On compositeness of $D_{s0}^*(2317)$ and its decay to $D_s\pi^0$

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Summary

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The $D_{s0}^*(2317)$ Puzzle

- Experiments
  - BaBar: $D_{s0}^*(2317)^+ \to D_s^+\pi^0$
  - Belle: $D_{s0}^*(2317)^+ \to D_s^{*+}\gamma$
- Its nature remains unclear.
  - ? **Low mass**: below GI predictions $\mathrm{m}(c\bar{s}\,^3P_0) = 2.480$ GeV
  - ? **Subthreshold**: below the DK threshold
  - ? **Isospin violation**: observed in $D_s\pi^0$
  - ? **Narrow width**: too small to be precisely measured
- Theoretical interpretations
  - Conventional $c\bar{s}$
  - Compact tetraquark
  - DK hadronic molecule

$$\text{Belle: } \mathcal{R} = \frac{\mathcal{B}(D_{s0}^*(2317)^+ \to D_s^{*+}\gamma)}{\mathcal{B}(D_{s0}^*(2317)^+ \to D_s^+\pi^0)} = [7.14 \pm 0.70(\text{stat.}) \pm 0.23(\text{syst.})]\%$$

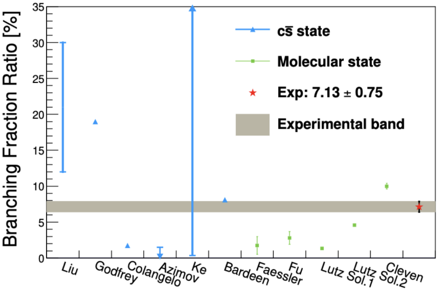

Fig. 1: $\mathcal{R}$ values for different scenarios. Adapted from Jiasen's presentation.

Can we describe the $D_{s0}^*(2317)$ and its decay within a unified framework incorporating both the $c\bar{s}$ state and the DK continuum?

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Lee-Friedrichs model

- The total Hamiltonian:

$$
\begin{aligned}
H = & m_0|0\rangle\langle 0| + \sum_{n,S,L}\int_{M_n}^{\infty} \mathrm{d}E\, E|E,[n]_{SL}\rangle\langle E,[n]_{SL}| \\
& + \sum_{n,S,L}\int_{M_n}^{\infty} \mathrm{d}E f_n^{SL}(E)|0\rangle\langle E,[n]_{SL}| + h.c.,
\end{aligned}
\tag{1}
$$

- $H\Psi(x) = x\Psi(x)$ can be exactly solved. The $D_{s0}^*(2317)$ could be represented as a **bound-state** pole in this picture.
- **The wave function of** $D_{s0}^*(2317)$

$$
\begin{aligned}
|D_{s0}^*(2317)^+\rangle = & N_B\bigg(\left|c\bar{s}(1^3P_0)\right\rangle + \int_{M_{0+}}^{\infty} \frac{\boxed{f_{0+}(E)}}{z_X - E}\left|E,[D^0K^+]\right\rangle \mathrm{d}E \\
& + \int_{M_{+0}}^{\infty} \frac{f_{+0}(E)}{z_X - E}\left|E,[D^+K^0]\right\rangle \mathrm{d}E\bigg),
\end{aligned}
\tag{2}
$$

The physical $D_{s0}^*(2317)$ emerges from the coupling between a bare $c\bar{s}$ state and the DK continuum wthin L-F scheme.

The isospin violated decay amplitude

- **With the wave function of $D_{s0}^*(2317)$, the strong decay amplitude can be obtained**

$$
\begin{aligned}
&M_{S'L'}\left(D_{s0}^*(2317) \to D_s\pi^0\right) = \left\langle [D_s^+\pi^0]_{S'L'} | H_I | D_{s0}^*(2317)^+ \right\rangle \\
=&N_B \Bigg(\boxed{\left\langle [D_s^+\pi^0]_{S'L'} | H_I | c\bar{s}(1^3P_0) \right\rangle} \Longrightarrow \text{bare } c\bar{s} \text{ state} \quad (c\bar{s} \to D_s\eta \to \pi^0-\eta \text{ mixing}) \\
&+ \boxed{\int_{M_{0+}}^{\infty} \sum_{SL} \frac{f_{0+}^{SL}(E)}{z_X - E} \left\langle [D_s^+\pi^0]_{S'L'} \right| H_I \left| [D^0K^+]_{SL} \right\rangle \mathrm{d}E} \\
&+ \boxed{\int_{M_{+0}}^{\infty} \sum_{SL} \frac{f_{+0}^{SL}(E)}{z_X - E} \left\langle [D_s^+\pi^0]_{S'L'} \right| H_I \left| [D^+K^0]_{SL} \right\rangle \mathrm{d}E} \Bigg). \Longrightarrow DK \text{ continuum state}
\end{aligned}
\tag{3}
$$

