rightarrow 3\pi^0, \quad 2\pi^2, \quad \pi^02\eta, \quad 3\eta.$$ 

The $f_0(2100)$ is one of the three $\eta\eta$ resonances and its mass and decay width are determined to be

$$M = 2104 \pm 20\text{MeV}, \quad \Gamma = 203 \pm 10\text{MeV}.$$ 

This state has not been identified definitely in the $\pi\pi$ channel and the quantum numbers are not determined in this study. In Ref. [3] the $f_0(2100)$ has been discovered in

$$\bar{p} + p \rightarrow \eta\eta, \quad \eta\eta', \quad .....$$

The $f_0(2100)$ appears strongly in $\eta\eta$ channel and

$$M = 2105 \pm 10\text{MeV}, \quad \Gamma = 200 \pm 25\text{MeV}.$$
The $f_0(2100)$ appears weakly in the $\pi^0\pi^0$ data, contributing only $(4.6 \pm 1.5\%)$ of the cross section, comparing with $(38 \pm 5\%)$ in $\eta\eta$ channel. The cross section for $\eta\eta'$ contains a weak peak at about $2150$ MeV.

Recently, the BES III Collaboration has reported the discovery of the $\eta\eta$ resonance $f_0(2100)$ in $J/\psi \rightarrow \gamma\eta\eta$ [4]. Its mass and decay width are determined to be

$$m = 2081 \pm 13\text{MeV}, \quad \Gamma = 273^{+27}_{-24}\text{MeV}$$

respectively, which are in agreement with the measurements [2,3]. The product branching ratio is measured to be

$$B(J/\psi \rightarrow \gamma f_0(2100) \rightarrow \gamma\eta\eta) = (1.13^{+0.09}_{-0.1}) \times 10^{-4}.$$  

On the other hand, the discovery of $f_0(2100)$ has not been reported in $K\bar{K}$ channels of $J/\psi \rightarrow \gamma K\bar{K}$ [4] and $pp \rightarrow pf(K\bar{K})p_s$ [5,6].

In Ref. [6] in $J/\psi \rightarrow \gamma\pi^+\pi^-$ besides a $2^{++}$ state $\theta(1700)$ a $X(2100)$ is reported

$$M = 2027 \pm 12\text{MeV}, \quad \Gamma = 220 \pm 30\text{MeV}.$$  

However, it is claimed that the angular distributions of $X(2100)$ are similar to those of the $\theta(1700)$ which has been determined to be a $2^{++}$ state. In Ref. [7] in the decay $J/\psi \rightarrow \gamma\pi\pi$ a wide resonance $f_0(2020)$ is seen, which is listed in Ref. [1]. It seems that the results from
these two experiments do not agree each other. On the other hand, in Ref. [1] the scalar resonance $f_0(2100)$ is not listed in the $\pi\pi$ channel in $J/\psi \rightarrow \gamma\pi\pi$.

The experimental study of the scalar resonance in the $4\pi$ channel lasts a pretty long time. Now it is needed to check whether the $f_0(2100)$ has $4\pi$ decay mode. $J/\psi \rightarrow \gamma 4\pi$ and $pp \rightarrow pf(4\pi)p_\pi$ are the two processes to search for $X \rightarrow 4\pi$.

1. MARK II has done a study of $J/\psi \rightarrow \gamma 4\pi$ [8] and it is found that the $\gamma\rho\rho$ are the components of these channels. It is no mentioned whether there is resonance of $\rho\rho$ around 2 GeV.

2. In Ref. [9] a $0^{-+}$ resonance $\eta(2100)$ which decays to both $\rho^+\rho^-$ and $\rho^0\rho^0$ has been observed by DM2 and $f_0(2100) \rightarrow \rho\rho$ has not been reported.

