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Spectroscopic and two-body strong decay properties of possible $Y_c K^{(*)}$ molecules

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Outline

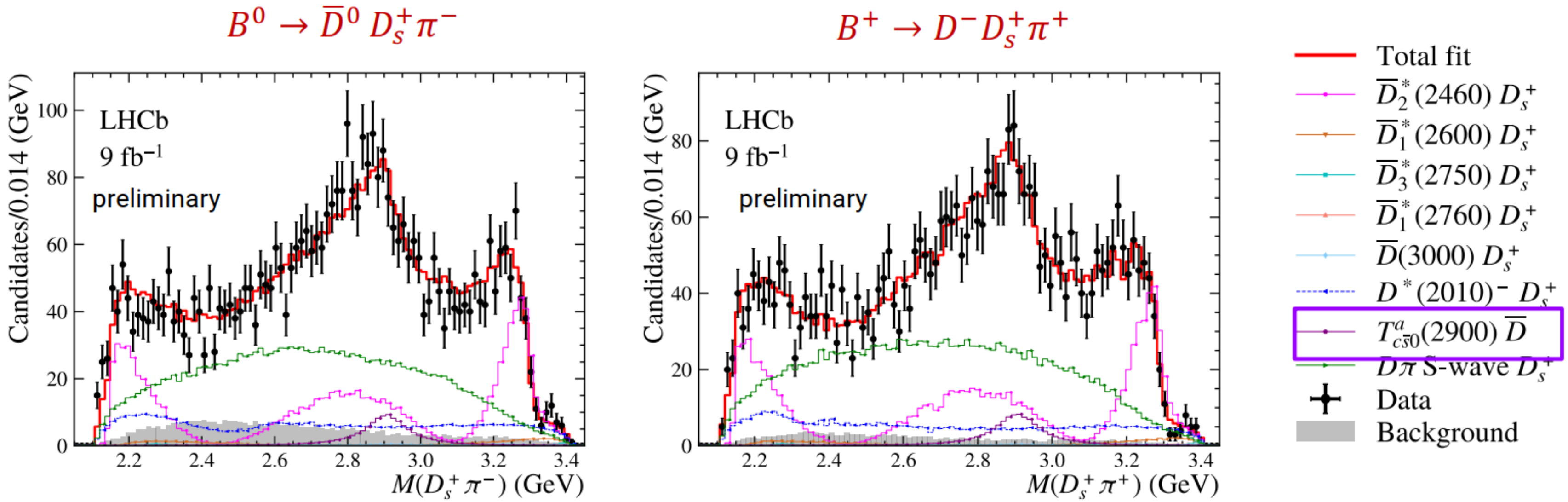
- Background: From the molecular explanations to Tcs(2900) and X(2900) to possible $Y_c K^{(*)}$ molecules

- Mass spectrum of the $Y_c K^{(*)} (Y_c = \Lambda_c, \Sigma_c)$ molecules (Phys. Rev. D 108, 054011 (2023))

- Two-body strong decay behaviors (Preliminary result)

- Summary

Tcs(2900)



$M(D_s\pi)$ well described by adding a $J^P = 0^+$ $T^a_{c\bar{s}0}(2900)$ in each channel

$T^a_{c\bar{s}0}(2900)^{++}: M = 2921 \pm 17 \pm 19$ MeV, $\Gamma = 137 \pm 32 \pm 14$ MeV;

$T^a_{c\bar{s}0}(2900)^{0}: M = 2892 \pm 14 \pm 15$ MeV, $\Gamma = 119 \pm 26 \pm 12$ MeV.

First tetraquarks composed of $[c\bar{s}u\bar{d}]$ and $[c\bar{s}\bar{u}d]$

- Isospin triplet

$B^+ \to D^- D_s^+ \pi^+ + B^0 \to \bar{D}^0 D_s^+ \pi^-$

Significance: $> 9\sigma$

Spin-parity: $J^P = 0^+$

Mass & width: $M \sim 2.9$ GeV; $\Gamma \sim 136$MeV

Theoretical explanations

Compact open-charm pentaquark

1. $\bar{c}q - s\bar{q}$: Diquark(vector)-diquark(vector) picture, QCD sum, M=2.91 GeV

Chen W, Chen H-X, Liu X, Steele T G and Zhu S-L, *Phys. Rev.* D **95** 114005

2. The chromo-magnetic interaction model, the mass of the predicted state with JP=0+ close to 2900 MeV

- Guo T, Li J, Zhao J and He L, *Phys. Rev.* D**105** 054018
- Cheng J-B, Li S-Y, Liu Y-R, Liu Y-N, Si Z-G and Yao T, *Phys. Rev.* D **101** 114017

