More kaonic bound states and a comprehensive interpretation of the $D_{s,J}$ states

Feng-Kun Guo$^1$ and Ulf-G. Meiβner$^{1,2}$

$^1$Helmholtz-Institut für Strahlen- und Kernphysik and Bethe Center for Theoretical Physics, Universität Bonn, D–53115 Bonn, Germany and
$^2$Institut für Kernphysik, Jülich Center for Hadron Physics and Institute for Advanced Simulation, Forschungszentrum Jülich, D–52425 Jülich, Germany

Abstract

The leading order interaction between a Goldstone boson and a matter field is universally dominated by the Weinberg-Tomozawa term. Based on this observation, we predict a rich spectrum of bound states of a kaon and a heavy meson. We argue that if the life time of an excited heavy meson is significantly longer than the range of forces, then the finite width of that state can be neglected in a first approximation. Then, the $D_{s0}^*(2317)$, $D_{s1}(2460)$, $D_{sJ}(2860)$ and $D_{sJ}(3040)$ are generated as $DK$, $D^*K$, $D_s(2420)K$ and $D^*(2600)K$ bound states, respectively. In addition to the remarkable agreement with the measured masses, the decay patterns of the $D_{sJ}(2860)$ and $D_{sJ}(3040)$ can also be understood. Two more $D_{sJ}$ states, and kaonic bound states with the bottom mesons as well as the doubly charmed baryon are also predicted.

PACS numbers: 14.40.Lb, 12.39.Fe, 13.25.Ft

The leading order (LO) interaction between a Goldstone boson and a matter field is universally dominated by the Weinberg-Tomozawa (WT) term. With the kaon being a Goldstone boson of the spontaneous chiral symmetry breaking, the $D_{s0}^*(2317)$ and $D_{s1}(2460)$ can be generated as bound states of the $DK$ and $D^*K$ systems, respectively \cite{1,2}. Considering a heavy matter field $H$ with a mass $M_H$ much larger than the kaon mass $M_K$, the heavy field can be treated nonrelativistically. Then the LO S-wave elastic scattering amplitude from the WT term can be given in a simple form,

$$V(s) = C \frac{M_H E_l(s)}{F^2_\pi},$$  \hspace{1cm}(1)$$

where $s$ is the squared energy in the center-of-mass frame, $E_l$ is the energy of the light meson in the center-of-mass frame, and $F_\pi = 92.4$ MeV is the pion decay constant. The coefficient $C = -2$ for the $I = 0 \: HK \rightarrow HK$ channel. The heavy matter fields for which Eq. (1) can be applied include the excited heavy mesons with flavor contents $c\bar{q}, b\bar{q}$, and the doubly heavy antibaryons $c\bar{c}q$ and $b\bar{b}q$. (A subtlety related to the finite width effects will be discussed later.) Therefore, if the $D_{s0}^*(2317)$ is a $DK$ bound state as suggested in Refs. \cite{3,4,5,6,7}, one can easily expect that there must be more bound states. In fact, the $B$ and $B^*K$ bound states have been predicted \cite{3,4,5,6,7}. Here a bound state does not strictly mean a state with a zero width. It means if all the other particles are neglected, then it has a vanishing width. If some other particles with lower masses are switched on as in the real world, these “bound states” will have a finite width.

On the experimental side, besides the $D_{s0}^*(2317)$ and $D_{s1}(2460)$, more charmed strange mesons have been discovered in recent years. They include the $D_{s1}(2700)$ \cite{11,12}, $D_{sJ}(2860)$ \cite{11} and $D_{sJ}(3040)$ \cite{13}. Both the $D_{s1}^*(2700)$ and the $D_{sJ}(2860)$ decay into $DK$ and $D^*K$, while the $D_{sJ}(3040)$ was only observed in the $D^*K$ final state \cite{13}. The ratios between different decay modes of the $D_{sJ}(2860)$ were measured to be \cite{14}

$$R_{D_{sJ}(2860)} = \frac{\Gamma(D_{sJ}(2860) \rightarrow D^*K)}{\Gamma(D_{sJ}(2860) \rightarrow DK)} = 1.10 \pm 0.24,$$  \hspace{1cm}(2)$$