mass difference between D^0K^+ and D^+K^0 thresholds

- Construct the coupling vertex $f_{c\bar{s}\to DK}^{SL}(E)$
- Construct the $c\bar{s} \to D_s\pi^0$, $DK \to D_s\pi^0$ transition amplitude

The coupling vertex $f^{SL}(E)$

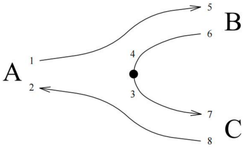

Fig. 2: QPC model

- **The transition operator T**

$$T = -3\gamma \sum_m \langle 1m, 1-m|00\rangle \int d^3p_3\, d^3p_4\, \delta^3(\vec{p}_3+\vec{p}_4)$$
$$\times \mathcal{Y}_1^m\left(\frac{\vec{p}_3-\vec{p}_4}{2}\right)\chi^{34}_{1-m}\phi^{34}_0\omega^{34}_0 b^\dagger_3(\vec{p}_3)d^\dagger_4(\vec{p}_4).$$

- **The helicity amplitude** $\langle BC|T|A\rangle = \delta^3(\vec{P}_f-\vec{P}_i)\mathcal{M}^{\sigma_A\sigma_B\sigma_C}$,
- **The partial-wave amplitude**

$$\mathcal{M}^{SL}(P) = \sum_{\substack{\sigma_B,\sigma_C\\ M_S,M_L}} \langle LM_L SM_S|j_A\sigma_A\rangle\langle j_B\sigma_B j_C\sigma_C|SM_S\rangle \int d\Omega\, Y^*_{LM_L}(\Omega) M^{\sigma_A\sigma_B\sigma_C}(\vec{P}).$$

- **The coupling vertex** $\boxed{f^{SL}(E) = \rho^{1/2}\mathcal{M}^{SL}(P)}$

The $c\bar{s} \to D_s^+\pi^0$

$$c\bar{s}(1^3P_0) \xrightarrow[\text{QPC model}]{\textbf{Strong decay}} D_s^+\eta \xrightarrow{\pi^0\text{–}\eta\ \textbf{mixing}} D_s^+\pi^0$$

isospin-conserving isospin breaking

$$\boxed{\left\langle [D_s^+\pi^0]_{S'L'} \left| H_I \right| c\bar{s}(1^3P_0) \right\rangle = \epsilon_{\pi^0\eta}\, \rho^{1/2}_{D_s\pi}\, \mathcal{M}^{SL}_{D_s\eta}(P')} \tag{5}$$

$\epsilon_{\pi^0\eta}$ denotes the π^0–η mixing parameter.

The $\epsilon_{\pi^0\eta}$ was estimated in **the leading order** of chiral perturbation theory as to be

$$\boxed{\epsilon_{\pi^0\eta} = \frac{\sqrt{3}}{4}\frac{m_u - m_d}{m_s - (m_u + m_d)/2}.} \tag{6}$$

The $DK \to D_s\pi^0$ scattering amplitude

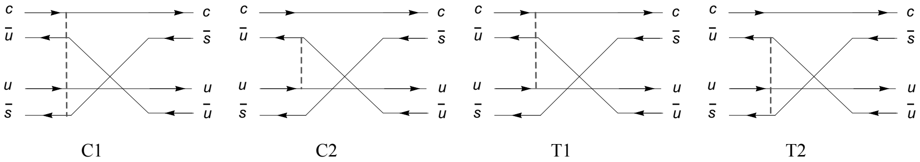

Fig. 3: Barnes-Swanson(BS) model

- **The $AB \to CD$ scattering matrix element**

$$S_{fi} = 2\pi i\,\delta^{(3)}(\vec{P}_f - \vec{P}_i)\,\delta(E_f - E_i)\,\mathcal{M}^{\sigma_C\sigma_D,\sigma_A\sigma_B}(\vec{k}', \vec{k}), \tag{7}$$