Hadronic molecular explanations

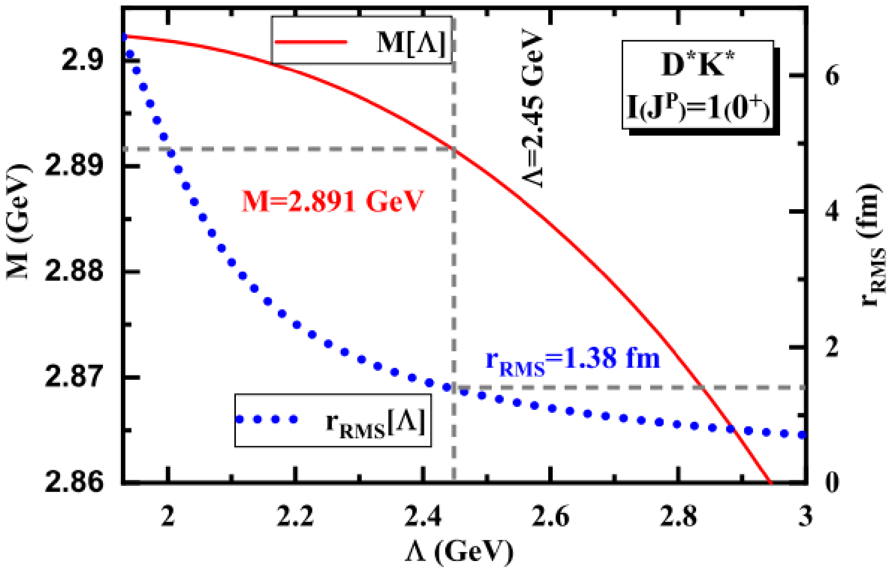
3. QCD sum rule: $D_s^*\rho$ molecular state

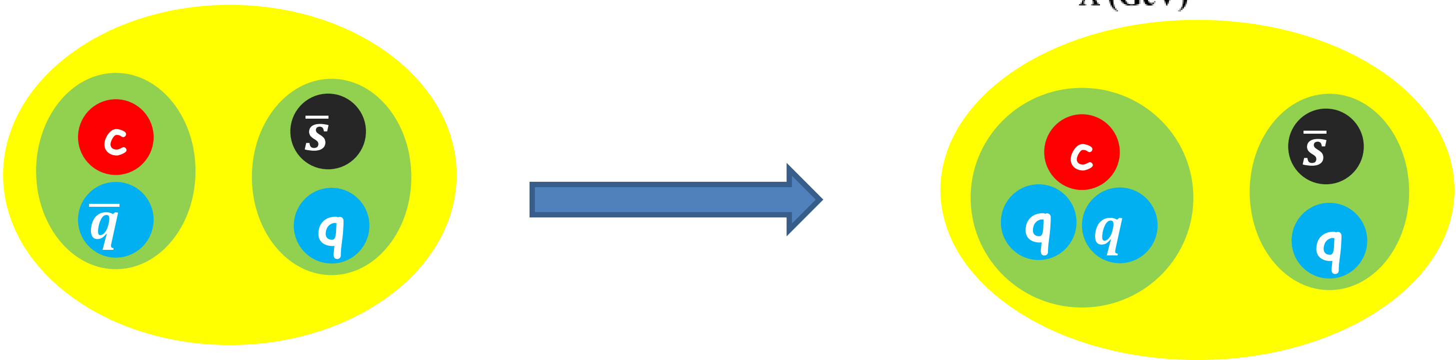
Agaev S S, Azizi K and Sundu H, *J. Phys. G: Nucl. Part. Phys.* **50** 055002

Can there exist possible open-charm molecular pentaquarks?

Ds0(2317)~DK, Ds1(2460)~D*K, Tcs(2900)~D*K*

With the same parameters, reproduce the masses of the Ds0(2317), Ds1(2460), and Tcs(2900) in the meson-meson molecular states, simultaneously.





- Diquark has the same color structure with the antiquark
- Indirect test of molecular state picture for Tcs(2900)
- Understanding interactions between charmed baryon and strange meson

One-boson-exchange (OBE) model

Yukawa, Proc. Phys. Math. Soc. Japan 17, 48 (1935)

- 1935, Yukawa: pion-exchange and nucleon-nucleon interaction
- Nijimegen potential and Bonn potential: scalar meson **σ exchange~two π** exchange; vector meson-ρ/ω exchange~**multi-π** exchange

1
- OBE model
- Scattering amplitude

$$\langle f|S|i\rangle = \delta_{fi} + i\langle f|T|i\rangle = \delta_{fi} + i(2\pi)^4\delta^4(p_f - p_i)\mathcal{M}_{fi}$$

$$\langle f|S|i\rangle = \delta_{fi} - i(2\pi)\delta(E_f - E_i)V_{fi}(p)$$

2
- Breit approximation
- Effective potential in momentum space

$$V_{fi}(p) = -\frac{\mathcal{M}_{fi}}{\sqrt{\prod_f 2p_f^0 \prod_i 2p_i^0}} \approx -\frac{\mathcal{M}_{fi}}{\sqrt{\prod_f 2m_f^0 \prod_i 2m_i^0}}$$

3
- Fourier transformation
- Effective potential in coordinate space

$$V(r) = \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} e^{i\boldsymbol{q}\cdot\boldsymbol{r}} \mathcal{V}_{fi}(\boldsymbol{q}) \mathcal{F}^2(q^2, m_E^2)$$

One free parameter

Form factor $\mathcal{F}(q^2, m^2) = \frac{\Lambda^2 - m^2}{\Lambda^2 - q^2}$ Λ, m and q are the cutoff, mass and four-momentum of the exchanged meson, respectively.

