Semileptonic D^0 and D^+ decays as a probe of the $a_0(980)$ nature

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Abstract. The $D^+ \to d\bar{d}\, e^+\nu \to a_0^0(980)\, e^+\nu \to \pi^0\eta\, e^+\nu$ and $D^0 \to d\bar{u}\, e^+\nu \to a_0^-(980)\, e^+\nu \to \pi^-\eta\, e^+\nu$ decays (with the charge conjugated ones) are the direct probe of the constituent two-quark components in the $a_0^\pm(980)$ and $a_0^0(980)$ wave functions. Recent BESIII experiment is the first step in experimental study of these decays. We suggest adequate formulas for the data analysis and present a variant of $\eta\pi$ invariant mass distribution when $a_0(980)$ has no constituent two-quark component at all.

1 Introduction

The $a_0(980)$ and $f_0(980)$ mesons are well-established parts of the assumed light scalar meson nonet [1]. From the beginning, the $a_0(980)$ and $f_0(980)$ mesons became one of the central problems of nonperturbative QCD, as they are important for understanding the way chiral symmetry is realized in the low-energy region and, consequently, for understanding confinement. Many experimental and theoretical papers have been devoted to this subject.

There is much evidence that supports the four-quark model of light scalar mesons [2, 3].

Recently BES Collaboration measured the decays $D^0 \to d\bar{u}\, e^+\nu \to a_0^- e^+\nu \to \pi^-\eta e^+\nu$ and $D^+ \to d\bar{d}\, e^+\nu \to a_0^0 e^+\nu \to \pi^0\eta e^+\nu$ for the first time.

It will be shown that in the scenario, based on the four-quark model, it is possible to describe the data on different reactions in agreement with the BESIII data [4], while $a_0(980)$ has no constituent two-quark component at all, that is, $g_{d\bar{u}a_0^-} = g_{d\bar{d}a_0^0} = 0$, $g^{(0)}_{a_0\gamma\gamma} = 0$. More precise data would allow to check this variant better.

2 The model

The amplitude of the $D^0 \to S\,(\text{scalar})\, e^+\nu$ decay reads [5]

$$M[D^0(p) \to S(p_1)W^+(q) \to S(p_1)\, e^+\nu] = \frac{G_F}{\sqrt{2}} V_{cd} A_\alpha L^\alpha\,, \tag{1}$$

$$\begin{aligned} A_\alpha &= f_+^S(q^2)(p+p_1)_\alpha\,,\\ L_\alpha &= \bar{\nu}\gamma_\alpha(1+\gamma_5)e\,, \qquad q=(p-p_1)\,. \end{aligned} \tag{2}$$

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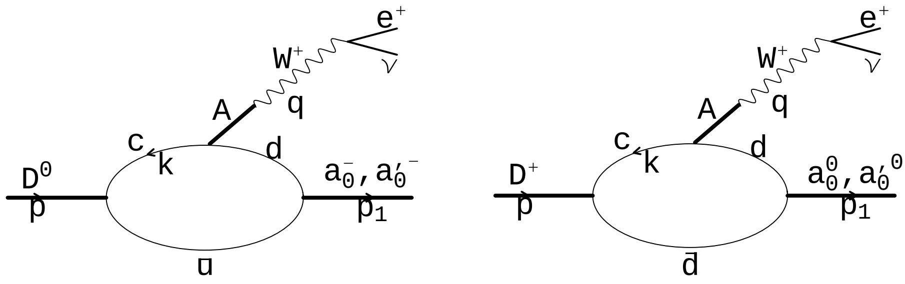


Figure 1. Model of the $D^0 \to (a_0^-, a_0'^-)\, e^+\nu$ and $D^+ \to (a_0^0, a_0'^0)\, e^+\nu$ decays.

$$f_+^S(q^2) = f_+^S(0)\frac{m_A^2}{m_A^2 - q^2} = f_+^S(0) f_A(q^2) = g_{D^0 c\bar{u}} F_S\, g_{d\bar{u}S}\, f_A(q^2)\,, \tag{3}$$

where $A = D_1(2420)^\pm$, F_S - loop integral, assumed to be constant in the region of interest.

