S-WAVE INTERACTIONS BETWEEN CHARMED MESONS AND GOLDSTONE BOSONS FROM CHIRAL DYNAMICS*

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We study the interaction between the charmed mesons and the Goldstone bosons using unitarized chiral perturbation theory. In this scheme the $D_{s0}^*(2317)$ is dynamically generated in the $(S,I)=(1,0)$ channel, and its isospin violating decay width is calculated including both the strong and electromagnetic contributions. Furthermore, the S-wave scattering lengths for charmed mesons scattering off Goldstone bosons, as well as their quark mass dependences, are investigated. We suggest two different ways to identify the nature of the $D_{s0}^*(2317)$.

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1. Introduction

Since the $D_{s0}^*(2317)$ was observed, six years have passed. However, its nature is still under debate. Here we report our recent studies on the interactions between charmed mesons and Goldstone bosons [1, 2]. Within this approach the $D_{s0}^*(2317)$ emerges as a hadronic molecule consistent with previous investigations [3]. Here we propose two ways towards understanding the nature of the $D_{s0}^*(2317)$. From the experimental side, we suggest to measure the decay width of the $D_{s0}^*(2317)$. From the point of view of lattice simulations, we suggest to calculate the S-wave scattering length of the kaon off the D-meson in the isospin-0 channel.

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2. Chiral Lagrangians and unitarization

We book the masses and momenta of the Goldstone mesons, as well as $p_D^2 - M_D^2$, with p_D and m_D being the four-momentum and the mass of the charmed meson, as quantities of $\mathcal{O}(p)$. Since the decay $D_{s0}^*(2317) \to D_s\pi^0$ violates isospin symmetry, the electromagnetic (e.m.) contribution should also be taken into account. The unit electric charge e is counted as $\mathcal{O}(p)$. Then we can write the chiral effective Lagrangian order by order, and the one from strong interaction up to $\mathcal{O}(p^2)$ is

$$\begin{aligned}\mathcal{L}_{\rm str} \;=\;& \mathcal{D}_\mu D \mathcal{D}^\mu D^\dagger - \mathring{M}_D^2 D D^\dagger \\ &+ D\big(-h_0\langle\chi_+\rangle - h_1\tilde{\chi}_+ + h_2\left\langle u_\mu u^\mu\right\rangle - h_3 u_\mu u^\mu\big)\bar{D} \\ &+ \mathcal{D}_\mu D\big(h_4\langle u^\mu u^\nu\rangle - h_5\{u^\mu, u^\nu\} - h_6[u^\mu, u^\nu]\big)\mathcal{D}_\nu \bar{D}\,, \end{aligned} \qquad (1)$$

with $D = (D^0, D^+, D_s^+)$ collecting the charmed mesons with the chiral limit mass $\mathring{M}_D$. The building blocks are defined as $\mathcal{D}_\mu = \partial_\mu + \left(u^\dagger\partial_\mu u + u\partial_\mu u^\dagger\right)/2$, $\chi_+ = u^\dagger\chi u^\dagger + u\chi u$, $\tilde{\chi}_+ = \chi_+ - \frac{1}{3}\left\langle\chi_+\right\rangle$, and $u_\mu = iu^\dagger\mathcal{D}_\mu U u^\dagger$. The Goldstone bosons are collected in $u = \sqrt{U} = \exp(i\phi/\sqrt{2}F)$ with F being the pion decay constant in the chiral limit and ϕ the 3×3 matrix for pseudoscalar mesons. The e.m. Lagrangian relevant here starts from $\mathcal{O}(p^2)$, because there are no explicit photons involved. We have

$$\mathcal{L}_{\rm e.m.}^{(2)} = F_\pi^2 D\left[g_0\left(Q_+^2 - Q_-^2\right) + g_1\left\langle Q_+^2 - Q_-^2\right\rangle + g_2 Q_+\left\langle Q_+\right\rangle + g_3\left\langle Q_+\right\rangle^2\right]\bar{D}\,, \qquad (2)$$

where $Q_\pm = \frac{1}{2}\left(u^\dagger Q u \pm u Q u^\dagger\right)$. The diagonal quark mass matrix and the D–meson charge matrix are $\chi = 2B\,\mathrm{diag}\,\{m_u, m_d, m_s\}$, $Q = e\,\mathrm{diag}\,\{0,1,1\}$, respectively, with B related to the quark condensate $B = |\langle 0|\bar{q}q|0\rangle|/F_\pi^2$.