$\Lambda \sim 1.0$ GeV

N. A. Tornqvist, Z. Phys. C 61, 525 (1994)
N. A. Tornqvist, Nuovo Cim. A 107, 2471 (1994)

Interactions

The relevant Lagrangians --- the heavy quark limit and chiral symmetry

$$
\begin{aligned}
\mathcal{L}_{\mathcal{B}_{\bar{3}}} &= l_B\langle\bar{\mathcal{B}}_{\bar{3}}\sigma\mathcal{B}_{\bar{3}}\rangle + i\beta_B\langle\bar{\mathcal{B}}_{\bar{3}}v^{\mu}(\mathcal{V}_{\mu}-\rho_{\mu})\mathcal{B}_{\bar{3}}\rangle,\\
\mathcal{L}_{\mathcal{B}_6} &= l_S\langle\bar{\mathcal{S}}_{\mu}\sigma\mathcal{S}^{\mu}\rangle - \frac{3}{2}g_1\varepsilon^{\mu\nu\lambda\kappa}v_{\kappa}\langle\bar{\mathcal{S}}_{\mu}A_{\nu}\mathcal{S}_{\lambda}\rangle\\
&\quad + i\beta_S\langle\bar{\mathcal{S}}_{\mu}v_{\alpha}\left(\mathcal{V}^{\alpha}_{ab}-\rho^{\alpha}_{ab}\right)\mathcal{S}^{\mu}\rangle + \lambda_S\langle\bar{\mathcal{S}}_{\mu}F^{\mu\nu}(\rho)\mathcal{S}_{\nu}\rangle\\
\mathcal{L}_{\mathcal{B}_{\bar{3}}\mathcal{B}_6} &= ig_4\langle\bar{\mathcal{S}}^{\mu}A_{\mu}\mathcal{B}_{\bar{3}}\rangle + i\lambda_I\varepsilon^{\mu\nu\lambda\kappa}v_{\mu}\langle\bar{\mathcal{S}}_{\nu}F_{\lambda\kappa}\mathcal{B}_{\bar{3}}\rangle + h.c..
\end{aligned}
$$

Y.-R. Liu and M. Oka, Phys. Rev. D **85**, 014015 (2012)

SU(3) symmetry

$$
\begin{aligned}
\mathcal{L}_{PPV} &= \frac{ig}{2\sqrt{2}}\langle\partial^{\mu}P\left(PV_{\mu}-V_{\mu}P\right)\rangle,\\
\mathcal{L}_{VVP} &= \frac{g_{VVP}}{\sqrt{2}}\epsilon^{\mu\nu\alpha\beta}\left\langle\partial_{\mu}V_{\nu}\partial_{\alpha}V_{\beta}P\right\rangle,\\
\mathcal{L}_{VVV} &= \frac{ig}{2\sqrt{2}}\langle\partial^{\mu}V^{\nu}\left(V_{\mu}V_{\nu}-V_{\nu}V_{\mu}\right)\rangle
\end{aligned}
$$

Z.-w. Lin and C. M. Ko, Phys. Rev. C **62**, 034903 (2000).
H. Nagahiro, L. Roca, and E. Oset, Eur. Phys. J. A **36**, 73(2008)

Quark model: estimate all the coupling constants and phase factors

R. Chen, A. Hosaka, and X. Liu, Phys. Rev. D **97**, 036016 (2018).
O. Kaymakcalan, S. Rajeev, and J. Schechter, Phys. Rev. D **30**, 594 (1984)

Numerical results: single channel

Reasonable loosely bound state solution

- ✓ E: several to several tens MeV
- ✓ A loosely bound state: $R_{MS} > R_A + R_B$

TABLE III: The Λ dependence of the obtained bound-state solutions (the binding energy E and the root-mean-square radius r_{RMS}) for the single $\Sigma_c K^*$ systems. Here, E, r_{RMS}, and Λ are in units of MeV, fm, and GeV, respectively.

$I(J^P)$	Λ	E	r_{RMS}	$I(J^P)$	Λ	E	r_{RMS}
$1/2(1/2^-)$	1.70	−0.50	5.32	$1/2(3/2^-)$	0.88	−0.25	6.06
	2.00	−3.32	2.64		0.98	−3.32	2.58
	2.30	−8.31	1.81		1.08	−10.72	1.59
	2.60	−15.30	1.42		1.18	−23.27	1.15
$3/2(1/2^-)$	1.28	−0.11	6.24	$3/2(3/2^-)$	…	…	…
	1.31	−2.42	2.50		…	…	…
	1.34	−7.78	1.43		…	…	…
	1.37	−16.71	1.00		…	…	…

$\Lambda_c K^*$ and $\Sigma_c K$ systems

- ☐ No bound state in 0.8 ≲Λ ≲ 5.0 GeV
- ☐ The OBE effective potentials for the $\Lambda_c K$ system is not strong enough to bind a bound state

$\Sigma_c K^*$ systems

- ☐ OBE effective potentials: $\sigma, \pi, \eta, \rho, \omega$ −exchanges allowed;
- ☐ 3/2(3/2-): no bound state;
- ☐ Remaining three systems: good molecular candidates; **Λ ~1.00 GeV, R~fm, E>-20MeV**

Coupled channel effects case

TABLE I: The bound state solutions (the binding energy E, the root-mean-square radius r_{RMS}, and the probabilities $P_i(\%)$ for all the discussed channels) for the coupled $\Lambda_c K^*/\Sigma_c K^*$ systems with $I(J^P) = 1/2(1/2^-)$ and $1/2(3/2^-)$. Here, E, r_{RMS}, and Λ are in units of MeV, fm, and GeV, respectively. The dominant channels are labeled in a bold manner.