and a similar ratio for the $D_{s1}^*(2700)$ is $R_{D_{s1}^*(2700)} = 0.91 \pm 0.18$. Both states have a natural parity, i.e. a positive (negative) parity for an even (odd) spin, because they decay into the $DK$ channel. Using the LO heavy hadron chiral perturbation theory (HHChPT), which is model-independent, the decay pattern of the $D_{s1}^*(2700)$ for a $(2S, J^P = 1^-)$ assignment was calculated to be $R_{D_{s1}^*(2700)} = 0.91 \pm 0.14$ \cite{17}, fully consistent with the data. Furthermore, the mass of the $D_{s1}^*(2700)$ agrees well with the prediction in the Godfrey-Isgur quark model \cite{16}. So there is little doubt that the $D_{s1}^*(2700)$ is the $(2S, 1^-)$ $c\bar{s}$ meson. The situation for the $D_{sJ}(2860)$ and $D_{sJ}(3040)$ is not clear yet. Their quantum numbers are not known. The LO results from the HHChPT for $R_{D_{sJ}(2860)}$ were given in \cite{17} for different assignments. They are $1.23$, $0.63$, $0.06$, and $0.09$ for $(2S, 1^-)$, $(2P, 0^+)$, $(2P, 2^+)$, $(1D, 1^-)$, and $(1D, 3^-)$, respectively. Comparing with the measured value, one can conclude that the only possibilities are $(2S, 1^-)$ and $(2P, 2^+)$. However, the $(2S, 1^-)$ $c\bar{s}$ meson has already been identified as the $D_{s1}^*(2700)$, and the $(2P, 2^+)$ one would have a mass as large as $3.1$ GeV \cite{18}. Various explanations of the $D_{sJ}(2860)$ and $D_{sJ}(3040)$ have already been discussed in the literature \cite{19,20}.

In this paper, we will show that all of the $D_{s0}^*(2317)$, $D_{s1}(2460)$, $D_{sJ}(2860)$ and $D_{sJ}(3040)$ mesons can be interpreted as charmed-meson kaon bound states. The $D_{sJ}(2860)$ and $D_{sJ}(3040)$ are interpreted as $D_1(2420)K$ and $D^*(2600)K$ bound states, respectively. In addition, more kaonic bound states will be predicted.

One important issue requires discussion. Both the $D$ and $D^*$ have a negligible width, however, the excited heavy mesons normally have a width of tens of MeV or even larger than 100 MeV. The finite width presents...
another energy scale which might invalidate the use of
the WT term. A natural question is: how large a width
can be neglected for a given case? Let us consider a
hadron with a finite life time $\tau$. If $\tau$ is long enough so
that the interaction responsible for the binding takes
place, then one can neglect the width in calculating
the bound state masses. Mathematically, this means
$\tau \gg r$, with $r$ the range of forces, i.e. $\Gamma \ll 1/r$. For
the interaction between a kaon and a heavy meson, since
a pion cannot be exchanged, the range of forces is set by
$1/r \sim M_p$ or more safely by $2M_p$. Therefore, if the width
of the other hadron is much smaller than $M_p$, then in
a first approximation, the width can be neglected.

These heavy mesons, written in terms of $\{H, \bar{H}\}$ in the same
SU(3) triplet, include $\{D, \bar{D}\}$, $\{D^*, \bar{D}^*\}$, $\{D_1(2420), \bar{D}_1(2536)\}$, $\{D_2^*(2460), D_2^{*2}(2573)\}$, $\{D(2550), ?\}$, $\{D^*(2600), D_2^*(2700)\}$, and $\{\bar{B}, \bar{B}_s\}$, $\{B^*, \bar{B}^*_s\}$, $\{B_s(5720), B_s(5830)\}$, $\{B_s^*(5747), B_s^*(5840)\}$, and their strange partners. Among them, the $D(2550)$ and
$D^*(2600)$ were discovered very recently by the BABAR
Collaboration \[38\]. The properties of the $D^*(2600)$ are
consistent with the radially excited $(2S, 1^-)$ charmed
meson. The $D(2550)$ might be the $(2S, 0^-)$ state since
it has the correct angular distribution \[38\]. However,
its width is much larger than the prediction using the
LO HHCChPT, $\Gamma_{D(2550)} = 0.55\Gamma_{D^*(2600) \sim 50 \text{ MeV}}$ \[29\].
Nevertheless, we will tentatively assume the $D(2550)$ as
the $2S$ pseudoscalar charmed meson. On the contrary,
however, this is not the case for the $D_1(2430)D^*$ system
which was considered in Ref. \[30\]. The width of the
$D_1(2430)$ is $\sim 400 \text{ MeV} \gg M_{\pi_s}$, whose inverse sets the
range of forces for this system, and hence the finite
width effect cannot be neglected. Indeed, it was shown
that, after considering the finite width or the three-body
cut, the bound state disappears \[31\]. The impact of the
finite width effect on the line shape of a composite
c Particle was considered in Ref. \[32\] (see also \[33\]).