3. MARK III did a study on $J/\psi \rightarrow \gamma\pi^+\pi^-\pi^+\pi^-$ [10]. The $f_0(2104)$ has been reported in the $4\pi$ channel with $\Gamma = 203$MeV and $\sigma\sigma$ is the dominant decay channel. Large branching ratios are reported

$$B(J/\psi \rightarrow \gamma X(2104))B(X(2104) \rightarrow 4\pi) = (3.0 \pm 0.8) \times 10^{-4},$$

$$B(J/\psi \rightarrow \gamma X(2104))B(X(2104) \rightarrow \rho\rho) = (6.8 \pm 1.8) \times 10^{-4}.$$ 

4. BES has reported a partial wave analysis of $J/\psi \rightarrow \gamma\pi^+\pi^-\pi^+\pi^-$ [11]. $f_0(2100)$ has
been found in the $4\pi$ channel with

$$M = 2090^{+30}_{-30}\text{MeV}, \quad \Gamma = 330^{+100}_{-100}\text{MeV}.$$ 

$f_0(2100) \to \sigma\sigma$ decay is reported. From the values of the mass and width of $f_0$ is hard to say the resonance is $f_0(2100)$ or $f_0(2020)$.

From the current data it is difficult to draw a conclusion whether the $f_0(2100)$ has been found in the $4\pi$ channel produced in the $J/\psi$ radiative decays.

The process $pp \to p_f(4\pi)p_s$ has been studied by WA102 [12] and broad scalar with

$$m = 2020 \pm 35\text{MeV}, \quad \Gamma = 410 \pm 50\text{MeV}$$

has been found. The resonance decays to $\rho\pi\pi$ and $\rho\rho$. It is the $f_0(2020)$ resonance. In Ref. [13] a spin analysis of the $4\pi$ channels produced in central pp interactions has been done. It is mentioned that the $J^P = 0^+$ $\rho\rho$ distribution shows a peak at 1.45 MeV together with a broad enhancement around 2 GeV. These experiments show that the $0^+$ resonance found in the $4\pi$ channel produced in pp collision is the broad $f_0(2020)$.

The experimental data mentioned above show that the scalar resonance $f_0(2100)$ discovered in $p\bar{p}$ annihilation and $J/\psi$ radiative decay decays to $\eta\eta$ dominantly. It has weak coupling with $\pi\pi$ channel in $p\bar{p}$ annihilation and it is not found in $J/\psi \to \gamma\pi\pi$. The $f_0(2100)$ weakly decays to $\eta\eta'$. It is not discovered in the $K\bar{K}$ channels of $J/\psi$ radiative decay and $p\bar{p}$ collision. The data of $p\bar{p} \to p_s(4\pi)p_f$ show that there is no sign of the $f_0(2100) \to 4\pi$. 

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The authors of Ref. [3] claim that \( f_{0}(2100) \) decays dominantly through a \( s\bar{s} \) component and the strong production in \( p\bar{p} \) strongly suggest exotic character. It is either a glueball or a hybrid and there maybe mixing with \( q\bar{q} \) and \( s\bar{s} \).

In this paper possible exotic character of the \( f_{0}(2100) \) is investigated. We explore the possibility that the \( f_{0}(2100) \) is a four quark state of \( s\bar{s}s\bar{s} \) [14]. The possible direct decay channels of \( s\bar{s}s\bar{s} \) are \( \eta\eta, \eta\eta', \eta'\eta', \phi\phi, \) etc.. The \( \eta\eta \) mode has the largest phase space. Therefore, the \( \eta\eta \) is the dominant decay mode of the \( f_{0}(2100) \). The \( \pi\pi, K\bar{K}, 4\pi \) decays of the \( f_{0}(2100) \) are via the meson loop diagrams, \( \eta\eta \rightarrow \pi\pi, K\bar{K}, 4\pi \) completed. In a meson theory [15] it shows that the tree diagrams of mesons are at the leading order in the \( N_C \) expansion and the meson loop diagrams are at next leading order. For example, in this meson theory [15] the amplitude of \( \phi \rightarrow K\bar{K} \) is at \( O(N_C) \). The decay \( \phi \rightarrow \rho\pi \) is via one-loop meson diagrams completed. The amplitude of this decay is at \( O(1) \) in the \( N_C \) expansion. Comparing with \( \phi \rightarrow K\bar{K} \), the decay \( \phi \rightarrow \rho\pi \) is suppressed. For the decays of the \( f_{0}(2100) \) the \( f_{0}(2100) \rightarrow \eta\eta \) is resulted in tree diagram and the \( \pi\pi, K\bar{K}, 4\pi \) channels are resulted in loop diagrams of mesons, therefore, they are suppressed in the \( N_C \) expansion.