$I(J^P)$	Λ	E	r_{RMS}	$\Lambda_c K^*(^2S_{1/2})$	$\Lambda_c K^*(^4D_{1/2})$	$\Sigma_c K^*(^2S_{1/2})$	$\Sigma_c K^*(^4D_{1/2})$
$1/2(1/2^-)$	1.56	−0.14	6.11	**98.82**	∼ 0	1.14	0.04
	1.58	−2.14	2.62	**97.11**	0.01	2.82	0.06
	1.60	−6.02	1.56	**95.12**	0.02	4.79	0.07
	1.62	−11.57	1.12	**93.18**	0.03	6.72	0.07

Four channels

Six channels

$I(J^P)$	Λ	E	r_{RMS}	$\Lambda_c K^*(^4S_{3/2})$	$\Lambda_c K^*(^2D_{3/2})$	$\Lambda_c K^*(^4D_{3/2})$	$\Sigma_c K^*(^4S_{3/2})$	$\Sigma_c K^*(^2D_{3/2})$	$\Sigma_c K^*(^4D_{3/2})$
$1/2(3/2^-)$	1.34	−0.07	6.35	**94.23**	0.03	0.11	4.89	0.22	0.52
	1.36	−3.06	2.07	**84.54**	0.08	0.28	13.36	0.53	1.20
	1.38	−8.93	1.18	**75.92**	0.12	0.42	21.07	0.76	1.71
	1.40	−16.80	0.87	**69.12**	0.14	0.52	27.27	0.91	2.05

1/2(1/2-)

ΛcK: no bound state

ΛcK*: Λ ~ 1.60 GeV, reasonable loosely bound state solutions(r~fm, E~MeV), S-wave ΛcK* channel is the dominant channel; a good hadronic molecular candidate

1/2(3/2-)

ΛcK*: Λ ~ 1.35 GeV, reasonable loosely bound state solutions(r~fm, E~MeV), S-wave ΛcK* channel is the dominant channel; a good hadronic molecular candidate

TABLE II: The bound state solutions (the binding energy E, the root-mean-square radius r_{RMS}, and the probabilities $P_i(\%)$ for all the discussed channels) for the single $\Sigma_c K$ and the coupled $\Sigma_c K/\Lambda_c K^*/\Sigma_c K^*$ systems with $I(J^P) = 1/2(1/2^-)$ and $3/2(1/2^-)$. Here, E, r_{RMS}, and Λ are in units of MeV, fm, and GeV, respectively. The dominant channels are labeled in a bold manner.

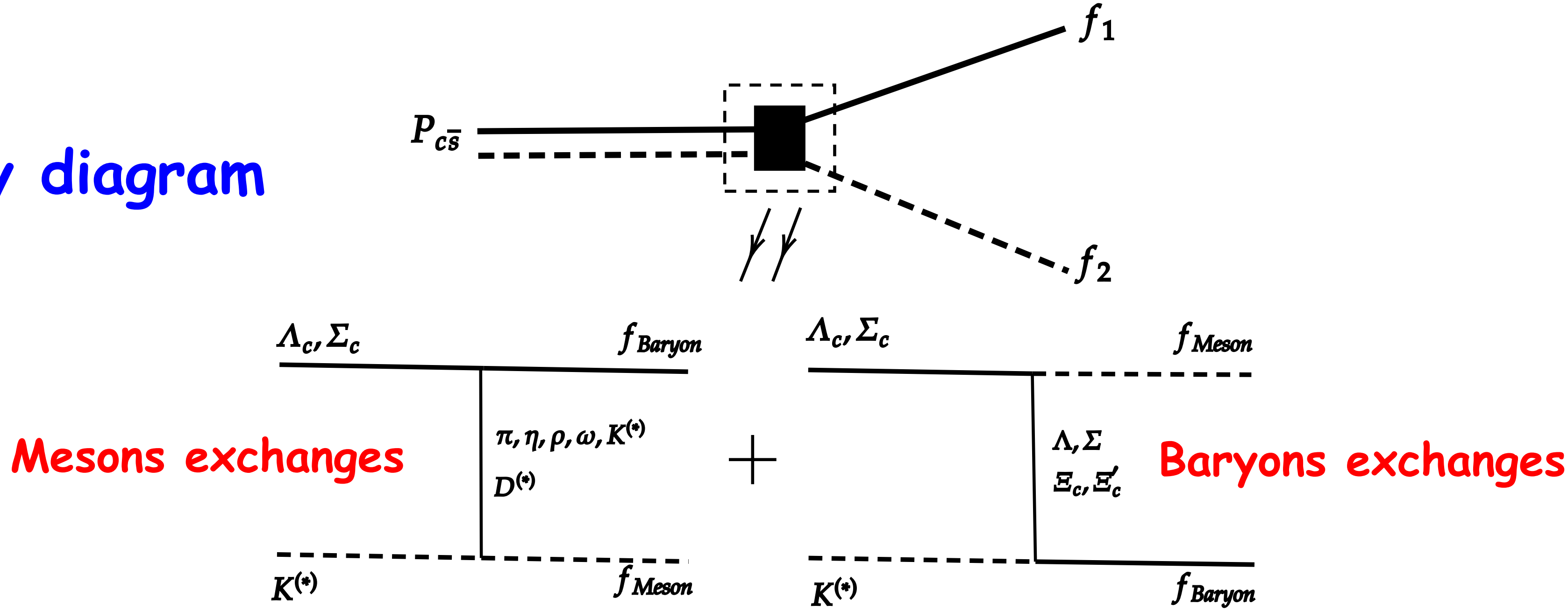
	Single channel			Coupled channel							
$I(J^P)$	Λ	E	r_{RMS}	Λ	E	r_{RMS}	$\Sigma_c K(^2S_{1/2})$	$\Lambda_c K^*(^2S_{1/2})$	$\Lambda_c K^*(^4D_{1/2})$	$\Sigma_c K^*(^2S_{1/2})$	$\Sigma_c K^*(^4D_{1/2})$
$1/2(1/2^-)$	2.00	−0.94	4.78	0.90	−0.36	6.14	**98.85**	0.61	0.47	0.01	0.06
	2.20	−4.80	2.44	0.95	−3.28	3.04	**97.61**	1.34	0.92	0.02	0.12
	2.40	−10.96	1.68	1.00	−9.27	1.91	**96.11**	2.25	1.42	0.04	0.18
	2.60	−18.92	1.31	1.05	−18.44	1.42	**94.60**	3.18	1.92	0.06	0.24