The decay rate into the stable S state is

$$\frac{d\Gamma(D^0 \to S\ e^+\nu)}{dq^2} = \frac{G_F^2 |V_{cd}|^2}{24\pi^3} p_1^3(q^2)|f_+^S(q^2)|^2, \tag{4}$$

$$p_1(q^2) = \frac{\sqrt{m_{D^0}^4 - 2m_{D^0}^2(q^2 + m_S^2) + (q^2 - m_S^2)^2}}{2m_{D^0}}\,. \tag{5}$$

The amplitude of the $D^0 \to d\bar{u}\, e^+\nu \to [a_0^-(980) + a_0'^-]\, e^+\nu \to \eta\pi^-\, e^+\nu$ decay is

$$M(D^0 \to d\bar{u}\, e^+\nu \ \to \eta\pi^-\ e^+\nu) = \frac{G_F}{\sqrt{2}} V_{cd}\, L^\alpha\, (p + p_1)_\alpha\, g_{D^0 c\bar{u}}\, f_A(q^2)$$

$$\times\frac{1}{\Delta(m)}\Big(F_{a_0^-} g_{d\bar{u}a_0^-} D_{a_0'^-}(m) g_{a_0\eta\pi} + F_{a_0^-} g_{d\bar{u}a_0^-} \Pi_{a_0^- a_0'^-}(m) g_{a_0'\eta\pi}$$

$$+ F_{a_0'^-} g_{d\bar{u}a_0'^-} \Pi_{a_0'^- a_0^-}(m) g_{a_0\eta\pi} + F_{a_0'^-} g_{d\bar{u}a_0'^-} D_{a_0^-}(m) g_{a_0'\eta\pi}\Big)\,, \tag{6}$$

where m is the invariant mass of the $\eta\pi^-$ system, $\Delta(m) = D_{a_0'^-}(m) D_{a_0^-}(m) - \Pi_{a_0'^- a_0^-}(m)\Pi_{a_0^- a_0'^-}(m)$, $D_{a_0^-}(m)$ and $D_{a_0'^-}(m)$ are the inverted propagators of the a_0^- and $a_0'^-$ mesons, and $\Pi_{a_0^- a_0'^-}(m) = \Pi_{a_0'^- a_0^-}(m)$ is the nondiagonal element of the polarization operator, which mixes the a_0^- and $a_0'^-$ mesons [5].

Table 1. Properties of the resonances and the description quality

$m_{a_0^0}$, MeV	988.3	$m_{a_0'}$, MeV	1423.9	R, fm	6.3
$g_{a_0^0 K^+K^-}$, GeV	4.06	$g_{a_0'^0 K^+K^-}$, GeV	4.19	λ	1
$g_{a_0\eta\pi}$, GeV	3.99	$g_{a_0'\eta\pi}$, GeV	0.80	$\chi^2_{\gamma\gamma}$ / 36 points	13.8
$g_{a_0\eta'\pi}$, GeV	−4.24	$g_{a_0'\eta'\pi}$, GeV	1.27	χ^2_{sp} / 49 points	65.5
$g^{(0)}_{a_0^0\gamma\gamma}$	0	$g^{(0)}_{a_0'^0\gamma\gamma}$, 10^{-3} GeV^{-1}	−12.90	χ^2_{corr} / 29 points	28.4
$m_{a_0^+}$, MeV	997.6	$C_{a_0 a_0'}$, GeV^2	−0.163	$(\chi^2_{\gamma\gamma}+\chi^2_{sp}+\chi^2_{corr})$/n.d.f.	107.8/99

The double differential rate of the $D^0 \to d\bar{u}\, e^+\nu \to [a_0^-(980) + a_0'^-]\, e^+\nu \to \eta\pi^-\, e^+\nu$ decay is

$$\frac{d^2\Gamma(D^0 \to \eta\pi^-\, e^+\nu)}{dq^2 dm} =$$

$$= \frac{G_F^2\, |V_{cd}|^2}{192\,\pi^5}\, g^2_{D^0 c\bar{u}}\, |f_A(q^2)|^2\, p_1^3(q^2, m)\, \rho_{\eta\pi^-}(m)\, m \left|\frac{1}{\Delta(m)}\right|^2$$

$$\times \Big| F_{a_0^-} g_{d\bar{u}a_0^-} D_{a_0'^-}(m) g_{a_0\eta\pi} + F_{a_0^-} g_{d\bar{u}a_0^-} \Pi_{a_0^- a_0'^-}(m) g_{a_0'\eta\pi}$$

