Vacuum properties of open charmed mesons in a chiral symmetric model

Walaa I. Eshraim

Institute for Theoretical Physics, Goethe-University, Max-von-Laue-Str. 1, 60438 Frankfurt am Main, Germany

E-mail: weshraim@th.physik.uni-frankfurt.de

Abstract. We present a $U(4)_R \times U(4)_L$ chirally symmetric model, which in addition to scalar and pseudoscalar mesons also includes vector and axial-vector mesons. A part from the three new parameters pertaining to the charm degree of freedom, the parameters of the model are fixed from the $N_f = 3$ flavor sector. We calculate open charmed meson masses and the weak decay constants of nonstrange open charm D and strange open charm D_S. We also evaluate the (OZI-dominant) strong decays of open charmed mesons. The results are turn out to be in quantitative agreement with experimental data.

1. Introduction

Open charmed mesons, composite states of charm quark (c) and up (u), down (d), or strange (s) antiquark, were observed two years later than the discovery of the J/ψ particle in 1974. Since that time, the study of charmed meson spectroscopy and decays has made significant experimental [1, 2, 3] and theoretical process [4, 5, 6, 7]. We show in the present work how the original $SU(3)$ flavor symmetry of hadrons can be extended to $SU(4)$ in the framework of a chirally symmetric model with charm as an extra quantum number. Note that, chiral symmetry is strongly explicitly broken by the current charm quark mass.

The development of an effective hadronic Lagrangian plays an important role in the description of the masses and the interactions of low-lying hadron resonances [8]. To this end, we developed the so-called extended Linear Sigma Model (eLSM) in which (pseudo)scalar and (axial-)vector $q\bar{q}$ mesons and additional scalar and pseudoscalar glueball fields are the basic degrees of freedom. The eLSM has already shown success in describing the vacuum phenomenology of the nonstrange-strange mesons [9, 10, 11, 12, 13]. The eLSM emulates the global symmetries of the QCD Lagrangian; the global chiral symmetry (which is exact in the chiral limit), the discrete C, P, and T symmetries, and the classical dilatation (scale) symmetry. When working with colorless hadronic degrees of freedom, the local color symmetry of QCD is automatically preserved. In eLSM the global chiral symmetry is explicitly broken by non-vanishing quark masses and quantum effects [14], and spontaneously by a non-vanishing expectation value of the quark condensate in the QCD vacuum [15]. The dilatation symmetry is broken explicitly by the logarithmic term of the dilaton potential, by the mass terms, and by the $U(1)_A$ anomaly.

In these proceedings, we present the outline of the extension of the eLSM from the three-flavor case to the four-flavor case including the charm quark [16, 17, 18]. Most parameters of our eLSM are taken directly from Ref.[12] where the nonstrange-strange mesons were considered. There are only new three parameters pertaining to the charm degree of freedom. We compute open charmed meson masses, the weak decay constants of the pseudoscalar D and D_s mesons, and the (OZI-dominant) strong decays of open charmed mesons.

2. The $U(4)_R \times U(4)_L$ Linear Sigma Model

In Refs.[16, 17, 18], we presented the outline of the extension of the eLSM from the three-flavor case to the four-flavor case including charm quark. In this extension, we introduced the (pseudo)scalar and (axial-)vector meson fields in terms of 4×4 (instead of 3×3) matrices, which the charmed mesons appear in the fourth row and fourth column as follows: The matrix of pseudoscalar fields P (with quantum numbers $J^{PC} = 0^{-+}$) reads

$$P = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{1}{\sqrt{2}}(\eta_N + \pi^0) & \pi^+ & K^+ & D^0 \\ \pi^- & \frac{1}{\sqrt{2}}(\eta_N - \pi^0) & K^0 & D^- \\ K^- & \overline{K}^0 & \eta_S & D_S^- \\ \overline{D}^0 & D^+ & D_S^+ & \eta_c \end{pmatrix}, \tag{1}$$

and the matrix of scalar fields S (with quantum numbers $J^{PC} = 0^{++}$) reads

$$S = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{1}{\sqrt{2}}(\sigma_N + a_0^0) & a_0^+ & K_0^{*+} & D_0^{*0} \\ a_0^- & \frac{1}{\sqrt{2}}(\sigma_N - a_0^0) & K_0^{*0} & D_0^{*-} \\ K_0^{*-} & \overline{K}_0^{*0} & \sigma_S & D_{S0}^{*-} \\ \overline{D}_0^{*0} & D_0^{*+} & D_{S0}^{*+} & \chi_{c0} \end{pmatrix}, \tag{2}$$

which are used to construct the matrix $\Phi = S + iP$. In the pseudoscalar sector there are: an open charmed state $D^{0,\pm}$, open strange-charmed states $D_S^{\pm}$, and a hidden charmed ground state $\eta_C(1S)$. In the scalar sector there are open charmed $D_0^{*0,\pm}$ and strange charmed meson $D_{S0}^{*\pm}$ which are assigned to $D_0^*(2400)^{0,\pm}$ and $D_{S0}^*(2317)^{\pm}$, respectively.