Five channels

- **Loosely bound state with I=1/2:** Λ ~1.00 GeV; prime hadronic molecular candidate; S-wave $\Sigma_c K$ dominant channel; coupled channel effects very important
- **Loosely bound state with I=3/2:** Λ ~1.00 GeV; bound state solutions are very sensitive with cutoff; not a good molecular candidate

Two-body strong decay behaviors

Decay diagram



Interactions

$$\langle f_1 f_2|V|i\rangle = \sum_n \langle f_1 f_2|V|A_n B_n\rangle\langle A_n B_n|i\rangle = \sum_n \int \frac{d^3k d^3r}{(2\pi)^3} e^{-i\boldsymbol{k}\cdot\boldsymbol{r}} \psi_{A_n B_n}(\boldsymbol{r})\langle f_1 f_2|V|A_n B_n\rangle$$

In the rest frame of the molecular state, two-body decay width can be expressed as

$$d\Gamma = \frac{1}{2J+1}\frac{|\boldsymbol{p}|}{32\pi^2 m_i^2}|\mathcal{M}(i \to f_1 + f_2)|^2 d\Omega$$

Decay channels and exchanged particles

	$\Sigma_c K$	$\Lambda_c K^*$	$\Sigma_c K^*$
$D_s N$	Σ, D^*	$\Lambda, D^{(*)}$	$\Sigma, D^{(*)}$
$D_s^* N$	$\ldots$	$\Lambda, D^{(*)}$	$\Sigma, D^{(*)}$
$\Lambda_c K$	$\rho, \Xi_c^{(\prime)}$	$\eta, \omega, \Xi_c^{(\prime)}$	$\pi, \rho, \Xi_c^{(\prime)}$
$\Lambda_c K^*$	$\ldots$	$\ldots$	$\pi, \rho, \Xi_c^{(\prime)}$
$\Sigma_c K$	$\ldots$	$\pi, \rho, \Xi_c^{(\prime)}$	$\pi, \eta, \rho, \omega, \Xi_c^{(\prime)}$
$\Sigma_c^* K$	$\ldots$	$\ldots$	$\pi, \eta, \rho, \omega, \Xi_c^{(\prime)}$