$\vec{k}/\vec{k}'$: the relative momenta of the initial/final meson pairs

- **The helicity amplitude**

$$\mathcal{M}^{\sigma_C\sigma_D,\sigma_A\sigma_B} = h_{fi}^{C_1} + h_{fi}^{C_2} + h_{fi}^{T_1} + h_{fi}^{T_2}, \tag{8}$$

- **Factorization of each quark-interchange diagram**

$$h_{fi}^X = (-1)\, I_{\text{flavor}}^X\, I_{\text{color}}^X\, I_{\text{spin}}^X\, I_{\text{space}}^X, \qquad X = C_1, C_2, T_1, T_2. \tag{9}$$

Same potential and wave functions used → No additional parameters introduced

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The $DK \to D_s\pi^0$ transition amplitude

- **Partial-wave projection**

$$\mathcal{M}_j^{S'L',SL} = \rho_{AB}^{1/2}\rho_{CD}^{1/2} \sum_{\substack{M_S,M_{S'},M_L,M_{L'} \\ \sigma_A,\sigma_B,\sigma_C,\sigma_D}} \langle j_A\sigma_A\, j_B\sigma_B|SM_S\rangle\langle j_C\sigma_C\, j_D\sigma_D|S'M_{S'}\rangle \times \langle SM_S\, LM_L|jM\rangle\langle S'M_{S'}\, L'M_{L'}|jM\rangle \times \int d\Omega_{\vec{k}}\, d\Omega_{\vec{k}'}\, \mathcal{M}^{\sigma_C\sigma_D,\sigma_A\sigma_B}(\vec{k}',\vec{k})\, Y_{LM_L}(\hat{k})\, Y^*_{L'M_{L'}}(\hat{k}') \qquad (10)$$

- **Decay width**
  - $d\Gamma(A \to BC) = 2\pi\, |M_{BC,A}|^2\, \delta^{(4)}(p_A - p_B - p_C)\, d^3\vec{p}_B\, d^3\vec{p}_C.$
  - $\langle E|E'\rangle = \delta(E - E') \Longrightarrow$ **Phase-space factor absorbed into** $f^{SL}(E)$ **and** $\langle[D_s^+\pi^0]_{S'L'}|H_I|[D^+K^0]_{SL}\rangle$
  - **No extra phase-space factor** in the final decay-width formula

$$\boxed{\Gamma = 2\pi \sum_{S',L'} \left| M_{S'L'}\left(D^*_{s0}(2317) \to D_s\pi^0\right)\right|^2} \qquad (11)$$

Isospin-violating contribution from the DK continuum

- **Decay amplitude**

$$M_{S'L'}\left(D_{s0}^*(2317)\to D_s\pi^0\right)=\langle[D_s^+\pi^0]_{S'L'}|H_I|D_{s0}^*(2317)^+\rangle$$

$$=N_B\Bigg(\boxed{\langle[D_s^+\pi^0]_{S'L'}|H_I|c\bar{s}(1^3P_0)\rangle}\Longrightarrow \text{bare } c\bar{s} \text{ state} \quad (c\bar{s}\to D_s\eta\to\pi^0-\eta \text{ mixing})$$

$$+\boxed{\int_{M_{0+}}^{\infty}\sum_{SL}\frac{f_{0+}^{SL}(E)}{z_X-E}\left\langle[D_s^+\pi^0]_{S'L'}\left|H_I\right|[D^0K^+]_{SL}\right\rangle \mathrm{d}E}$$

$$+\boxed{\int_{M_{+0}}^{\infty}\sum_{SL}\frac{f_{+0}^{SL}(E)}{z_X-E}\left\langle[D_s^+\pi^0]_{S'L'}\left|H_I\right|[D^+K^0]_{SL}\right\rangle \mathrm{d}E}\Bigg). \Longrightarrow DK \text{ continuum state} \tag{12}$$

- **Origin of isospin violation**

$$\boxed{I_{\text{flavor}}^{D^0K^+}=+\frac{1}{\sqrt{2}}, \qquad I_{\text{flavor}}^{D^+K^0}=-\frac{1}{\sqrt{2}}.} \tag{13}$$