We now turn to the vector sector. The matrix V^μ which includes the vector degrees of freedom is:

$$V^\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{1}{\sqrt{2}}(\omega_N + \rho^0) & \rho^+ & K^*(892)^+ & D^{*0} \\ \rho^- & \frac{1}{\sqrt{2}}(\omega_N - \rho^0) & K^*(892)^0 & D^{*-} \\ K^*(892)^- & \bar{K}^*(892)^0 & \omega_S & D_S^{*-} \\ \overline{D}^{*0} & D^{*+} & D_S^{*+} & J/\psi \end{pmatrix}^\mu, \tag{3}$$

where the nonstrange-charmed fields D^{*0}, $D^{*\pm}$ correspond to $\bar{q}q$ resonances $D^*(2007)^0$ and $D^*(2010)^{\pm}$, respectively, while the strange-charmed $D_0^{*\pm}$ is assigned to the resonance $D_0^{*\pm}$ (with mass $m_{D_0^{*\pm}}$), and there is the lowest vector charmonium state $J/\psi(1S)$.

The matrix A^μ describing the axial-vector degrees of freedom is given by:

$$A^\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{1}{\sqrt{2}}(f_{1,N} + a_1^0) & a_1^+ & K_1^+ & D_1^0 \\ a_1^- & \frac{1}{\sqrt{2}}(f_{1,N} - a_1^0) & K_1^0 & D_1^- \\ K_1^- & \bar{K}_1^0 & f_{1,S} & D_{S1}^- \\ \bar{D}_1^0 & D_1^+ & D_{S1}^+ & \chi_{c,1} \end{pmatrix}^\mu, \tag{4}$$

where the open charmed mesons D_1 and D_{S1} are assigned to $D_1(2420)$ and $D_{S1}(2536)$, respectively, whereas the charm-anticharm state χ_{c1} corresponds to the $c\bar{c}$ resonance $\chi_{c1}(1P)$. From the matrices V^μ and A^μ we construct the left-handed and right-handed vector fields

$L^\mu = V^\mu + A^\mu$ and $R^\mu = V^\mu - A^\mu$, respectively.

This study is a straightforward extension of Ref. [12]. Therefore, the Lagrangian of the $N_f = 4$ model with global chiral invariance has an analogous structure as the corresponding eLSM Lagrangian for $N_f = 3$. However, for a better fit to the masses, we add an additional term $-2\,\mathrm{Tr}[E\Phi^\dagger\Phi]$:

$$\begin{aligned}
\mathcal{L} &= \frac{1}{2}(\partial_\mu G)^2 - \frac{1}{4}\frac{m_G^2}{\Lambda_G^2}\left[G^4 \ln\left(\frac{\mathrm{G}}{\Lambda_\mathrm{G}}\right) - \frac{\mathrm{G}^4}{4}\right] + \mathrm{Tr}[(\mathrm{D}^\mu\Phi)^\dagger(\mathrm{D}^\mu\Phi)] - \mathrm{m}_0^2\left(\frac{\mathrm{G}}{\mathrm{G}_0}\right)^2 \mathrm{Tr}(\Phi^\dagger\Phi) \\
&- \lambda_1[\mathrm{Tr}(\Phi^\dagger\Phi)]^2 - \lambda_2 \mathrm{Tr}(\Phi^\dagger\Phi)^2 + \mathrm{Tr}[H(\Phi+\Phi^\dagger)] - 2\,\mathrm{Tr}[E\,\Phi^\dagger\Phi] + c(\det\Phi - \det\Phi^\dagger)^2 \\
&+ \mathrm{Tr}\left\{\left[\left(\frac{G}{G_0}\right)^2 \frac{m_1^2}{2} + \Delta\right]\left[(L^\mu)^2 + (R^\mu)^2\right]\right\} - \frac{1}{4}\mathrm{Tr}[(L^{\mu\nu})^2 + (R^{\mu\nu})^2] \\
&+ ic_{\tilde{G}\Phi}\tilde{G}(\det\Phi - \det\Phi^\dagger) + i\frac{g_2}{2}\{\mathrm{Tr}(L_{\mu\nu}[L^\mu, L^\nu]) + \mathrm{Tr}(R_{\mu\nu}[R^\mu, R^\nu])\} \\
&+ \frac{h_1}{2}\mathrm{Tr}(\Phi^\dagger\Phi)\mathrm{Tr}[(L^\mu)^2 + (R^\mu)^2] + h_2 \mathrm{Tr}[(\Phi R^\mu)^2 + (L^\mu\Phi)^2] + 2h_3 \mathrm{Tr}(\Phi R_\mu \Phi^\dagger L^\mu) + \ldots\,, \qquad (5)
\end{aligned}$$