The masses of the bound states can be calculated by
searching for poles in the resummed S-wave $I = 0$ scattering
amplitudes $T(s) = V(s)[1 - G(s)V(s)]^{-1}$ \[34\] \[35\]. We will consider two coupled channels for each case,
which means all of $T(s), V(s)$ and $G(s)$ are $2 \times 2$
matrices. Denoting the nonstrange (strange) heavy meson
by $H(s)$, the matrix elements of the symmetric matrix
$V(s)$ is given by Eq. \[14\]. For $I = 0$, the coefficient
$C = -2.0$ and $-\sqrt{3}$ for $V_{HH \rightarrow HH}(s), V_{HH \rightarrow \bar{H}H\bar{s}}(s)$ and
$V_{HH \rightarrow H\bar{H}s}(s)$, respectively. $G(s)$ is a diagonal matrix
with the nonvanishing elements given by the loop func-
tion for a nonrelativistic heavy meson and a relativistic
light meson \[3\]

$$G_{Ht}(s) = \frac{1}{16\pi^2 M_H} \left\{ E_l \left[A(\mu) + \log \left(\frac{M_H^2}{\mu^2}\right)\right] + 2|\mathbf{p}_l| \cosh^{-1} \left(\frac{E_l}{M_l}\right) - 2\pi i |\mathbf{p}_l| \right\},$$

with $a(\mu)$ a subtraction constant, $\mu$ the scale of dimen-
sional regularization, and $\mathbf{p}_l$ the three-momentum
(mass) of the light meson. Equation \[1\] seems to imply
that the heavier the matter field is, the stronger the
interaction will be. However, the factor $M_H$ will be
 canceled by a factor of $1/M_H$ in the loop function in the
resummed amplitudes, as required by the heavy quark
symmetry. It is natural to choose the same value of the
subtraction constant $a(\mu)$ for all the heavy hadrons.
A change in the scale $\mu$ can be balanced by a corre-
sponding change in $a(\mu)$. However, for checking the stability
of the results, we will also fix the subtraction constant
while allowing $\mu$ varying from $1 \text{ GeV} \rightarrow M_H$. For
a given $\mu$, $a(\mu)$ is fixed by reproducing the mass of the
$D(2317)^0$, and we get $a(1 \text{ GeV}) = -3.84$. The results
for the charmed mesons are summarized in Table \[1\] with
the expected dominant decay modes. We use the cen-
tral values for the masses of the constituents. The error
bars reflect the variation of $\mu$. It has been assumed that
the unknown strange partner of the $D(2550)$ has a mass
$100 \text{ MeV}$ heavier than the $D(2550)$. In fact, neglect-
ing the $H_s\bar{q}$ channel and keeping only the $HK$
channel, the results are almost the same, with a difference
within $4 \text{ MeV}$. This means one can interpret the gener-
ated states as heavy-meson kaon bound states. We can see
that with input only from the $D(2410)^0$, the masses of the
$D_1(2420), D_{sJ}(2860)$ and $D_{sJ}(3040)$ can be well
reproduced. In the following, we will focus on the latter
two states, which are interpreted as S-wave $D_1(2420)K$
and $D^*(2600)K$ bound states, respectively. In this sce-
nario, the $J^P$ are $1^-$ for the $D_{sJ}(2860)$, and $1^+$ for the
$D_{sJ}(3040)$. We also checked that, using $F_K$ instead of
$F_\pi$ in Eq. \[1\], which represents some of the higher order
corrections in the chiral expansion, the results are very
stable. The predicted masses change for no more than
$3 \text{ MeV}$ with the subtraction constant refitted to the mass
of the $D(2317)$. Inclusion of other coupled channels
such as those listed as decay modes in Table \[1\] involves
unknown coupling constants. As long as the threshold
of the coupled channel $T_{CC}$ is far from the bound state
mass, which can be characterized as $|T_{CC} - M_{BS}| \gg \epsilon$, with $\epsilon$ being the binding energy, they will modify the mass
only marginally. However, their presence will give a
finite width to the bound state. Now let us discuss
their decay modes.