S-wave

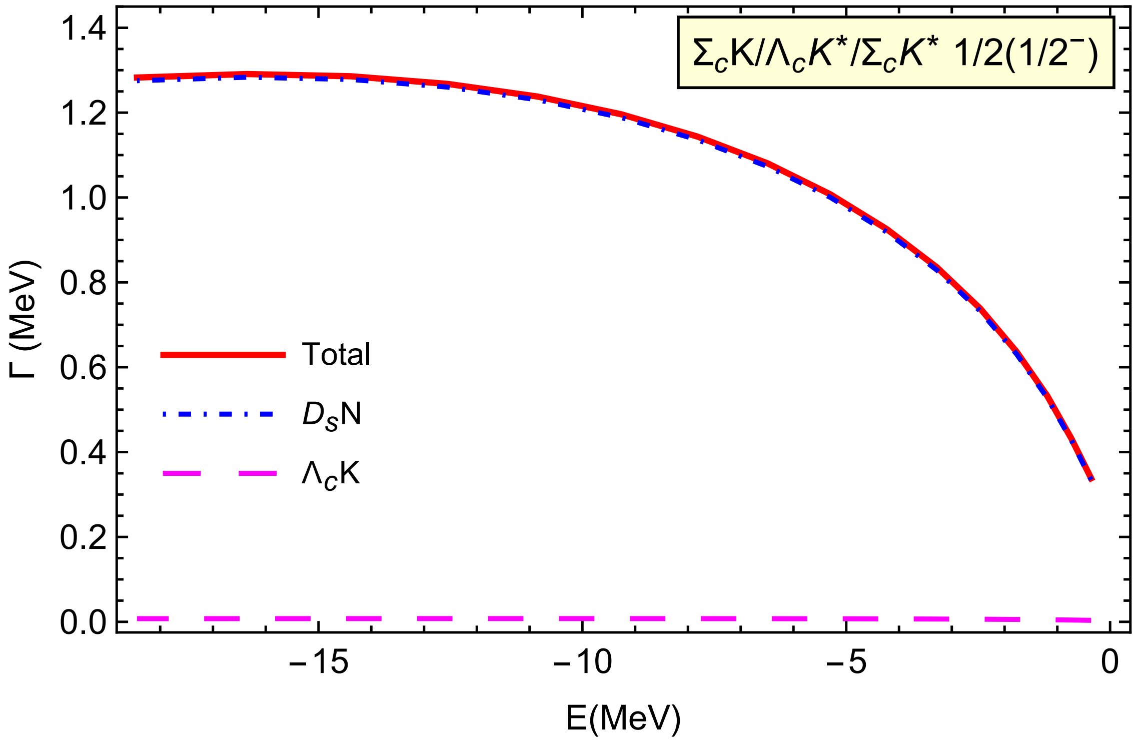
Effective Lagrangians in SU(4) symmetry

$$\mathcal{L} = \mathcal{L}_{PPV} + \mathcal{L}_{VVP} + \mathcal{L}_{VVV}$$

$$= \frac{ig}{2\sqrt{2}}\langle\partial^\mu P\left(PV_\mu - V_\mu P\right)\rangle + \frac{g_{VVP}}{\sqrt{2}}\epsilon^{\mu\nu\alpha\beta}\left\langle\partial_\mu V_\nu \partial_\alpha V_\beta P\right\rangle + \frac{ig}{2\sqrt{2}}\langle\partial^\mu V^\nu\left(V_\mu V_\nu - V_\nu V_\mu\right)\rangle,$$

Phys. Rev. C 65, 015203 (2002), arXiv:2402.10594, Phys. Rev. C 62, 034903 (2000), Eur. Phys. J. A 36, 73 (2008),

Numerical results

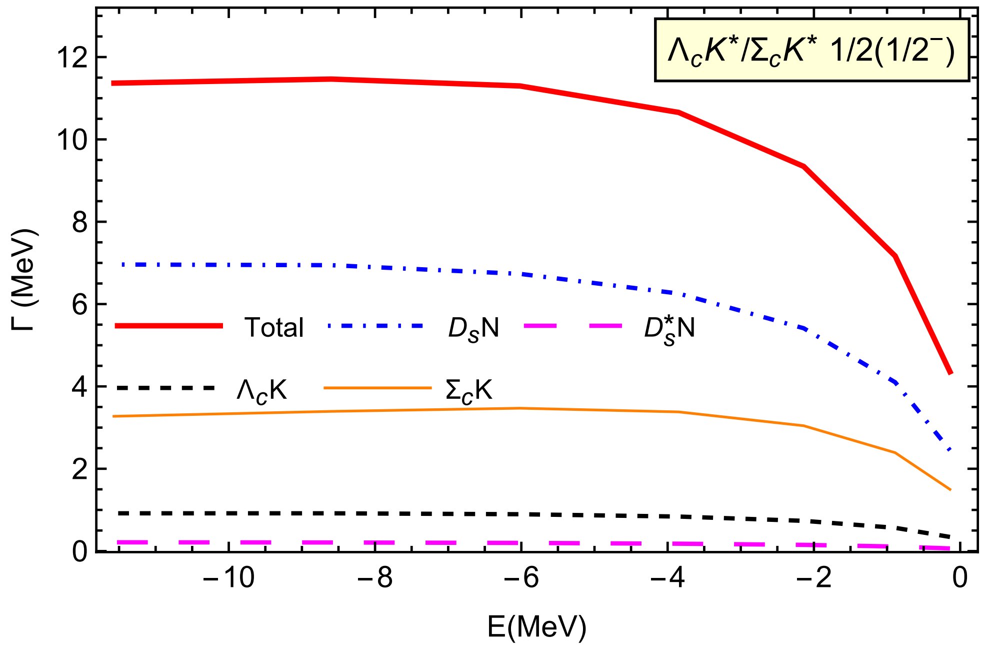


$E(MeV)$	Γ_C	Γ_S	Γ_{Meson}	Γ_{Baryon}
−0.36	0.34	0.18	0.09	0.08
−3.28	0.84	0.48	0.23	0.20
−9.27	1.20	0.62	0.33	0.29
−18.44	1.28	0.69	0.34	0.32

