High Energy Physics and Nuclear Physics

Volume 14, Number 3

A Possible Explanation for the Axial-Vector Meson E/f_1(1420)

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The mixing mechanism of the three axial-vector mesons f_1(1285), f_1(1530) and E/f_1(1420) is discussed. The results show that the main component of the E/f_1(1420) is the glueball. On this basis we calculate the ratio of the helicity amplitudes and expect an experimental test for this result.

1. INTRODUCTION

The quark model predicts the existence of a ground-state nonet with spin-parity $J^{PC} = 1^{++}$. The a_1(1260) is a member of the nonet with isospin $I = 1$. The member with isospin $I = 1/2$ is the K_1(1440) [1]. In addition, there are two members with isospin $I = 0$. The D/f_1(1285) has been considered as one of them. Its main components are uu and dd. Since the discovery of the E/f_1(1420) [2], it has been considered that the E/f_1(1420) be the other member with isospin $I = 0$ [3]. Therefore, $s\bar{s}$ seems to be a major component of the E/f_1(1420).

However, the experiments in recent years show that the E/f_1(1420) seems unlikely to be the member of the axial-vector nonet, in which ss is the main component. The important reasons are the following: First the E/f_1(1420) can be strongly procured in ordinary hadronic collisions such as $\pi^{-}p$ and $p\bar{p}$ [2,4]. Secondly, the E/f_1(1420) is not observed in the hypercharge exchange reaction $K^{-}p$ $K\bar{K}\pi\Lambda$ [5]. Thirdly the reaction probability of the process $J/\psi \to \phi f_1(1420)$ is smaller than the one of the process $J/\psi \to \omega f_1(1420)$ by more than a factor of 5 [6].

In 1988, the LASS Collaboration at SLAC discovered a new axial-vector particle, the f_1(1530), in the reaction $K^{-}p \to K\bar{K}\pi\Lambda$ [5]. It was further confirmed by the ACNO group at CERN in 1982 [7]. From then on it is recognized that the f_1(1530) is more possibly the other member of the axial-vector nonet with isospin $I = 0$. Its main content is the ss sector.

Unfortunately, a new problem has arisen. What kind of particle is the E/f_1(1420) if the a_1(1260), K_1(1400), f_1(1285) and f_1(1530) form a nonet with $J^{PC} = 1^{++}$ which consists of a quark and an antiquark? Some experimental groups believed that the E/f_1(1420) observed in hadronic reactions was perhaps a particle with $J^{PC} = 0^{-+}$ [8]. However, after the discovery of the E/f_1(1420) in the two-

Supported by the National Natural Science Foundation of China
Received on October 11, 1989

photon reaction $\gamma\gamma^* \rightarrow K_s^0 K^\pm \pi^\mp$ by TPC/2γ [9], Mark II [10], JADE [11] and CELLO [12] collaborations, almost all people think that the spin of the E/f_1(1420) is equal to 1 rather than 0. Furthermore, the E/f_1(1420) can not be a radial excitation state of the nonet with $J^{PC} = 1^{++}$ because that its mass is not big enough [13]. The angular distribution analysis for the two-photon experiment favored a positive space parity P for the E/f_1(1420) but the opposite possibility can not be excluded. M. Chanowitz proposed a possible explanation [14], namely E/f_1(1420) may be a hybrid $q\bar{q}g$ with $J^{PC} = 1^{-+}$. The models of the four quark states [15], KK* molecule [16] and others have also been suggested.

We note that the mass, width and the main $K\bar{K}\pi$ decay mode of the E/f_1(1420) discovered in the two-photon reactions are the same as that observed in the hadronic processes, so that they must be the same particle. Consequently, we think that the spin-parity and the isospin of the E/f_1(1420) are $J^{PC} = 1^{++}$ and $I = 0$, respectively. On this basis, the mixing among the f_1(1285), f_1(1530) and E/f_1(1420) is investigated by using the method given in reference [17], their $q\bar{q}$ and glueball contents are determined and the ratio of helicity amplitudes of the E/f_1(1420) is calculated in this paper. Experimental examinations are expected.