In Ref. [14] the spectrum and the properties of \( Q^{2}\bar{Q}^{2} \) states have been studied in the MIT bag model. The \( Q^{2}\bar{Q}^{2} \) states studied in Ref. [14] have been successfully applied to study the reactions \( \gamma\gamma \rightarrow \rho^{0}\rho^{0} \) and \( \gamma\gamma \rightarrow \rho^{+}\rho^{-} \) [16]. Recently, a \( 0^{++} \) resonance, \( f_{0}(1810) \), has been discovered in \( J/\psi \rightarrow \gamma\omega\phi \) [17]. If this new resonance is just one of the ordinary
mesons the process $J/\psi \rightarrow \gamma f_0(1810), f_0(1810) \rightarrow \omega \phi$ would be doubled OZI suppressed. In Ref. [18] the new $\omega \phi$ resonance has been interpreted as the production of the $Q \bar{Q}$ state, $C^s(9)$ [14], in $J/\psi$ radiative decay and the doubled OZI suppression is avoided.

Now we take the $0^{++}$ $C^{ss}(36)$ state studied in Ref. [14] as the $s\bar{s}s\bar{s}$ state

$$C^{ss}(36) = \eta_s\eta_s, \eta_s = s\bar{s},$$

whose mass has been predicted to be

$$m = 1950\text{MeV}.$$  \hspace{1cm} (2)

This value is very close to the mass of the $f_0(2100)$. The color wave function of $C^{ss}(36)$ state consists of color octet- color octet and color singlet-color singlet two parts [14]. The recoupling coefficients of this state are shown in Table I [14](the color octet is indicated by underline).

|           | PP   | VV   | P·P  | V·V  |
|-----------|------|------|------|------|
| $C^{ss}(36)$ | -0.644 | 0.269 | -0.322 | -0.639 |

In this study the $C^{ss}(36)$ with mass 2100 MeV is taken as the $f_0(2100)$ and the decays and productions of the $C^{ss}(36)$ state are investigated. We study the decays first, then the
productions. Through a "fall apart" [14] mechanism the $C^{ss}(36)$ decays to $\eta \eta$, $\eta \eta'$, $\phi \phi$, etc.. For the decay $s\bar{s}s\bar{s} \rightarrow PP$ the $s\bar{s}s\bar{s}$ is expressed as

$$s\bar{s} = \frac{1}{2\sqrt{3}} \eta' - \sqrt{\frac{2}{3}} \eta,$$

$$s\bar{s}s\bar{s} = \frac{2}{3} \eta \eta + \frac{1}{3} \eta' \eta' - \frac{2\sqrt{2}}{3} \eta \eta',$$

(3)

where $\eta = \frac{1}{\sqrt{6}} (u\bar{u} + d\bar{d} - 2s\bar{s})$ and $\eta' = \frac{1}{\sqrt{3}} (u\bar{u} + d\bar{d} + s\bar{s})$ are taken. The three decay amplitudes are via the mechanism of "fall apart" obtained

$$<\eta\eta|T|f_0(2100)> = -0.644 a \eta \frac{4}{3},$$

$$<\eta\eta'|T|f_0(2100)> = 0.644 a \eta' \frac{2\sqrt{2}}{3},$$

$$<\eta'\eta'|T|f_0(2100)> = -0.644 a \eta' \frac{2}{3},$$

(4)

where $a$ is a unknown constant from the mechanism of the fall apart, -0.644 is the recoupling coefficient from Tab. I, $m = 2100\text{MeV}$. The decay widths are derived as

$$\Gamma(f_0 \rightarrow \eta\eta) = \frac{0.644^2}{18\pi} a^2 m (1 - \frac{4m_{\eta}^2}{m^2})^{\frac{1}{2}} = 1.34 \times 10^{-2} a^2 \text{GeV},$$

$$\Gamma(f_0 \rightarrow \eta\eta') = \frac{0.644^2}{9\pi} a^2 \frac{1}{4m^2} (m^2 + m_{\eta}^2 - m_{\eta'}^2)^2 - m_{\eta}^2)^{\frac{1}{2}} = 1.05 \times 10^{-2} a^2 \text{GeV},$$

$$\Gamma(f_0 \rightarrow \eta'\eta') = \frac{0.644^2}{72\pi} a^2 m (1 - \frac{4m_{\eta'}^2}{m^2})^{\frac{1}{2}} = 1.58 \times 10^{-3} a^2 \text{GeV},$$