Single channel | Meson exchange | Baryon exchange

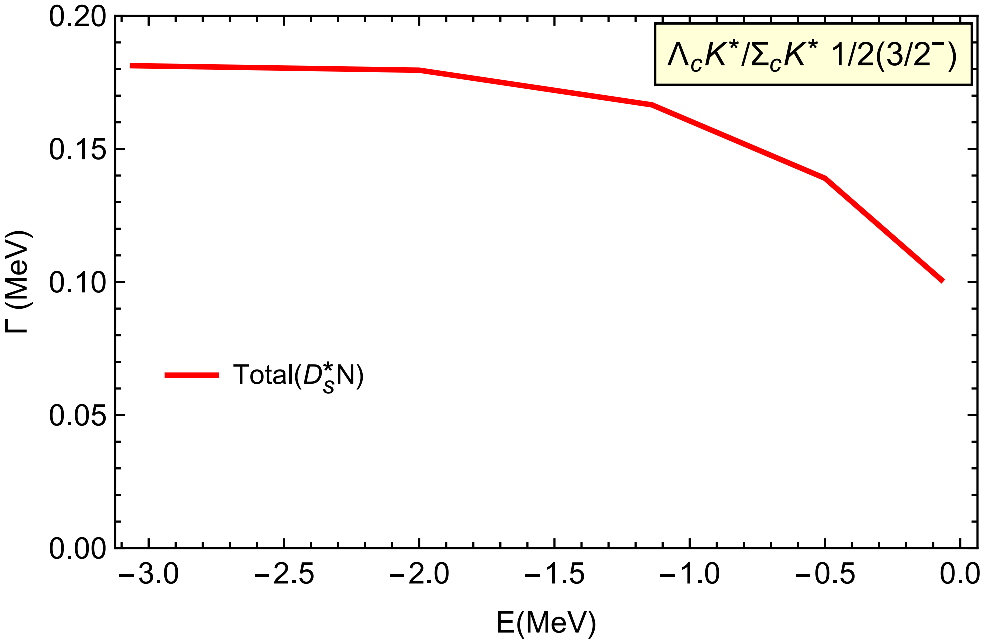
$\Sigma_c K/\Lambda_c K^*/\Sigma_c K^*$ 1/2(1/2$^-$)

- Total decay width: in the order of 1 MeV.
- Dominant decay mode: DsN.
- Both of the mesons and baryons exchanges can be important.
- The coupled channel effects play an important role.



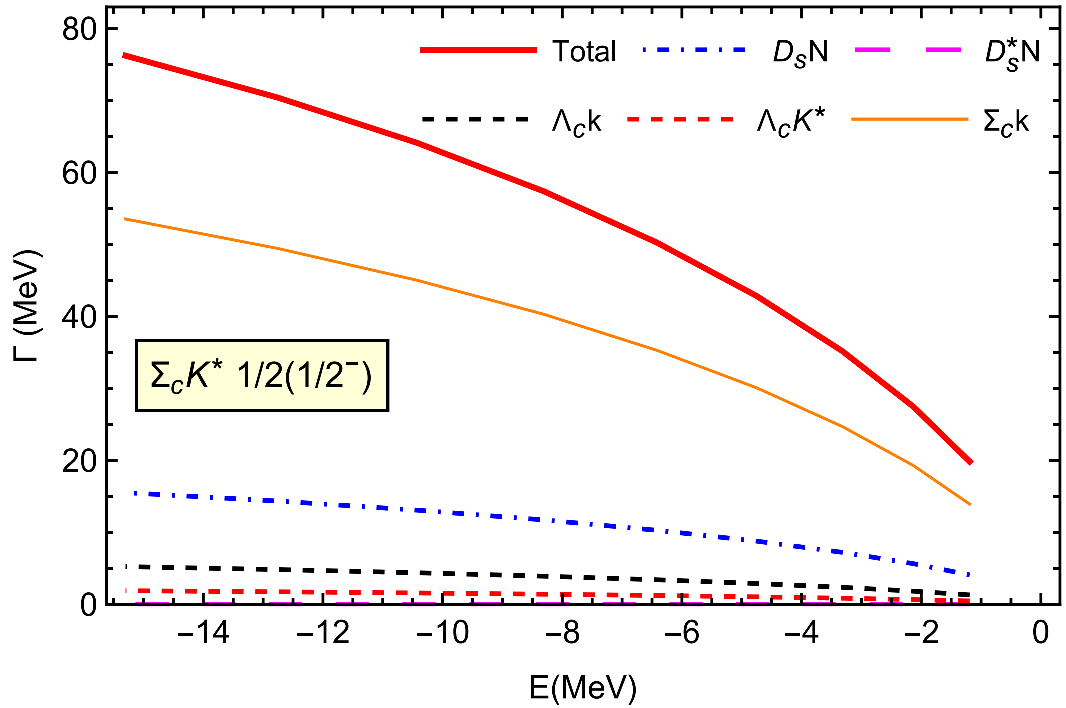
$\Lambda_c K^*/\Sigma_c K^*$ $1/2(1/2^-)$

- ☐ Total decay width: in the order of 10 MeV.
- ☐ Dominant decay mode: DsN.
- ☐ $\Sigma_c K$ is the secondly dominating decay channel.