The dimensionless LECs h_1 and $g_0 + 2g_2$ are determined from the mass differences $M_{D_s^+} - M_{D^+}$ and $M_{D^+} - M_{D^0}$,

$$h_1 = 0.42 \pm 0.00\,, \qquad g_0 + 2g_2 = 11 \pm 3\,, \qquad (3)$$

The h_0, h_2 and h_4 terms will be dropped since they are suppressed in the large N_C — limit of QCD. The h_6 term is suppressed by the commutator structure. The g_1 and g_3 terms are also not relevant here. So the only unknown parameters are h_3 and h_5. They will be constrained by a naturalness assumption and by demanding that the mass of the $D_{s0}^*(2317)$ is reproduced.

The leading-order (LO) and next-to-leading-order (NLO) tree level scattering amplitudes, $V_{\rm LO}(s)$ and $V_{\rm NLO}(s)$, can be easily obtained from the Lagrangians given above, see Refs. [1, 2]. Then we unitarize the S-wave projected amplitudes by the following equation [4]

$$T(s) = V(s)[1 - G(s)V(s)]^{-1}\,, \qquad (4)$$

where $G(s)$ is a divergent scalar two-meson loop function, and the divergence is regulated by a subtraction constant $a(\mu)$ with μ being the scale of dimensional regularization. After unitarizing the amplitudes, several poles are found in the channels with attractive interactions (for a list, we refer to Tables 3 and 4 in Ref. [2]). Especially, for $(S, I) = (1, 0)$ (here and in the following, (S, I) means strangeness and isospin), in the isospin symmetric case, a bound state pole on the real axis in the first Riemann sheet can be found corresponding to the $D^*_{s0}(2317)$. The subtraction constant is fixed by reproducing the mass $M_{D^*_{s0}(2317)} = 2317.8$ MeV [5] when taking $V(s) = V_{\rm LO}(s)$. Assuming the same value of the subtraction constant when taking $V(s) = V_{\rm NLO}(s)$, h_3 can be fixed for each given value of $h'_5 \equiv h_5 M^2_{D^0}$. The dimensionless h'_5 is chosen in a natural range $[-1, 1]$.

3. Decay width of the $D^*_{s0}(2317) \to D_s\pi^0$

In order to calculate the isospin violating decay width of the $D^*_{s0}(2317)^+$, four physical channels should be taken into account, namely D^0K^+, D^+K^0, $D^+_s\eta$ and $D^+_s\pi^0$. For all mesons involved we use the physical masses including the inner multiplet splittings. The threshold of $D^+_s\pi^0$ is below 2317 MeV. So the coupling to this channel moves the bound state pole corresponding to the $D^*_{s0}(2317)^+$ from the real axis in the first Riemann sheet to the second Riemann sheet with a small but non-vanishing imaginary part. The pole position is $\sqrt{s}_{\rm pole} = M_{D^*_{s0}(2317)} - i\Gamma_{D^*_{s0}(2317)\to D_s\pi^0}/2$. Taking into account the uncertainties from both the experimental inputs and neglecting higher order contributions, the hadronic decay width of the $D^*_{s0}(2317)$ is obtained as 180 ± 110 keV. Our result is consistent with the results from other groups assuming the $D^*_{s0}(2317)$ being a hadronic molecule [6], the order of the magnitude being about 100 keV, while much larger than the results from other assumptions, being about 10 keV. Thus the width $\Gamma(D^*_{s0}(2317) \to D_s\pi^0)$ qualifies as a probe of the nature of the charmed scalar state.