(5)

The ratios of the three decay channels of the $f_0(2100)$ are

$$\Gamma(\eta\eta) : \Gamma(\eta\eta') : \Gamma(\eta'\eta') \sim 1 : 0.78 : 0.12.$$  

(6)
This $s\bar{s}s\bar{s}$ scheme [14] predicts very small decay rate for the channel $\eta'\eta'$, which is caused by two factors: small phase space and small coefficient of the decomposition (3). This mechanism also predicts a smaller decay rate for the channel $\eta\eta'$. In Ref. [3] a weaker peak in the channel $\eta\eta'$ at 2150 MeV has been reported.

It is known that there is mixing between $\eta$, $\eta'$ and the $0^{-+}$ glueball which is believed to be $\eta(1405)$ [19]. The mixing makes the $0^{-+}$ glueball $\eta(1405)$ have $s\bar{s}$ component [19]. Therefore, the decay $f_0(2100) \to \eta\eta(1405)$ exists and have a small decay rate. Using the results presented in the first paper of Ref. [19] it is estimated $\Gamma(f_0(2100) \to \eta\eta(1405)) \sim 0.09\Gamma(f_0(2100) \to \eta\eta)$. However, this decay channel will provide useful information for accurate determination of the $\eta - \eta' - \eta(1405)$ mixing. Because the coefficients of the mixing determined by different authors [19] are different the mixing effects on Eqs. (5,6) won’t be studied in this paper.

In the same way the decay $f_0(2100) \to \phi\phi$ can be studied

$$< \phi_{\lambda_1}(k_1)\phi_{\lambda_2}(k_2)|T|f_0(2100)> = 2b m 0.269 \epsilon^{\lambda_1}(k_1) \cdot \epsilon^{\lambda_2}(k_2),$$
$$\Gamma(f_0 \to \phi\phi) = \frac{1}{8\pi}(0.269)^2m(1 - \frac{4m_\phi^2}{m^2})\{2 + \frac{m^4}{4m_\phi^4}(1 - \frac{2m_\phi^2}{m^2})\}b^2 = 0.633 \times 10^{-2} b^2 \text{ GeV} \quad (7)$$

where $b$ is a parameter and the relationship between $a$ and $b$ is unknown.

Because the parameter $b$ is unknown and it is not able to do reliable prediction for the decay rate of the $\phi\phi$ channel. It is worth to search for the resonance $f_0(2100)$ in the
φφ channel. Comparing with the ηη channel, the small phase space and the recoupling coefficient of the φφ channel make the decay rate of \( f_0(2100) \to φφ \) much small. However, there are other two factors which enhance the decay rate of \( f_0(2100) \to φφ \). The amplitude of this decay contains a factor \( \epsilon^{λi}(k_i) \cdot \epsilon^{λ2}(k_2) \), where \( λ_i(i = 1, 2) \) and \( k_i(i = 1, 2) \) are the polarization and momentum of the two φ mesons respectively. This polarization factor contributes a factor 4.38 to the decay rate. The second factor is that for the channel φφ the factor for the s̅s̅s̅ component is one and for the ηη channel this factor is \( \frac{4}{9} \) (3). All the factors together makes the decay rate of \( f_0(2100) \to φφ \) not too small. If \( a \sim b \) is assumed we obtain

\[
\frac{Γ(f_0(2100) \to ηη)}{Γ(f_0(2100) \to φφ)} \sim 1 : 0.47.
\]

There are experimental study on \( J/ψ \to γφφ \) [20], in which the \( 0^{++} φφ \) at 2100MeV is not studied. It is worth to search for the \( f_0(2100) \) in the \( J/ψ \to γφφ \).

