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Is $f_1(1420)$ the Partner of $f_1(1285)$ in the $^3P_1$ $q\bar{q}$ Nonet ? *

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Based on a 2×2 mass matrix, the mixing angle of the axial vector states $f_1(1420)$ and $f_1(1285)$ is determined to be $51.5°$, and the theoretical results about the decay and production of the two states are presented. The theoretical results are in good agreement with the present experimental results, which suggests that $f_1(1420)$ can be assigned as the partner of $f_1(1285)$ in the $^3P_1$ $q\bar{q}$ nonet. We also suggest that the existence of $f_1(1510)$ needs further experimental confirmation.

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The quark model predicts that there are two isoscalar states in the $^3P_1$ $q\bar{q}$ nonet. However, up to date there have been three states $f_1(1285)$, $f_1(1420)$, and $f_1(1510)$ with $I = 0$ and $J^{PC} = 1^{++}$ listed by the Particle Data Group.[1] For $f_1(1285)$, it is believed that it is well established as the $u\bar{u} + d\bar{d}$ member of the $^3P_1$ $q\bar{q}$ nonet. Therefore, $f_1(1420)$ and $f_1(1510)$ compete for the $s\bar{s}$ assignment in the $^3P_1$ $q\bar{q}$ nonet, and one of them must be a non-$q\bar{q}$ state. On the one hand, in $K^-p \to \Lambda K\bar{K}\pi$,[2,3] $f_1(1510)$ has been observed but $f_1(1420)$. On the other hand, $f_1(1420)$ has been reported in K^-p but in π^-p,[4] while two experiments do not observe $f_1(1510)$ in K^-p.[4,5] These facts make the classification of $f_1(1420)$ and $f_1(1510)$ controversial.[2,6-10] However, the absence of $f_1(1510)$ in radiative J/ψ,[11,12] central collisions[13] and $\gamma\gamma$ collisions[14] leads to the conclusion that $f_1(1510)$ seems not to be well established and its assignment as the $s\bar{s}$ member of the $^3P_1$ $q\bar{q}$ nonet is premature.[10]

Recently, Close *et al.* assigned $f_1(1420)$ as the partner of $f_1(1285)$ by applying their glueball-$q\bar{q}$ filter technique to the axial vector nonet.[10] In this letter, we shall discuss the possibility of $f_1(1420)$ being the partner of $f_1(1285)$ in the $^3P_1$ $q\bar{q}$ nonet by studying the mixing effects of $f_1(1420)$ and $f_1(1285)$.

In the $|S\rangle = |s\bar{s}\rangle$, $|N\rangle = |u\bar{u} + d\bar{d}\rangle/\sqrt{2}$ basis, the mass square matrix describing the quarkonia-quarkonia mixing can be written as follows:[15]

$$M^2 = \begin{pmatrix} M_S^2 + A_S & \sqrt{2}A_{SN} \\ \sqrt{2}A_{NS} & M_N^2 + 2A_N \end{pmatrix}, \qquad (1)$$

where M_S and M_N are the masses of the bare states $|S\rangle$ and $|N\rangle$, respectively; A_S, A_N, A_{SN} and A_{NS} are the mixing parameters which describe the quarkonia-quarkonia transition amplitudes. Here, we assume that the physical states $|f_1(1420)\rangle$ and $|f_1(1285)\rangle$ are the eigenstates of the matrix M^2 with the eigenvalues of M_1^2 and M_2^2, respectively. From the above we can get the following equations:

$$M_S^2 + M_N^2 + 2A_N + A_S = M_1^2 + M_1^2, \qquad (2)$$

$$(M_S^2 + A_S)(M_N^2 + 2A_N) - 2A_{SN}A_{NS} = M_1^2 M_2^2. \qquad (3)$$

According to the factorization hypothesis[15]

$$A_{SN} = A_{NS} \equiv \sqrt{A_N A_S}, \qquad (4)$$

we can introduce a parameter R to get

$$A_{NS} = A_N R, \quad A_S = A_N R^2 \qquad (5)$$

with $0 < R \leq 1$. From Eqs. (2), (3) and (5), A_N and R can be expressed as

$$A_N = \frac{(M_N^2 - M_1^2)(M_N^2 - M_2^2)}{2(M_S^2 - M_N^2)}, \qquad (6)$$

$$R^2 = \frac{2(M_1^2 - M_S^2)(M_S^2 - M_2^2)}{(M_N^2 - M_1^2)(M_N^2 - M_2^2)}. \qquad (7)$$

