Possible Evidence for a Chiral Axial-Vector State in the $D$ Meson System

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We reanalyze the $D^{*+}\pi^−$ mass spectrum from CLEO II by the VMW method in order to examine the existence of a chiral axial-vector state, which is predicted in a covariant level-classification scheme recently proposed, other than normal orbitally-excited $P$-wave states in the $D$ meson system. A result of the present analysis seems to suggest that there exists an extra axial-vector meson, in addition to the two normal ones, in a similar mass region.

§1. Introduction

In the constituent quark model, together with heavy quark symmetry, the lowest-lying positive parity excitations of heavy-light $Q\bar{q}$ meson systems are expected, in the limit $m_Q \to \infty$, to be two degenerate spin doublets with the total angular momentum $j_q = 1/2$ and $3/2$ of the light quark, that is, four orbitally-excited states with $L = 1$ labeled as

$$j_nL_J = \frac{1}{2}P_0, \frac{1}{2}P_1 \quad \text{for the } j_q = \frac{1}{2} \text{ doublet},$$

$$= \frac{3}{2}P_1, \frac{3}{2}P_2 \quad \text{for the } j_q = \frac{3}{2} \text{ doublet}.$$  

In this limit heavy quark symmetry further requires that the $j_q = 1/2$ states decay to $\frac{1}{2}S_0 + \pi$ or $\frac{1}{2}S_1 + \pi$ only in an $S$-wave, while the $j_q = 3/2$ states decay only in a $D$-wave. It is therefore expected that the decay widths of the $j_q = 1/2$ and $3/2$ states are broad and narrow, respectively.

On the one hand, a covariant level-classification scheme of quark-antiquark meson systems has been proposed, which gives them a covariant quark representation with definite Lorentz and chiral transformation properties. In this scheme, assuming that chiral symmetry for the light-quark component in heavy-light meson systems is effective, the existence of extra scalar and axial-vector states is predicted, respectively, as chiral partners of the ground-state pseudoscalar and vector mesons. These what we call chiral scalar and axial-vector mesons are distinguished from the above-mentioned $P$-wave states, since the chiral scalar state is an analogue of the $\sigma(400-600)$ meson, which is difficult to be interpreted as the $^3P_0$ state, as a chiral partner of the $\pi$ meson in the light-quark system.

In this report we present a possible evidence for the chiral axial-vector state, $D_1^\chi$, in the $D$ meson system.
§2. Reanalysis of the $D^{*+}\pi^-$ mass spectrum from CLEO II

We reanalyze the $D^{*+}\pi^-$ mass spectrum, published by CLEO Collaboration, by the VMW method in which the production amplitude is expressed by a sum of Breit-Wigner amplitudes for relevant resonances.

In the present analysis we take into account the four states $D_2^*\left(\frac{3}{2}P_2\right)$, $D_1\left(\frac{3}{2}P_1\right)$, $D_1^*\left(\frac{1}{2}P_1\right)$ and $D_1^\chi$ which can decay to $D^{*}\pi$. Then, following the VMW method, the production amplitude is given by

$$|A(s)|^2 = |r_1 e^{i\theta_1} \Delta_{D_1^\chi}(s) + r_2 e^{i\theta_2} \Delta_{D_1^*}(s)|^2 + |r_3 e^{i\theta_3} \Delta_{D_1}(s)|^2 + |r_4 e^{i\theta_4} \Delta_{D_2^*}(s)|^2,$$

where $\Delta_R(s) = \frac{-m_R \Gamma_R}{s - m_R^2 + i m_R \Gamma_R}$, $r_1, ..., r_4$ and $\theta_1, ..., \theta_4$ are the production couplings and phases of respective resonances, and we assumed that $D_1^\chi$ and $D_1^*$ decay only through an $S$-wave, while $D_1$ only through a $D$-wave. The background $D^{*}\pi$ mass distribution is fit with a five-parameter threshold function given by

$$BG = \alpha(DM)^\beta \exp \left[-\gamma_1 DM - \gamma_2 (DM)^2 - \gamma_3 (DM)^3\right],$$

where the parameters $\alpha, \beta, \gamma_1, \gamma_2$ and $\gamma_3$ are fixed through the fit to the total $D^{*}\pi$ mass spectrum.

Using the above production amplitude and background, we fit the $D^{*}\pi$ mass spectrum in the following three cases:

(a) High-mass $D_1^*$ with a mass of $2500 < m_{D_1^*} < 2600$ in MeV,

(b) Low-mass $D_1^*$ with a mass of $2350 < m_{D_1^*} < 2500$ in MeV,

(c) No $D_1^\chi$ and $D_1^*$.

Here the case (c) corresponds to the original analysis by CLEO Collaboration, though the background parametrization is somewhat different. The results of fits are shown in Fig. 1 and obtained values of the resonance parameters are given in Table I. In both the fits with high- and low-mass $D_1^*$, it is found that the mass and width of $D_1^\chi$ are $\approx 2310$ MeV and $\approx 20$ MeV, respectively, and those of $D_1$ and $D_2^*$ are similar to the values reported so far. For the mass and width of $D_1^*$ we obtain $\approx 2600$ MeV and $\approx 200$ MeV in the high-mass fit, while $\approx 2420$ MeV and $\approx 200$ MeV in the low-mass fit.