If $M_{0+}=M_{+0}$,

$$\langle D_s\pi^0|H_I|D^0K^+\rangle=-\langle D_s\pi^0|H_I|D^+K^0\rangle. \tag{14}$$

Outline

Stable bound-state below threshold

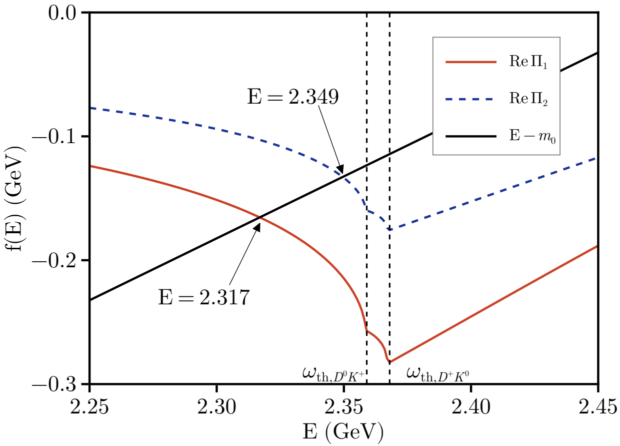

Fig. 4: The intersection of the real part of $\Pi(E)$ and $E - m_0$ curves.

- $\gamma = 8.75$ $\quad z_0 = 2.317$ GeV
- $\gamma = 6.90$ $\quad z_0 = 2.349$ GeV

Adopt $\gamma = 8.75$ for subsequent calculations.

Compositeness and Decay Width

Weinberg compositeness relation

$$Z = N_B^2, \qquad X_n = N_B^2 \int \frac{|f_n^{SL}(E)|^2}{(z_X - E)^2}\, dE. \tag{15}$$

$$Z: \ \text{bare } c\bar{s}(1^3P_0), \qquad X: \ DK \text{ continuum.}$$

Our results

$$Z = \mathbf{51.1}\%, \qquad X_{DK} = \mathbf{48.9}\%$$

Consistent with Z.-L. Zhang *et al.*, Phys. Rev. D **110**, 094037 (2024): $Z = 42\%$, $X_{DK} = 58\%$.

Strong decay width

$$\Gamma\left(D_{s0}^*(2317) \to D_s\pi^0\right) = \mathbf{40.3}\ \text{keV}$$

Strong decay widths in different works

Reference	Structure	$\Gamma(D_{s0}^{*} \to D_s\pi^0)$ (keV)
Lu et al. (2006)	$c\bar{s}$	32
Bardeen et al. (2003)	$c\bar{s}$	21.5
Godfrey et al. (2003)	$c\bar{s}$	~ 10
Wei et al. (2005)	$c\bar{s}$	$34 \sim 44$
Fajfer et al. (2015)	$c\bar{s}$	$2.4 \sim 4.7$
Colangelo et al. (2003)	$c\bar{s}$	7 ± 1
Ishida et al. (2003)	$c\bar{s}$	150 ± 70
Faessler et al. (2007)	DK	79.3 ± 32.6
Yue et al. (2025)	DK	$63.0 \sim 209$
Fu et al. (2021)	DK	132 ± 7
Zhou et al. (2025)	DK	$10.3^{+3.0}_{-2.9}$
Su et al. (2025)	DK	140 ± 10
Nielsen et al. (2005)	tetraquark	6 ± 2
This work	$c\bar{s} + DK$	$\mathbf{40.3^{+9.3}_{-4.9}}$

Table 1: Strong decay widths of $D_{s0}^{*}(2317) \to D_s\pi^0$ predicted in different theoretical approaches.

Outline

Summary

- $D_{s0}^*(2317)$ is generated as a **bound-state** pole in the extended Lee–Friedrichs model.
- The wave function of this state as $c\bar{s} + DK$ state can be **explicitly constructed**.
- Within this framework, **the elementariness and compositeness** of the bound state are obtained simultaneously with the physical wave function.
- The isospin-violated **strong decay** width is calculated self-consistently with **no additional free parameters**.

✓ **Self-consistent**

✓ **No additional free parameter**

✓ **Predictive power**

Thanks for your attention!