2. THE MIXING AMONG THE f_1(1285), f_1(1530) AND E/f_1(1420)

The quantum chromodynamics (QCD) predicts that the bound states consisting of pure gluons, glueballs, exist. The glueballs with $J^{PC} = 1^{++}$ have been described in the potential model [18], bag model [19] and other theoretical models. The mixing between the $q\bar{q}$ states with $J^{PC} = 1^{++}$ and the glueball with the same spin-parity is possible. In the following we first calculate the $q\bar{q}$ and glueball components in the f_1(1285), f_1(1530) and E/f_1(1420) using the method mentioned in Ref.[17].

Introduce three base vectors:

$$|N\rangle = \frac{1}{\sqrt{2}}|u\bar{u} + d\bar{d}\rangle, \quad |S\rangle = |s\bar{s}\rangle,$$
$$|G\rangle = |gg\rangle. \tag{1}$$

where u, d and s stand for the quarks with three flavors, respectively, and g the gluon. Every physical state $|j>$ can be represented by a linear combination of the three base vectors

$$|j\rangle = x_j|N\rangle + y_j|S\rangle + z_j|G\rangle. \tag{2}$$

where $j = 1, 2, 3$ symbolizes f_1(1285), f_1(1530) and f_1(1420), respectively; x_j, y_j and z_j are the contents of $u\bar{u} + d\bar{d}$, $s\bar{s}$ and the glueball particle j, respectively. They obey a normalization condition

$$x_j^2 + y_j^2 + z_j^2 = 1. \tag{3}$$

If the transition amplitudes between $q_i\bar{q}_i$ and $q_j\bar{q}_j$ (i and j are the flavor index of the quarks) are represented by symbol α and the annihilation amplitudes between quarkoniums $q_i\bar{q}_i$ and the glueball by symbol β, in the three-dimension space with the base vectors (1) the physical eigenstate $|j>$ satisfies the following equation

$$M^2\ |j> = m_j^2\ |j> \tag{4}$$

where the mixing matrix with square mass is defined as follows

Table 1
Values obtained with the parameter m_G, after inputting masses of physical particles and solving the matrix equation.

m_G(GeV)	α	β	x
0.0	0.00032	−0.026	4.4
0.4	0.00035	−0.026	4.4
0.8	0.00052	−0.027	4.1
1.0	0.00080	−0.029	3.7
1.2	0.0025	−0.039	2.6

$$M^2 = \begin{pmatrix} m_N^2 + 2\alpha & \sqrt{2}\,\alpha z & \sqrt{2}\,\beta \\ \sqrt{2}\,\alpha z & m_s^2 + \alpha z^2 & \beta z \\ \sqrt{2}\,\beta & \beta z & m_G^2 + \frac{\beta^2}{\alpha} \end{pmatrix}, \tag{5}$$

Here m_N, m_S and m_G are the masses of $|N>$, $|S>$ and $|G>$ without mixing. The factor Z is responsible for the difference on the wave functions at the origin between the nonstrange quarkonium and the strange quarkonium which arises from the different masses between the nonstrange quark and the strange quark [20]. It describes the $SU(3)$ breaking effect. At present we have

$$m_N^2 = m_{a_1}^2, \quad m_s^2 = 2m_{K_1}^2 - m_{a_1}^2. \tag{6}$$

By keeping m_G as a parameter, inputing the masses of the physical particles $f_1(1285)$, $f_1(1530)$ and $E/f_1(1420)$ and solving the matrix equation (4), we obtain the values of α, β and z (see Table 1). The $q\bar{q}$ and the glueball contents in the particles $f_1(1285)$, $f_1(1530)$ and $E/f_1(1420)$ are given in Table 2 for different values of m_G.

From Table 1 one sees that in a large range of m_G (0 GeV $\leq m_G \leq$ 1.2 GeV), the transition amplitudes between different quarknoiums and the annihilation amplitudes between quarkoniums and glueball are all smaller (especially the former), but the $SU(3)$ violation effects are larger. From Table 2 we can find that the $q\bar{q}$ and glueball contents included in the $f_1(1285)$, $f_1(1530)$ and $E/f_1(1420)$ change only a little as m_G increases from 0 GeV to 1.2 GeV. The dominant component in the $f_1(1285)$ is $u\bar{u} + d\bar{d}$ and the $s\bar{s}$ and glueball components are very small. A larger $s\bar{s}$ and a smaller glueball components are included in the $f_1(1530)$ while the $u\bar{u} + d\bar{d}$ sector is negligible. The glueball component dominates, the $s\bar{s}$ is smaller and the $u\bar{u} + d\bar{d}$ is of no importance for the $E/f_1(1420)$. It should be emphasized that the results listed in Table 2 are independent of the order of the three particles in the matrix equation (4).