Some of the decay mechanisms of the $D_{sJ}(2860)$ and
$D_{sJ}(3040)$ are shown in Fig. \[1\]. Note that this is not a
complete list, for instance, the $D_s\omega$ is another im-
portant decay channel of the $D_{sJ}(3040)$. In fact, this
channel can be used in distinguishing the $D^*(2600)K$
bound state picture from a $c\bar{s}$ picture, for which the decay into
$D_s\omega$ would be very small due to the OZI suppression.
Being a $1^+$ state, the $D_{sJ}(3040)$ cannot decay into the
$DK$. This is consistent with the experimental facts. The
two-body decays of the $D_{sJ}(2860)$ and $D_{sJ}(3040)$
occur through the scattering $D_1(2420)K \rightarrow D^0K$ and
where the amplitudes can be written as

$$ c\text{ay amplitudes} \text{ can be written as} $$

$\text{mentum of the limit}$. The axial-vector meson are the polarization vectors of the antisymmetric Levi-Civita tensor, and $\text{the} \text{antisymmetric} \text{Levi-Civita tensor}$.

$\text{The total angular momentum of the light degrees of freedom in a heavy hadron body decay modes } (\text{not} \text{a complete list}) \text{of the}$

$\text{Experimental data}$

$\text{predicted masses of charmed-meson kaon bound states}. \text{The experimental values are listed in the fourth row for a comparison}. \text{The expected dominant decay modes are also given}.$

TABLE I: Predicted masses of charmed-meson kaon bound states. The experimental values are listed in the fourth row for a comparison. The expected dominant decay modes are also given.

| Main constituents | $DK$ | $D^* K$ | $D_1(2420)K$ | $D_2(2460)K$ | $D(2550)K$ | $D^*(2600)K$ |
|------------------|------|--------|-------------|-------------|-------------|-------------|
| $J^P$            | 0$^+$| 1$^+$  | 1$^-$       | 2$^-$       | 0$^+$       | 1$^+$       |
| Predicted masses | 2317.8 (input) | 2458 ± 3 | 2870 ± 9   | 2910 ± 9   | 2984 ± 10  | 3052 ± 11  |
| Experimental data| 2317.8 ± 0.6 | 2459.5 ± 0.6 | 2862 ± 2$^{+5}_{-4}$ | 3044 ± 8$^{+20}_{-19}$ |
| Dominant decays  | $D_s \pi$ | $D_s^\ast \pi$ | $D^{(s)} \eta, D_s^\ast \eta, D^\ast K, D_s \omega, DK^\ast, D_s \phi$ |

One expects that the $D_{sJ}(2860)$ and $D_{sJ}(3040)$ can also decay through the decays of the $D_1(2420)$ and $D^*(2600)$, respectively. However, the partial widths of these sequential decays are not large. This is because they are suppressed by a $D$-wave and $P$-wave factor for the $D_{sJ}(2860)$ and $D_{sJ}(3040)$, respectively, as well as by the three-body phase space. In fact, this expectation can be confirmed by a rough estimate. For an $S$-wave loosely bound state, the binding energy $\epsilon$ and effective coupling constant $g$ for the bound state to its constituents are related by $g^2 = 16\pi (m_1 + m_2)^2 \sqrt{2\epsilon/\mu_1 + O(\sqrt{2\mu_2})}$, where $m_1,2$ are the masses of the constituents, and $\mu$ is their reduced mass. We get 1 and 26 MeV for such sequential decays of the $D_{sJ}(2860)$ and $D_{sJ}(3040)$, respectively, which means they only contribute a branching fraction of about 2% and 10%, respectively. However, these results can only be regarded as an order-of-magnitude estimate, since for both cases, $\sqrt{2\mu} \simeq 220$ MeV, and so the uncertainty in the so-estimated effective coupling is very large. Nevertheless, the two-body decays would be the dominant modes for these two states. Therefore, one expects $\Gamma_{D_{sJ}(3040)} > \Gamma_{D_{sJ}(2860)}$, consistent with the data, because the two-body decays of the $D_{sJ}(3040)$ and $D_{sJ}(2860)$ are in an $S$- and $P$-wave, respectively.