In all the three cases of fits the $\chi^2/N_{\text{dof}}$ is best for the high-mass $D_1^*$ fit, though they are not so different from each other. It would be worth while noting that the two cases of fits with $D_1^\chi$ seem to describe the data better than the fit without $D_1^\chi$ in the mass region $2.15-2.5$ GeV, where there appears to be an excess of data events at the mass $2.31-2.33$ GeV.

§3. Theoretical remarks on the results

We consider the mass splitting and mixing of $P$-wave meson multiplets, based on the Breit-Fermi Hamiltonian with vector-gluon and long-range-scalar exchange,
Fig. 1. The results of the fits to the $D^{*+} \pi^-$ mass spectrum with (a) high-mass $D_1^*$, (b) low-mass $D_1^*$, and (c) no $D_1^*$ and $D_1^*$. 

Table I. Values of the resonance parameters and $\chi^2/N_{\text{dof}}$ obtained from the respective fits.

| State (MeV) | (a) Fit with high-mass $D_1^*$ | (b) Fit with low-mass $D_1^*$ | (c) Fit without $D_1^*$ and $D_1^*$ |
|------------|-------------------------------|-------------------------------|-----------------------------------|
| $D_1^*$    | 2308 18.7                     | 2307 17.4                     | —                                 |
| $D_1^*$    | 2596 199                      | 2421 199                      | —                                 |
| $D_1^*$    | 2421 34.5                     | 2421 27.0                     | 2421 27.5                         |
| $D_1^*$    | 2472 35.0                     | 2468 35.0                     | 2466 35.0                         |
| $\chi^2/N_{\text{dof}}$ | 57.7/52                      | 58.0/52                       | 66.2/59                           |

where we ignore the $P$-wave $D_1$ and $D_1^*$ states mixing with the chiral $D_1^*$ state. Taking a static potential due to single vector-gluon exchange to be $-4\alpha_s/3r$, the spin-dependent part of the Hamiltonian for $P$-wave states can be expressed, to first order $1/m_Q$, as

$$\delta H = C_q \mathbf{L} \cdot \mathbf{S}_q + C_Q (\mathbf{L} \cdot \mathbf{S}_Q + S_T), \quad S_T = 3(\mathbf{S}_q \cdot \hat{r})(\mathbf{S}_Q \cdot \hat{r}) - \mathbf{S}_q \cdot \mathbf{S}_Q$$
with
\[ C_q = \left( \frac{1}{2m_q^2} + \frac{1}{m_q m_Q} \right) \left\langle \frac{4\alpha_s}{3r^3} \right\rangle - \frac{1}{2m_q^2} \left\langle \frac{1}{r} \frac{dV_s}{dr} \right\rangle, \]
\[ C_Q = \frac{1}{m_q m_Q} \left\langle \frac{4\alpha_s}{3r^3} \right\rangle, \]
where \( V_s(r) \) is the static potential due to long-range-scalar exchange and the spin-spin interaction is neglected because of its contact nature. The Hamiltonian \( \delta H \) gives rise to the mass splittings among \( P \)-wave multiplets and the mixing between the \( 3/2P_1 \) and \( 1/2P_1 \) states. Treating \( \delta H \) as a first-order perturbation and using the mass values of \( D_2^* \), \( D_1 \) and \( D_1^* \) obtained in the high-mass \( D_1^* \) fit, we find \( \approx 2470 \) MeV for the mass of \( D_2^*(1/2P_0) \) and \( \phi - \phi_{HQ} \approx -3.64^\circ \) for the deviation of the \( D_1(3/2P_1) - D_1^*(1/2P_1) \) mixing angle from the heavy-quark-symmetry limit with the parameter values of the unperturbed mass \( M_0 = 2490 \) MeV common to all four states, \( C_q = -73.81 \) MeV and \( C_Q = 47.15 \) MeV, where we have chosen a solution with \( C_Q > 0 \) in accord with the above definition of \( C_Q \). For the low-mass \( D_1^* \) case of fits there is no solution.

§4. Concluding remarks

We have reanalyzed the \( D^{*+}\pi^- \) mass spectrum published by CLEO Collaboration and found a possible evidence for the chiral axial-vector meson \( D_1^X \) with a mass and width of \( \approx 2310 \) MeV and \( \approx 20 \) MeV, respectively. We have also found the mass and width of \( D_1^* \) to be \( \approx 2600 \) MeV and \( \approx 200 \) MeV, together with similar masses and widths of \( D_1 \) and \( D_2^* \) to those reported so far, among which the spin-dependent Hamiltonian arising from one-vector-gluon and long-range-scalar exchange could account for the mass splittings. To confirm the existence of \( D_1^* \) it goes without saying that further analyses, including other experimental data with high statistics, are necessary in a more precise way.

Furthermore, in establishing the covariant level-classification scheme of meson systems it is important to examine the existence of the chiral scalar meson \( D_0^X \) as well as \( B_0^X \) and \( B_1^X \) in the \( B \) meson system. An analysis of the \( B\pi \) mass spectrum, to study the existence of \( B_0^X \), is in progress and its preliminary result has been presented.\[^{[3]}\]

References

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