4. *S*-wave scattering lengths

We now turn to a discussion of lattice QCD calculations for Goldstone boson–D-meson scattering. Since the lattice simulations were performed for equal light quark masses in the absence of e.m. interactions, in this section we also only consider the isospin symmetric case, and the masses of all mesons are taken as the average masses of each isospin multiplet. The results for the $(1, 0)$ DK and $(0, 1/2)$ $D\pi$ from calculations at LO and NLO are given in Table I. The results using unitarized amplitudes are also given in the two columns denoted by UChPT and CUChPT, representing one-channel and coupled-channel unitarized chiral perturbation theory, respectively. A complete list of the results for all the channels can be found in Ref. [2]. Note that unitarization makes the attractive interactions stronger. For the

$(1,0)$ DK, the attraction becomes strong enough to form a bound state. As a result, the sign of the scattering length in this channel changes after unitarization. For comparison, we also list the results extracted from the lattice simulations of the heavy to light semi-leptonic form factors [7]. For the $(1,0)$ DK, their result of "effectively infinite" means a DK bound state at threshold, which is in qualitative agreement with our result. For the $(0,1/2)$ $D\pi$, their result is consistent with ours within uncertainty.

TABLE I

The S-wave scattering lengths for the $(1,0)$ DK and $(0,1/2)$ $D\pi$ (units in fm).

Channel	LO	NLO	UChPT	CUChPT	Ref. [7]
$(1,0)$ DK	0.72	0.67(4)	−1.47(20)	−0.93(5)	effectively infinite
$\left(0,\frac{1}{2}\right)$ $D\pi$	0.24	0.23(0)	0.36(1)	0.35(1)	0.41(6)

In Refs. [8] it was shown that for an S-wave bound state near a threshold one may write model-independently for the scattering length

$$a = -2\left(\frac{1-Z}{2-Z}\right)\frac{1}{\sqrt{2\mu\epsilon}}\,. \tag{5}$$

Applied to the $D_{s0}^*(2317)$ we have $\epsilon = M_D + M_K - M_{D_{s0}^*(2317)}$ for the binding energy, and $\mu = M_D M_K/(M_D + M_K)$ for the reduced mass. The quantity Z, which can be identified with the wave function renormalization constant, is a measure of the molecular component of the state, with $Z = 1$ ($Z = 0$) for a pure elementary (molecular) state. Taking $Z = 0$, the above equation gives $a_{DK\to DK}^{(1,0)} = -1.05$ fm, which is close to the UChPT value listed in Table I. Thus, would this value be extracted from lattice simulations in the future, it would be a direct proof for the molecular nature of the $D_{s0}^*(2317)$.

Assuming the subtraction constant being pion mass independent, we can predict the pion mass, or equivalently quark mass, dependences of the scattering lengths. Our predictions from unitarization are compared with the lattice data [9] in Fig. 1. The pion mass dependences for the $(0,1/2)$ $D\pi$ and $(1,0)$ DK are shown in Fig. 2. The interaction strength for the $(0,1/2)$ $D\pi$ is controlled by the pion mass. The left panel in Fig. 2 shows clearly the changing pattern when the attraction is increased. The scattering length grows to infinity when the attraction becomes strong enough to form a bound state. Increasing the attraction further, the scattering length changes its sign. On the contrary, the pion mass dependence in the $(1,0)$ DK channel is weak as can be expected from the moderate pion mass dependence of M_K which controls the interaction strength in this channel.

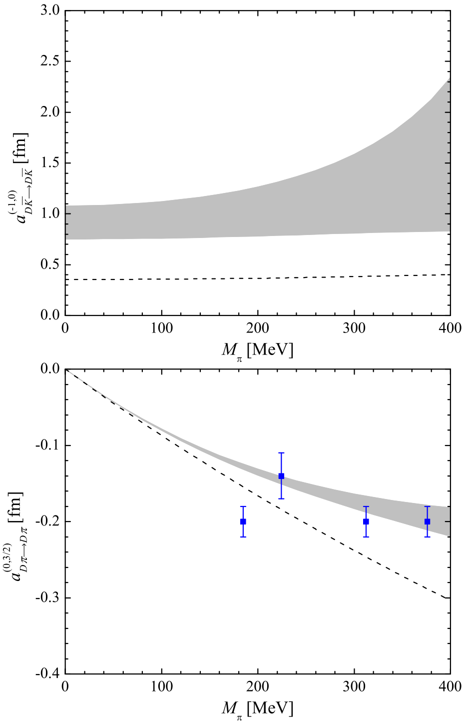

Fig. 1. Chiral extrapolation for the LO results (dashed lines) and the full UChPT calculation (bands) compared with the lattice data.