In the picture of four quark state the mechanism of the productions of the ηη resonance \( f_0(2100) \) (\( C^{ss}(36) \)) in \( p\bar{p} \) collisions and \( J/ψ \) radiative decay can be understood qualitatively. A proton is made of uud quarks and the \( f_0(2100) \) is a s̅s̅ component. How this s̅s̅s̅ state is produced in \( p\bar{p} \) collision? It is known that half of the energy of a proton is carried by gluons. Therefore, \( p\bar{p} \to gg + ..., gg \to f_0(2100) \) is the process for the production of the \( f_0(2100) \) in \( p\bar{p} \) collisions. In QCD the \( J/ψ \) radiative decay is described as \( J/ψ \to γgg \). Therefore, the
same \( gg \rightarrow f_0(2100) \rightarrow \ldots \) is responsible for the production of the \( f_0(2100) \) in \( J/\psi \) radiative decay. In this study the \( f_0(2100) \) is taken as the \( C^{ss}(36) \) in which there is a component 
\(-0.639 \, \phi \cdot \bar{\phi} \) (Tab. I), where \( \phi \) is the color octet \( \phi \). The Vector Meson Dominance (VMD) works well in particle physics, in which photon is coupled to the vector mesons (\( \rho \), \( \omega \), \( \phi \)). A similar mechanism is proposed in Refs. [21,22], in which gluon is coupled to color octet vector, \( V \)

\[
\frac{1}{\sqrt{2}} g_s \, g_{\bar{\phi}} \, g^a \, \bar{\phi}^a,
\]

where the \( a \) is the color index, \( g_s \) is the coupling constant of QCD, \( g_{\bar{\phi}}^2 = \frac{2}{3} g^2 \), \( g = 0.395 \) is determined in Ref. [15], \( g^a \) is the gluon field. The process \( g + g \rightarrow \phi \bar{\phi} \rightarrow f_0(2100) \rightarrow \eta \eta \) is responsible for the productions of the \( f_0(2100) \) in both \( p \bar{p} \) annihilation and \( J/\psi \) radiative decay. Using this mechanism, the amplitude of the production of \( f_0(2100) \) is at \( O(g_s^2) \). Comparing with glueball production in \( J/\psi \) radiative decay, the amplitude of the production of the \( f_0(2100) \) is suppressed by \( O(\frac{1}{N_C}) \) and is at the same order of magnitude of the production of the hadrons made of quarks. Roughly speaking, the production rate of glueball in \( J/\psi \) radiative decay is at about \( O(10^{-3}) \) and the \( f_0(2100) \) is at \( O(10^{-4}) \). This is consistent with the analysis above. This mechanism has been applied to study \( J/\psi \rightarrow \gamma X(1810), X(1810) \rightarrow \omega \phi \) [18]. Usually, the \( J/\psi \rightarrow \gamma \omega \phi \) is a double OZI suppressed process. However, if \( X(1810) \) is a four quark state the double OZI suppression no longer exists.
In summary, the study shows that all the decay properties of the $\eta\eta$ resonance $f_0(2100)$ can be understood by the four quark state $s\bar{s}s\bar{s}$, $C_{ss}(36)$. The $\eta\eta$ channel is the dominant decay mode. The study predicts that the $f_0(2100) \to \eta\eta'$ has less decay rate. The decay channels, $\pi\pi$, $K\bar{K}$, $4\pi$, are at next leading order in $N_C$ expansion and suppressed. The existence of the decay mode of $f_0(2100) \to \phi\phi$ is predicted and the measurement of this channel is significant for the $q^2\bar{q}^2$ scheme of the $f_0(2100)$. Because of $\eta - \eta' - \eta(1405)$ mixing the $\eta(1405)$ should have small $s\bar{s}$ component. Therefore, $f_0(2100) \to \eta\eta(1405)$ exists. The production of $f_0(2100)$ in $J/\psi$ radiative decay and $p\bar{p}$ collisions are resulted in $gg \to f_0(2100)$.

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