where the field G denotes the dilaton field and the parameter $\Lambda_G \sim N_C\,\Lambda_{QCD}$ sets the energy scale of the gauge theory. The dilaton potential breaks the dilatation symmetry explicitly. $D^\mu\Phi \equiv \partial^\mu\Phi - ig_1(L^\mu\Phi - \Phi R^\mu)$ is the covariant derivative; $L^{\mu\nu} \equiv \partial^\mu L^\nu - \partial^\nu L^\mu$, and $R^{\mu\nu} \equiv \partial^\mu R^\nu - \partial^\nu R^\mu$ are the left-handed and right-handed field strength tensors. In eLSM Lagrangian (5) the dots refer to further chirally invariant terms listed in Ref. [12]: these terms do not affect the masses and decay widths studied in the present work and we therefore omitted them. The term $ic_{\tilde{G}\Phi}\tilde{G}\left(\det\Phi - \det\Phi^\dagger\right)$ describes the interaction between the pseudoscalar glueball $\widetilde{G} \equiv |gg>$ and (pseudo-)scalar mesons, which is used to study the phenomenology of the pseudoscalar glueball in the case of $N_f = 3$ [19]. The terms $\mathrm{Tr}[H(\Phi+\Phi^\dagger)]$ with $H = 1/2\,\mathrm{diag}\{h_{0N},\, h_{0N},\, \sqrt{2}h_{0S},\, \sqrt{2}h_{0C}\}$, $-2\,\mathrm{Tr}[E\Phi^\dagger\Phi]$ with $E = \mathrm{diag}\{\varepsilon_N,\, \varepsilon_N,\, \varepsilon_S,\, \varepsilon_C\}$, $\varepsilon_i \propto m_i^2$, $\varepsilon_N = \varepsilon_S = 0$, and $\mathrm{Tr}\left[\Delta(L^{\mu 2} + R^{\mu 2})\right]$ with $\delta = \mathrm{diag}\{\delta_N,\, \delta_N,\, \delta_S,\, \delta_C\}$, $\delta_i \sim m_i^2$, $\delta_N = \delta_S = 0$, break chiral symmetry due to nonzero quark masses and are especially important for mesons containing the charm quark. When $m_0^2 < 0$ spontaneous symmetry breaking occurs and the scalar-isoscalar fields condense as well as the glueball field $G = G_0$. To implement this breaking we shift σ_N, σ_S, G, and χ_{C0} by their respective vacuum expectation values ϕ_N, ϕ_S, G_0, and ϕ_C [16, 17, 18] as

$$\sigma_N \to \sigma_N + \phi_N,\ \sigma_S \to \sigma_S + \phi_S\ , G \to G + G_0,\ \text{and}\ \chi_{\mathrm{C}0} \to \chi_{\mathrm{C}0} + \phi_{\mathrm{C}}\,. \qquad (6)$$

Most of the parameters of the model were already fixed in the three-flavor study of Ref. [12] by requiring a minimum error of 5% for experimental quantities entering the fit which is obtained a reduced χ^2 of about 1.23. There are only three new parameters appear and all of them are related to the bare mass of the charm quark. We then slightly change our fit strategy by enlarging the experimental errors to 7% Ref. [16] of the respective 12 (open and hidden) charmed mesons masses listed by the PDG [20] to obtain the χ^2 of a bout one from

$$\chi^2 \equiv \sum_i^{12}\left(\frac{M_i^{th} - M_i^{exp}}{\xi M_i^{exp}}\right)^2, \qquad (7)$$

where ξ is a constant. Note that, we do not use the experimental errors for the masses to reach the same precision with our effective model. As an outcome, the charm-anticharm condensate is sizable, $\phi_C = 178 \pm 28$ MeV.