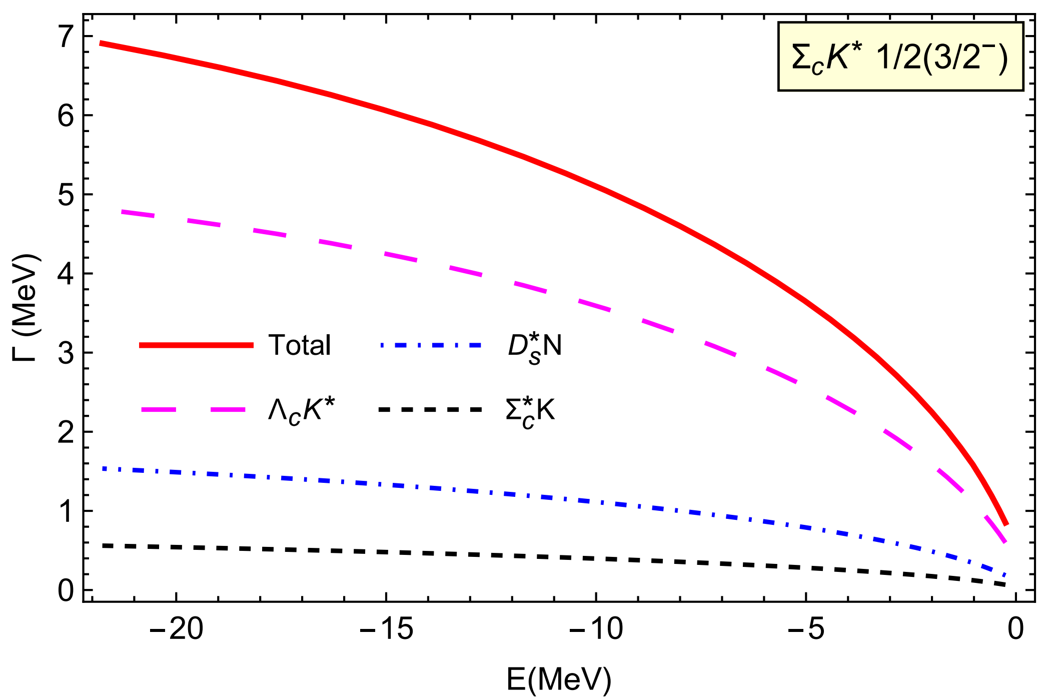
$\Lambda_c K^*/\Sigma_c K^*$ $1/2(3/2^-)$

- ☐ Total decay width: in the order of 0.1 MeV.



$\Sigma_c K^*$ 1/2(1/2$^-$)

- ☐ Total decay width: around 50 MeV or larger.
- ☐ Dominant decay mode: $\Sigma_c K$.
- ☐ DsN is the secondly dominating decay channel.



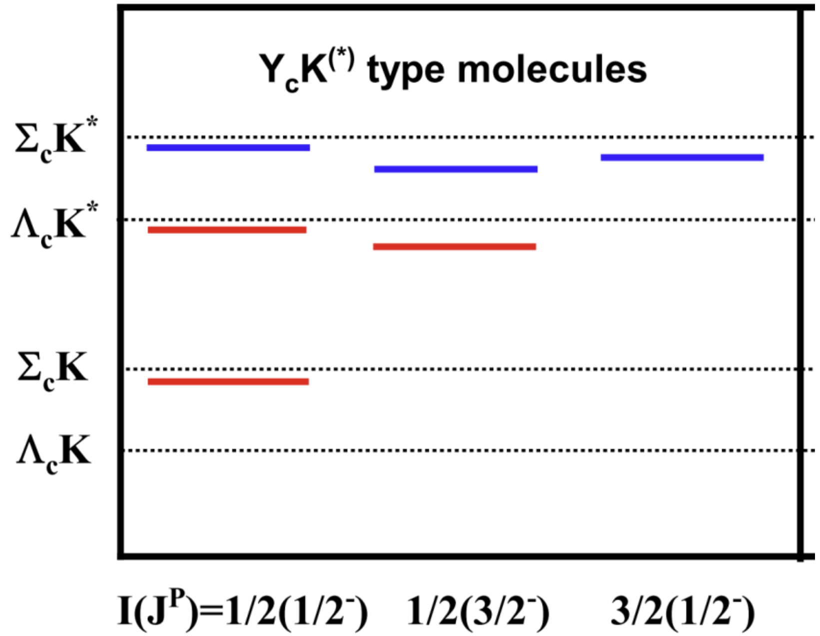
$\Sigma_c K^*$ 1/2(3/2$^-$)

- ☐ Total decay width: in the order of several MeV.
- ☐ Dominant decay mode: ΛcK*.

Summary

1. $Y_cK^{(*)}(Y_c = \Lambda_c, \Sigma_c)$ interactions:

Using the OBE model, considering both of the S-D wave mixing effects and the coupled channel effects, predicting several possible molecular candidates



2. Exploring their two-body strong decay behaviors using the effective Lagrangians method, input the obtained wave functions

States	Σ_cK [1/2(1/2-)]	Λ_cK^* (1/2-)	Λ_cK^* (3/2-)	Σ_cK^* [1/2(1/2-)]	Σ_cK^* [1/2(3/2-)]	Σ_cK^* [3/2(1/2-)]
Width (MeV)	1	10	0.1	60	5	40
Dominant modes	DsN	DsN	Ds*N	Σ_cK	ΛcK^*	Σ_cK

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