Diagonalizing the matrix M^2, we can get a unitary matrix U which transforms the states $|S\rangle$ and $|N\rangle$ to the physical states $|f_1(1420)\rangle$ and $|f_1(1285)\rangle$,

$$U = \begin{pmatrix} x_1 & y_1 \\ x_2 & y_2 \end{pmatrix} = \begin{pmatrix} \dfrac{\sqrt{2}A_N R}{-C_1} & \dfrac{M_1^2 - M_S^2 - A_N R^2}{-C_1} \\ \dfrac{\sqrt{2}A_N R}{-C_2} & \dfrac{M_2^2 - M_S^2 - A_N R^2}{-C_2} \end{pmatrix} \qquad (8)$$

with $C_1 = \sqrt{2A_N^2 R^2 + (M_1^2 - M_S^2 - A_N R^2)^2}$, $C_2 = \sqrt{2A_N^2 R^2 + (M_2^2 - M_S^2 - A_N R^2)^2}$.

We choose $M_1 = 1.4262$ GeV, $M_2 = 1.2819$ GeV and $M_N = 1.23$ GeV, the mass of the isovector state $a_1(1260)$.[1] M_S can be obtained from the Gell-Mann-Okubo mass formula $M_S^2 = 2M_{K_{1A}}^2 - M_{a_1}^2$,[16] where $M_{K_{1A}} = 1.313$ GeV.[17] We take M_1, M_2, M_N and M_S as input and get the numerical form of the matrix U as follows:

$$U = \begin{pmatrix} x_1 & y_1 \\ x_2 & y_2 \end{pmatrix} = \begin{pmatrix} -0.96 & -0.28 \\ -0.28 & 0.96 \end{pmatrix}. \qquad (9)$$

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The physical states $|f_1(1420)\rangle$ and $|f_1(1285)\rangle$ can be read as

$$|f_1(1420)\rangle = -0.96|S\rangle - 0.28|N\rangle, \quad (10)$$

$$|f_1(1285)\rangle = -0.28|S\rangle + 0.96|N\rangle. \quad (11)$$

If we re-express the physical states $|f_1(1420)\rangle$ and $|f_1(1285)\rangle$ in the Gell-Mann basis $|8\rangle = |u\bar{u} + d\bar{d} - 2s\bar{s}\rangle/\sqrt{6}$, $|1\rangle = |u\bar{u} + d\bar{d} + s\bar{s}\rangle/\sqrt{3}$, the physical states $|f_1(1420)\rangle$ and $|f_1(1285)\rangle$ can be read as

$$|f_1(1420)\rangle = \cos\theta|8\rangle - \sin\theta|1\rangle, \quad (12)$$

$$|f_1(1285)\rangle = \sin\theta|8\rangle + \cos\theta|1\rangle. \quad (13)$$

with $\theta = 51.5°$, which is in good agreement with the result $\theta \sim 50°$ given by Close et al.[10]

Performing an elementary $SU(3)$ calculation,[18-20] we obtain

$$\frac{Br[f_1(1285) \to \phi\gamma]}{Br[f_1(1285) \to \rho\gamma]} = \frac{4}{9}\left(\frac{P_\phi}{P_\rho}\right)^3 \left(\frac{x_2}{y_2}\right)^2 = 0.007, \quad (14)$$

$$\frac{\Gamma[f_1(1420) \to \gamma\gamma]}{\Gamma[f_1(1285) \to \gamma\gamma]} = \left(\frac{M_1}{M_2}\right)^3 \frac{(y_1 + \sqrt{2}x_1/5)^2}{(y_2 + \sqrt{2}x_2/5)^2} = 0.539, \quad (15)$$