3. Results

The weak-decay constants of the pseudoscalar open charmed mesons D and D_S [16, 17, 18] are

$$f_D = \frac{\phi_N + \sqrt{2}\phi_C}{\sqrt{2}Z_D} = (254 \pm 17)\ \text{MeV}\ , \qquad f_{D_S} = \frac{\phi_S + \phi_C}{Z_{D_S}} = (261 \pm 17)\ \text{MeV}\ .$$

The experimental values $f_D = (206.7 \pm 8.9)\,\text{MeV}$ and $f_{D_s} = (260.5 \pm 5.4)\,\text{MeV}$ show how a slightly too large theoretical result for f_D and a good agreement for f_{D_S} [20].

The results for the open charmed meson masses are reported in Table **1** [16, 17]. They have been obtained through a fit to experimental data

Table 1 : Masses of open charmed meson.

Resonance	Our Value [MeV]	Experimental Value[MeV]
D^0	1981 ± 73	1864.86 ± 0.13
$D_S^{\pm}$	2004 ± 74	1968.50 ± 0.32
$D_0^*(2400)^0$	2414 ± 77	2318 ± 29
$D_{S0}^*(2317)^{\pm}$	2467 ± 76	2317.8 ± 0.6
$D^*(2007)^0$	2168 ± 70	2006.99 ± 0.15
D_s^*	2203 ± 69	2112.3 ± 0.5
$D_1(2420)^0$	2429 ± 63	2421.4 ± 0.6
$D_{S1}(2536)^{\pm}$	2480 ± 63	2535.12 ± 0.13

The results of (OZI-dominant) strong decay widths of the open charmed mesons described by the resonances D_0^*, D^*, and D_1 are summarized in Table **2** [16, 18].

Table 2: Decay widths of charmed mesons

Decay Channel	Theoretical result [MeV]	Experimental result [MeV]
$D_0^*(2400)^0 \to D\pi$	139^{+243}_{-114}	full width $\Gamma = 267 \pm 40$
$D_0^*(2400)^+ \to D\pi$	51^{+182}_{-51}	full width: $\Gamma = 283 \pm 24 \pm 34$
$D^*(2007)^0 \to D^0\pi^0$	0.025 ± 0.003	< 1.3
$D^*(2007)^0 \to D^+\pi^-$	0	not seen
$D^*(2010)^+ \to D^+\pi^0$	$0.018^{+0.002}_{-0.003}$	0.029 ± 0.008
$D^*(2010)^+ \to D^0\pi^+$	$0.038^{+0.005}_{-0.004}$	0.065 ± 0.017
$D_1(2420)^0 \to D^*\pi$	65^{+51}_{-37}	full width: $\Gamma = 27.4 \pm 2.5$
$D_1(2420)^0 \to D^0\pi\pi$	0.59 ± 0.02	seen
$D_1(2420)^0 \to D^+\pi^-\pi^0$	$0.21^{+0.01}_{-0.015}$	seen
$D_1(2420)^0 \to D^+\pi^-$	0	not seen; $\Gamma(D^+\pi^-)/\Gamma(D^{*+}\pi^-) < 0.24$
$D_1(2420)^+ \to D^*\pi$	65^{+51}_{-36}	full width: $\Gamma = 25 \pm 6$
$D_1(2420)^+ \to D^+\pi\pi$	0.56 ± 0.02	seen
$D_1(2420)^+ \to D^0\pi^0\pi^+$	0.22 ± 0.01	seen
$D_1(2420)^+ \to D^0\pi^+$	0	not seen

4. Conclusion

In this work we have presented the outline of the extension of the eLSM from the three-flavor case to the four-flavor case including the charm quark has been presented. Most parameters are determined in the low-energy study for the nonstrange-strange sector [12]. Three new unknown parameters have been fixed in a fit to the experimental values (details are presented in Ref.[16]). The weak decay constants of nonstrange charm D and strange charm D_S have been calculated. The open charmed meson masses in the eLSM (5) have been computed, which being in reasonably good agreement with experimental data [20]. We have evaluated the (OZI-dominant) decays of open charmed mesons. The results are compatible with the results and the upper bounds listed by the PDG [20]. Moreover, the decay of the vector and axial-vector chiral partners $D^*(2010)$ and $D_1(2420)$ are well described. That leads to the fact that an qualitative description is obtained by using a chiral model and by using the parameters determined by a study of $N_f = 3$ mesons, means that a remnant of chiral symmetry is present also in the sector of charmed mesons. The parameters of the eLSM do not vary too much as a function of the energy at which they are probed. All of this shows that chiral symmetry is still valid for charmed mesons.

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