In addition, heavy quark spin symmetry implies that each of the predicted bound states has its spin multiplet partner [36, 38]. For instance, the $D_{sJ}(2460)$ is the spin partner of the $D_{sJ}(2317)$. Because the kaon, which has a negative parity, interacts with the heavy meson in an $S$-wave, so for the $D^{(s)} K$ systems, $s_\ell^P = 1/2^+$, Note that they should not be confused with the $s_\ell^P = 1/2^+$ $c\bar{s}$ mesons because they have a different dynamical origin. Similarly, the $D_2(2460) K$ bound state, to be called $D_2^*(2910)$, is the spin partner of the $D_{sJ}(2860)$, and they have $s_\ell^P = 3/2^-$. The $D_{sJ}(3040)$ and the $D(2550) K$ bound state, to be called $D_{sJ}^*(2985)$, form another $s_\ell^P = 3/2^+$ doublet. They can be regarded as the excited states of the $D_{sJ}^*(2317)$ and $D_{sJ}(2460)$.

Assuming the decay modes given in Table VI exhaust the decay widths, ratios of the total widths can be predicted based on the HHChPT. At LO, we obtain

$$ \frac{\Gamma_{D_{sJ}^*(2910)}}{\Gamma_{D_{sJ}(2860)}} \simeq 0.2, \quad \frac{\Gamma_{D_{sJ}^*(2985)}}{\Gamma_{D_{sJ}(3040)}} < 1, \quad (6) $$

where the less-than sign is because the $DK^*, D_\omega, D_s \phi$
channels for the $D_{sJ}(3040)$ were not taken into account. Thus we have $\Gamma_{D_{sJ}(2910)} \sim 10$ MeV. Such a small width suggests that more experimental efforts should be devoted to the $D^*K$ data.

We can make further predictions for the bottom sector. The results are listed in Table I together with the expected dominant decay channels. In addition, there should also be kaonic bound states with the doubly heavy baryons. For instance, the $\bar{\Xi}_c(3520)$ bound state is predicted to have a mass of 3956 ± 20 MeV.

In summary, using chiral and heavy quark symmetry, we predicted a rich spectrum of kaonic bound states. We expect dominant decay channels. In addition, there are also predicted. The decay mode $D_{sJ}(3040) \to D_s\omega$ can serve as a criterion in distinguishing the present interpretation from a $c\bar{s}$ picture. The narrow $D_{sJ}(2910)$ and broader $D_{sJ}(2860)$ should be searched for in the $D^*K$ and $DK$ channels, respectively. In order to understand the low-energy strong interaction better, searching for these states should be an important experimental issue.

We are grateful to C. Hanhart for useful comments. We thank the HGF for funds provided to the virtual institute “Spin and strong QCD” (VH-VL231), the DFG (SFB/TR16) and the EU I3HP “Study of Strongly Interacting Matter” under the Seventh Framework Program of the EU. U.-G. M. also thanks the BMBF for support (Grant No. 06BN9006).

| Constituents | $\bar{B}K$ | $B^*K$ | $B^0_s(5720)K$ | $B^0_s(5747)K$ |
|--------------|------------|--------|----------------|----------------|
| $J^P$        | 0$^+$      | 1$^-$  | 1$^-$          | 2$^-$          |

**TABLE II: Predicted masses of bottom-meson kaon bound states. The expected dominant decay modes are also given.**

![Image of Table II](image)

---

* Electronic address: fkguo@hiskp.uni-bonn.de
† Electronic address: meissner@hiskp.uni-bonn.de