$$\frac{Br[J/\psi \to \gamma f_1(1420)]}{Br[J/\psi \to \gamma f_1(1285)]} = \left[\frac{P_{f_1(1420)}}{P_{f_1(1285)}}\right]^3 \frac{(\sqrt{2}y_1 + x_1)^2}{(\sqrt{2}y_2 + x_2)^2} = 1.36, \quad (16)$$

$$\frac{Br[J/\psi \to f_1(1420)\omega]}{Br[J/\psi \to f_1(1285)\phi]} = \frac{P_\omega}{P_\phi}\left[\frac{y_1}{x_2(1-2s)}\right]^2 > 1.029, \quad (17)$$

where P_j [$j = \phi$, ρ, ω, $f_1(1285)$, $f_1(1420)$] is the momentum of the final state meson j in the center of mass system, and s is the parameter describing the effects of $SU(3)$ breaking. For the axial vector mesons, we expect $0 < s \leq 1$.[20] Let r_{th} stand for the ratio of Eq. (15) to Eq. (16), so we have

$$r_{\text{th}} = 0.397. \quad (18)$$

Using the data cited by PDG,[1] we have

$$\frac{Br[f_1(1285) \to \phi\gamma]}{Br[f_1(1285) \to \rho\gamma]} = \frac{(7.9 \pm 3.0) \times 10^{-4}}{(5.4 \pm 1.2) \times 10^{-2}} = 0.015 \pm 0.009, \quad (19)$$

$$\frac{\Gamma[f_1(1420) \to \gamma\gamma]}{\Gamma[f_1(1285) \to \gamma\gamma]} = \frac{0.34 \pm 0.18}{Br(f_1(1420) \to K\bar{K}\pi)}, \quad (20)$$

$$\frac{Br[J/\psi \to \gamma f_1(1420)]}{Br[J/\psi \to \gamma f_1(1285)]} = \frac{(8.3 \pm 1.5) \times 10^{-4}}{(6.5 \pm 1.0) \times 10^{-4}} \cdot \frac{1}{Br(f_1(1420) \to K\bar{K}\pi)}, \quad (21)$$

$$\frac{Br[J/\psi \to f_1(1420)\omega]}{Br[J/\psi \to f_1(1285)\phi]} = \frac{(6.8 \pm 2.4) \times 10^{-4}}{(2.6 \pm 0.5) \times 10^{-4}} = 2.62 \pm 1.42. \quad (22)$$

The ratio r_{ex} of Eq. (20) to Eq. (21) gives

$$r_{\text{ex}} = 0.27 \pm 0.23. \quad (23)$$

From Eqs. (14)–(23), we find that the theoretical results are in good agreement with the experimental results, i.e., $|f_1(1420)\rangle = -0.96|S\rangle - 0.28|N\rangle$ and $|f_1(1285)\rangle = -0.28|S\rangle + 0.96|N\rangle$ are compatible with the experimental results. This suggests that the present experimental results support the assignment of $f_1(1420)$ as the partner of $f_1(1285)$ in the $^3P_1$ $q\bar{q}$ nonet.

We do not intend to discuss in detail the questionable interpretation of $f_1(1510)$ with dominant $s\bar{s}$ structure and that of the non-$q\bar{q}$ nature of $f_1(1420)$ in this letter (see Ref. 10). However, from our results, we believe that if $f_1(1510)$ with $I = 0$ and $J^{PC} = 1^{++}$ really exists, it should be a non-$q\bar{q}$ state. Its existence of $f_1(1510)$ needs further experimental confirmation.

In conclusion, by studying the mixing effects of $f_1(1285)$ and $f_1(1420)$, we find that the present experimental results support the assignment of $f_1(1420)$ as the partner of $f_1(1285)$ in the $^3P_1$ $q\bar{q}$ nonet. We also suggest that the existence of $f_1(1510)$ needs further experimental confirmation.

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