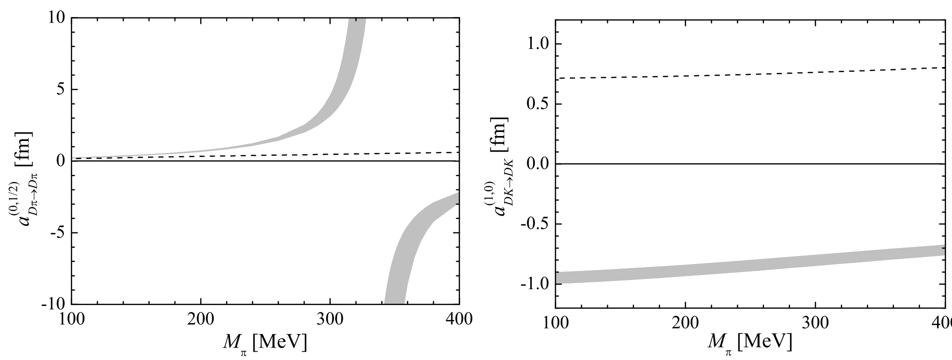

Fig. 2. Chiral extrapolation for the leading order results (dashed lines) and the full CUChPT calculation (bands) for the $(0,1/2)$ $D\pi$ and the $(1,0)$ DK channels.

5. Summary

Our recent systematic study on the S-wave interactions between the charmed pseudoscalar mesons and the Goldstone bosons is reported here. Unitarizing the S-wave amplitudes from the chiral expansion, some poles are found. Especially, there is a pole corresponding to the charmed scalar meson $D^*_{s0}(2317)$ in the $(S,I) = (1,0)$ channel. Taking into account the isospin symmetry breaking, the width of the $D^*_{s0}(2317)$ is predicted to be $\Gamma_{D^*_{s0}(2317)} = 180 \pm 110\,\text{keV}$. We also calculated the S-wave scattering lengths for the Goldstone bosons scattering off the charmed pseudoscalar mesons, and investigated their pion mass dependences. Our predictions agree well with the available lattice data. We provide two suggestions towards identifying the nature of the $D^*_{s0}(2317)$, namely measuring its width experimentally and calculating the S-wave $(1,0)$ DK scattering length using lattice simulations.

REFERENCES

[1] F.K. Guo, C. Hanhart, S. Krewald, U.-G. Meissner, *Phys. Lett.* **B666**, 251 (2008).

[2] F.K. Guo, C. Hanhart, U.-G. Meissner, *Eur. Phys. J.* **A40**, 171 (2009).

[3] E. van Beveren, G. Rupp, *Phys. Rev. Lett.* **91**, 012003 (2003); E.E. Kolomeitsev, M.F.M. Lutz, *Phys. Lett.* **B582**, 39 (2004); F.K. Guo, P.N. Shen, H.C. Chiang, R.G. Ping, *Phys. Lett.* **B641**, 278 (2006); D. Gamermann *et al.*, *Phys. Rev.* **D76**, 074016 (2007).

[4] J.A. Oller, U.-G. Meissner, *Phys. Lett.* **B500**, 263 (2001).

[5] [Particle Data Group] C. Amsler *et al.*, *Phys. Lett.* **B667**, 1 (2008).

[6] A. Faessler *et al.*, *Phys. Rev.* **D76**, 014005 (2007); M.F.M. Lutz, M. Soyeur, *Nucl. Phys.* **A813**, 14 (2008).

[7] J.M. Flynn, J. Nieves, *Phys. Rev.* **D75**, 074024 (2007).

[8] S. Weinberg, *Phys. Rev.* **137**, B672 (1965); V. Baru, J. Haidenbauer, C. Hanhart, Yu. Kalashnikova, A.E. Kudryavtsev, *Phys. Lett.* **B586**, 53 (2004).

[9] L. Liu, H.W. Lin, K. Orginos, *PoS* **LATTICE 2009**, 112 (2009).