$$+ F_{a_0'^-} g_{d\bar{u}a_0'^-} \Pi_{a_0'^- a_0^-}(m) g_{a_0\eta\pi} + F_{a_0'^-} g_{d\bar{u}a_0'^-} D_{a_0^-}(m) g_{a_0'\eta\pi} \Big|^2, \quad (7)$$

where $\rho_{\eta\pi^-}(m) = \sqrt{(1 - (m_\eta + m_{\pi^-})^2/m^2)(1 - (m_\eta - m_{\pi^-})^2/m^2)}$.
If a_0 does not contain two-quark state, then

$$\frac{d^2\Gamma(D^0 \to \eta\pi^-\, e^+\nu)}{dq^2 dm} = \frac{G_F^2\, |V_{cd}|^2}{192\,\pi^5}\, g^2_{D^0 c\bar{u}}\, |f_A(q^2)|^2\, p_1^3(q^2, m)\, \rho_{\eta\pi^-}(m)\, m \left|\frac{1}{\Delta(m)}\right|^2$$

$$\times |F_{a_0'^-} g_{d\bar{u}a_0'^-}|^2 \left| \Pi_{a_0'^- a_0^-}(m) g_{a_0\eta\pi} + D_{a_0^-}(m) g_{a_0'\eta\pi} \right|^2, \quad (8)$$

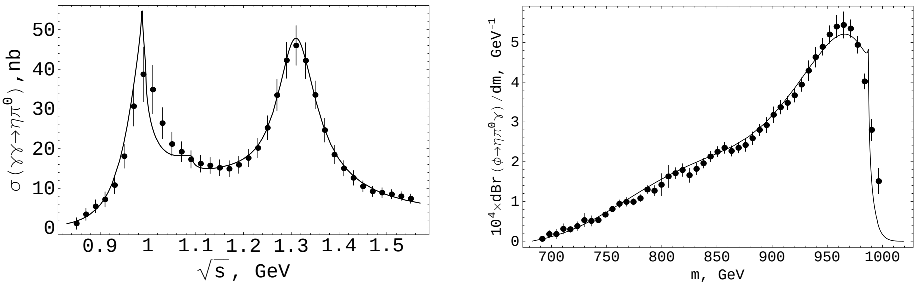
The $D^+ \to d\bar{d}\, e^+\nu \to S\; e^+\nu$ and $D^+ \to \eta\pi^0\, e^+\nu$ decays are described in the same way. It is enough to substitute $D^0 \to D^+, d\bar{u} \to d\bar{d}$, $a_0^- \to a_0^0$, $a_0'^- \to a_0'^0$, and $\pi^- \to \pi^0$. The coupling $g_{d\bar{d}a_0'^0} = g_{d\bar{u}a_0'^-} / \sqrt{2}$.

3 Results and perspectives

The results are shown in table 1 and figures 2, 3, 4, and 5. The data is described well, the $a_0(980)$ coupling constants agree with the four-quark model scenario, see [5].

In [10, 11] the program of studying light scalars in semileptonic D and B decays was suggested. Processes of interest are:

$D_s^+ \to s\bar{s}e^+\nu \to [\sigma(600) + f_0(980)]e^+\nu \to \pi^+\pi^-\, e^+\nu$
$D^+ \to d\bar{d}\, e^+\nu \to [\sigma(600) + f_0(980)]e^+\nu \to \pi^+\pi^- e^+\nu$
$D^0 \to d\bar{u}\, e^+\nu \to a_0^- e^+\nu \to \pi^-\eta e^+\nu$
$D^+ \to d\bar{d}\, e^+\nu \to a_0^0 e^+\nu \to \pi^0\eta e^+\nu$
$B^0 \to d\bar{u}\, e^+\nu \to a_0^- e^+\nu \to \pi^-\eta e^+\nu$
$B^+ \to u\bar{u}\, e^+\nu \to a_0^0 e^+\nu \to \pi^0\eta e^+\nu$
$B^+ \to u\bar{u}\, e^+\nu \to [\sigma(600) + f_0(980)]e^+\nu \to \pi^+\pi^- e^+\nu$



(a) (b)

Figure 2. Results of our fit, see Tables I and II, on a) the Belle data on $\gamma\gamma \to \eta\pi^0$ cross-section [6], and b) the KLOE data on the $\phi \to \eta\pi^0\gamma$ decay [7], m is the invariant $\eta\pi^0$ mass.