Table 2
Resulting values in the $q\bar{q}$ and glueball contents of the physical particles as m_G increases.

m_G	x_1	y_1	z_1	x_2	y_2	z_2	x_3	y_3	z_3
0.0	0.996	0.013	−0.089	0.024	0.92	0.40	0.087	−0.40	0.91
0.4	0.996	0.012	−0.090	0.024	0.92	0.39	0.087	−0.39	0.92
0.8	0.996	0.012	−0.094	0.026	0.92	0.39	0.092	−0.38	0.92
1.0	0.995	0.011	−0.10	0.028	0.93	0.37	0.098	−0.38	0.92
1.2	0.991	0.007	−0.14	0.041	0.94	0.35	0.13	−0.35	0.93

3. THE RATIO OF HELICITY AMPLITUDES FOR THE E/f_1(1420)

The results given in the last section show that the dominant component in the E/f_1(1420) is the glueball. Therefore, it is very likely that the E/f_1(1420) will be produced in the J/ψ radiative decay process J/$\psi \to \gamma$ + E/f_1(1420). As mentioned in Ref. [21], the main contribution to the S-matrix element for this process results from the glueball component in the E/f_1(1420), hence

$$\begin{aligned}\langle E_{\lambda_2}\gamma_{\lambda_1}|S|J_\lambda\rangle &= (2\pi)^4\delta^4(p_J - p_\gamma - p_E)\frac{eg^2}{3\sqrt{6\omega_\gamma}}\delta_{ab}e_\mu^{\lambda_1^*}(p_\gamma) \\ &\int dx_1dx_2\mathrm{Tr}[\chi_\lambda(0,x_1)\gamma^\alpha S_F(x_1 - x_2)\gamma^\beta S_F(x_2)\gamma^\mu \\ &\quad + \chi_\lambda(x_1,x_2)\gamma^\alpha S_F(x_2)\gamma^\mu S_F(-x_1)\gamma^\beta \\ &\quad + \chi_\lambda(x_2,0)\gamma^\mu S_F(-x_1)\gamma^\alpha S_F(x_1 - x_2)\gamma^\beta]G^{ab}_{\alpha\beta}(x_1,x_2)_{\lambda_2}.\end{aligned} \tag{7}$$

where the wave function of the J/ψ is

$$\chi_\lambda(x_1,\ x_2) = \frac{1}{2\sqrt{2}}\sqrt{\frac{m_J}{E_J}}\,e^{\frac{i}{2}p_J\cdot(x_1+x_2)}\left(1 + \frac{\not{p}_J}{m_J}\right)e^\lambda(p_J)\phi_J(x). \tag{8}$$

where $e^{\lambda_1}(p\gamma)$ and $e^\lambda(p_J)$ are the polarization vectors of the photon and the J/ψ particle, respectively, and $G^{ab}_{\alpha\beta}(x_1, x_2)_{\lambda_2}$ is the wave function of the glueball. For the glueball with $J^{PC} = 1^{++}$, two gluons form a state with the total spin $S = 2$ and the orbit angular momentum $l = 2$. Therefore, the wave function of the glueball can be written

$$\begin{aligned}G^{ab}_{\alpha\beta}(x_1,x_2)_{\lambda_2} &= \frac{\delta_{ab}}{\sqrt{2\,m_E}}e^{ip_E\cdot X}G(x)\sum_{m_1,\cdots,m_6}C^{1\ \ \lambda_2}_{2m_5 2m}\,C^{2\ \ m_6}_{1m_1 1m_2} \\ &\quad e^{m_1^*}_\alpha\ e^{m_2^*}_\beta\,C^{2m_5}_{1m_3 1m_4}\,m_E^2(x\cdot e^{m_3^*})(x\cdot e^{m_4^*})\end{aligned} \tag{9}$$

where $X = 1/2(x_1 + x_2)$, $x = x_1 - x_2$ and $C^{J\ \ l}_{j_1l_1 j_2l_2}$ is the usual Clebsch-Gordan coefficient.
The helicity amplitudes $T_{\lambda_2}(\lambda_2 = 0, \pm1)$ of the E/f_1(1420) are defined as