[1] S. Weinberg, Phys. Rev. Lett. 17, 616 (1966).
[2] Y. Tomozawa, Nuovo Cim. 46A, 707 (1966).
[3] E. E. Kolomeitsev, M. F. M. Lutz, Phys. Lett. B 582, 39 (2004).
[4] F.-K. Guo, P.-N. Shen, H.-C. Chiang et al., Phys. Lett. B 641, 278 (2006).
[5] F.-K. Guo, P.-N. Shen, H.-C. Chiang, Phys. Lett. B 647, 133 (2007).
[6] F.-K. Guo, C. Hanhart, S. Krewald, U.-G. Meißner, Phys. Lett. B 666, 251 (2008).
[7] F.-K. Guo, C. Hanhart, U.-G. Meißner, Eur. Phys. J. A 40, 171 (2009).
[8] M. Cleven, F.-K. Guo, C. Hanhart, U.-G. Meißner, Eur. Phys. J. A 47, 19 (2011).
[9] D. Garmemann, E. Oset, D. Struttman et al., Phys. Rev. D 76, 074016 (2007).
[10] T. Barnes, F. E. Close, H. J. Lipkin, Phys. Rev. D 68, 054006 (2003).
[11] B. Aubert et al. [BABAR Collaboration], Phys. Rev. Lett. 97, 222001 (2006).
[12] J. Brodzicka et al. [Belle Collaboration], Phys. Rev. Lett. 100, 092001 (2008).
[13] B. Aubert et al. [BABAR Collaboration], Phys. Rev. D 80, 092003 (2009).
[14] K. Nakamura et al. [Particle Data Group], J. Phys. G 37, 075021 (2010).
[15] F. Colangelo, F. De Fazio, S. Nicotri et al., Phys. Rev. D 77, 014012 (2008).
[16] S. Godfrey and N. Isgur, Phys. Rev. D 32, 189 (1985).
[17] F. Colangelo, F. De Fazio, S. Nicotri, Phys. Lett. B 642, 46 (2006).
[18] M. D. Di Pierro, E. Eichten, Phys. Rev. D 64, 114004 (2001).
[19] E. van Beveren, G. Rupp, Phys. Rev. Lett. 97, 202001 (2006); Phys. Rev. D 81, 118101 (2010).
[20] F. E. Close, C. E. Thomas, O. Lakhina, E. S. Swanson, Phys. Lett. B 647, 159 (2007).
[21] B. Zhang, X. Liu, W.-Z. Deng et al., Eur. Phys. J. C 50, 617 (2007).
[22] J. Vijande, A. Valcarce, F. Fernandez, Phys. Rev. D 79, 037501 (2009).
[23] X.-H. Zhong, Q. Zhao, Phys. Rev. D 81, 014031 (2010).
[24] D. Ebert, R. N. Faustov and V. O. Galkin, Eur. Phys. J. C 66, 197 (2010).
[25] F. Colangelo, F. De Fazio, Phys. Rev. D 81, 094001 (2010).
[26] B. Chen, D.-X. Wang, A. Zhang, Phys. Rev. D 80, 071502 (2009).
[27] Z.-F. Sun, X. Liu, Phys. Rev. D 80, 074037 (2009).
[28] P. del Amo Sanchez et al. [BABAR Collaboration], Phys. Rev. D 82, 111101 (2010).
[29] F.-K. Guo, U.-G. Meißner, in preparation.
[30] F. Close, C. Downum, Phys. Rev. Lett. 102, 242003 (2009).
[31] A. A. Filip, A. Romanov, V. Baru et al., Phys. Rev. Lett. 105, 019101 (2010).
[32] C. Hanhart, Y. .S. Kalashnikova, A. V. Nefediev, Phys. Rev. D81, 094028 (2010).
[33] P. Artoisenet, E. Braaten and D. Kang, Phys. Rev. D 82, 014013 (2010).
[34] J. A. Oller, E. Oset, Nucl. Phys. A 620, 438 (1997).
[35] J. A. Oller, U.-G. Meißner, Phys. Lett. B 500, 263 (2001).
[36] S. Weinberg, Phys. Rev. 130, 776 (1963); Phys. Rev. 131, 440 (1963); Phys. Rev. 137, B672 (1965).
[37] V. Baru, J. Haidenbauer, C. Hanhart, Yu. Kalashnikova and A. E. Kudryavtsev, Phys. Lett. B 586, 53 (2004).
[38] F.-K. Guo, C. Hanhart, U.-G. Meißner, Phys. Rev. Lett. 102, 242004 (2009).