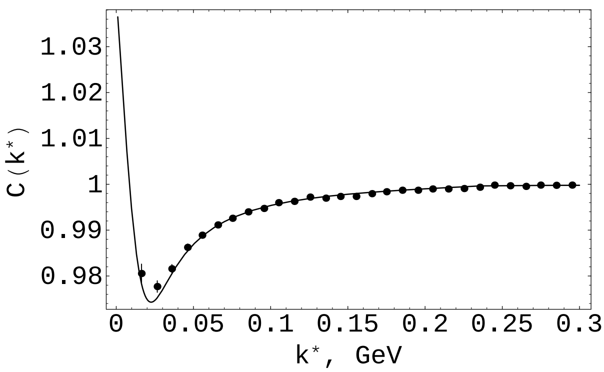


Figure 3. The $K_S^0 K^+$ correlation $C(k^*)$, see Ref. [8] and references therein. Solid line represents our fit, points are experimental data [9].

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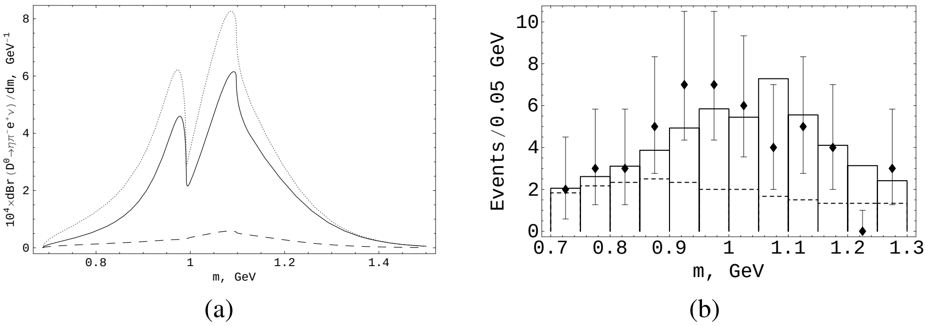

Figure 4. (a) The plot of $D^0 \to (a_0^-, a_0'^-)\, e^+\nu \to \eta\pi^- e^+\nu$ spectrum with parameters of our fit. The solid line is the total contribution, the dotted line is the term $\sim F_{a_0'^-} g_{d\bar{u}a_0'^-} \Pi_{a_0'^- a_0^-}(m) g_{a_0\eta\pi}$ contribution, and the dashed line is the term $\sim F_{a_0'^-} g_{d\bar{u}a_0'^-} D_{a_0^-}(m) g_{a_0'\eta\pi}$ contribution. (b) The data on the $D^0 \to (a_0^-, a_0'^-)\, e^+\nu \to \eta\pi^- e^+\nu$ decay and our fit. The solid histogram is the total contribution, and the dashed histogram represents the sum of backgrounds.

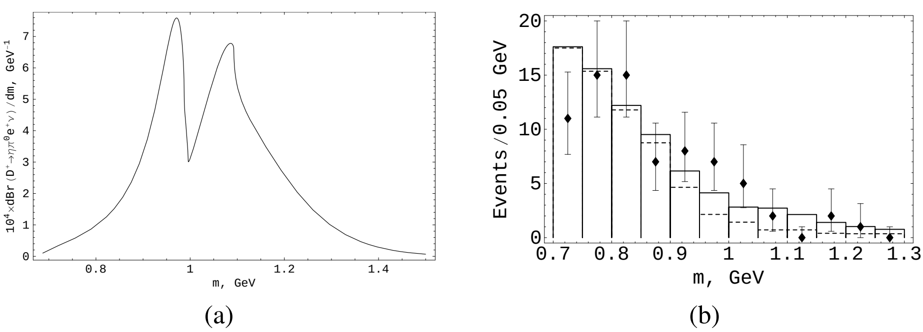

Figure 5. (a) The spectrum of the $D^+ \to (a_0^0, a_0'^0)\, e^+\nu \to \eta\pi^0 e^+\nu$ decay with parameters of our fit. (b) The spectrum of the $D^+ \to (a_0^0, a_0'^0)\, e^+\nu \to \eta\pi^0 e^+\nu$ decay. The solid histogram is the total contribution, and the dashed histogram represents the sum of backgrounds.