Table 3
The values of x as they correspond to the different values of m_c

m_c(GeV)	1.2	1.25	1.3	1.35	1.40	1.45	1.50
x	−0.41	−0.48	−0.54	−0.58	−0.63	−0.67	−0.70

$$\langle E_{\lambda_2}\gamma_{\lambda_1}|S|J_\lambda\rangle = (2\pi)^4\delta^4(p_J - p_\gamma - p_E)\frac{e}{\sqrt{8\omega_\gamma E_J E_E}}T_{\lambda_2} \tag{10}$$

T_{λ_2} satisfies the condition

$$T_{\lambda_2} = T_{-\lambda_2} \tag{11}$$

because of the parity conservation. Consequently there are only two independent helicity amplitudes T_1 and T_0. Substituting Eqs.(8) and (9) into Eq.(7) and comparing with Eq.(10), we obtain the helicity amplitudes as follows

$$\begin{aligned} T_1 = & \frac{4}{3\sqrt{30}} g^2 G(0)\psi_J(0)\frac{\sqrt{m_J}m_E^2}{m_c^4} \\ & \left\{\frac{80\ E_J}{m_J} + \frac{64 m_E p_J^2}{m_J(m_J^2 - 2m_E^2 + 4m_c^2)}\left(\frac{p_J^2}{m_c^2} - 5\right)\right. \\ & \left. + \frac{16 p_J^2}{m_c^4}\left[\frac{E_J}{m_J}\left(m_c^2 - \frac{m_E m_c p_J}{m_J}\right) - \frac{m_c m_E}{m_J^2}p_J^2\right]\right\} \end{aligned} \tag{12}$$

$$T_0 = -\frac{320}{3\sqrt{30}} g^2 G(0)\psi_J(0)\frac{m_E^2\sqrt{m_J}}{m_c^4}$$

where m_J, m_E and m_C are the masses of the J/ψ, E/f$_1$(1420) and charm quark, respectively, and

$$E_J = \frac{1}{2\ m_E}(m_J^2 + m_E^2), \quad p_J = \frac{1}{2\ m_E}(m_J^2 - m_E^2) \tag{13}$$

In obtaining Eq.(12), a reasonable approximation is used, namely the spatial wave functions $\psi_J(x)$ and $G(x)$ are replaced by the wave functions at the origin $\psi_J(0)$ and $G(0)$, respectively.

Define the helicity amplitude ratio of the E/f$_1$(1420)

$$x = T^1/T^0 \tag{14}$$

It is clear that there is only one parameter m_C in the expression of x. The values of x corresponding to the different values of m_C are shown in Table 3. Experimentally the value of the helicity amplitude ratio x can be determined by means of the measurement of the angular distribution. We expect experimental examinations.

4. DISCUSSION

On the basis of considering the interaction between the quark-antiquark pairs and the glueball and the $SU(3)$ breaking effect, the mixing among three axial-vector mesons $f_1(1285)$, $f_1(1530)$ and $E/f_1(1420)$ is discussed in this paper. The results show that almost all of the sectors included in the $f_1(1285)$ is the nonstrange quark-antiquark pair. For the $f_1(1530)$ the component is the strange quark-antiquark pair, and a smaller glueball sector is present. This is consistent qualitatively with the experimental result from the LASS group at SLAC. In this experiment the $f_1(1530)$ is seen clearly, but no evidence for the $f_1(1285)$ is found. We also know from our results that in addition to the smaller $s\bar{s}$ sector almost all of the remaining is the glueball sector in the $E/f_1(1420)$. On this basis we calculate the helicity amplitude ratio x of the $E/f_1(1420)$ and expect an experimental test for this result.

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