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

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Outline

1. **Background:** From the molecular explanations to Tcs(2900), Ds0(2317) and Ds1(2460) to possible $Y_c K^{(*)}$ molecules

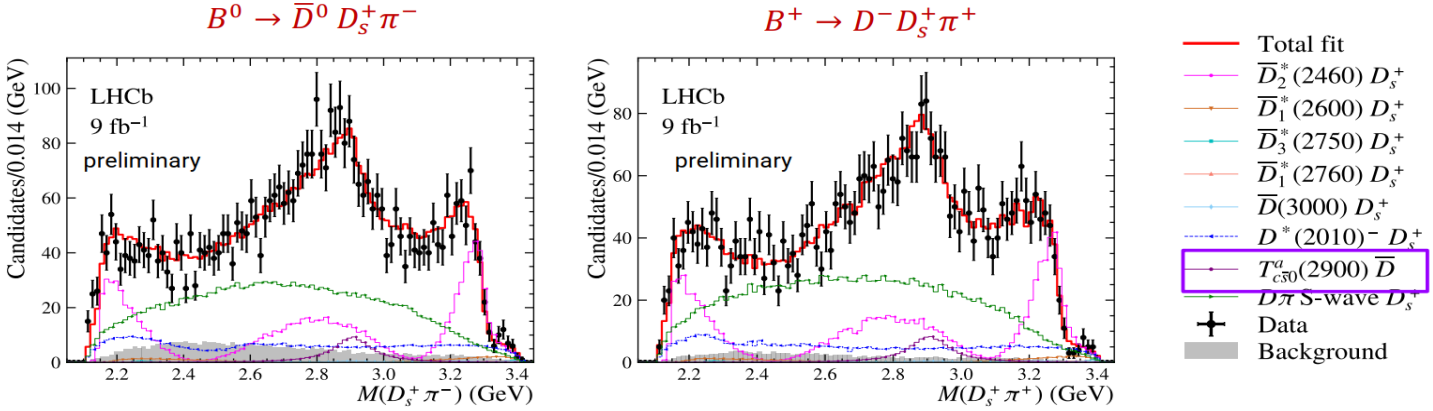
2. Two-body strong decay interactions

3. Numerical results

4. Summary

1. Background

1.1 Observations of charm-strange tetraquarks Tcs(2900)



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

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

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

Containing four different flavor quarks

R. Aaij et al. [LHCb], Phys. Rev. Lett. 131, 041902 (2023)
R. Aaij et al. [LHCb], Phys. Rev. D 108, 012017 (2023)

1.2 Theoretical explanations to Tcs(2900)

➢ Compact open-charm tetraquark

- W. Chen, H. X. Chen, X. Liu, T. G. Steele, and S. L. Zhu, *Phys. Rev.* D **95**, 114005 (2017)
- J. B. Cheng, S. Y. Li, Y. R. Liu, Y. N. Liu, Z. G. Si, and T. Yao, *Phys. Rev.* D **101**, 114017 (2020)
- T. Guo, J. Li, J. Zhao, and L. He, *Phys. Rev.* D**105**, 054018 (2022)
- X. S. Yang, Q. Xin, Z.G. Wang, Int. J. Mod. Phys. A **38**, 2350056 (2023)
- B. D. Wang and T. R. Wang, Eur. Phys. J. A 60:179 (2024)
- S. N. Li, L. Tang arXiv:2404.11145 [hep-ph]

➢ Hadronic molecular explanations

- R. Chen and X. Liu, Phys. Rev. D 94, 034006 (2016)
- H. W. Ke, Y. F. Shi, X. H. Liu, and X. Q. Li, Phys. Rev. D 106, 114032 (2022)
- S. S. Agaev, K. Azizi, and H. Sundu, J. Phys. G: Nucl. Part. Phys. 50, 055002 (2023)
- S. S. Agaev, K. Azizi, and H. Sundu, Phys. Rev. D 107, 094019 (2023)
- M. Y. Duan, M. L. Du, Z. H. Guo, E. Wang, and D. Y. Chen, Phys. Rev. D 108, 074006 (2023)
- B. Wang, K. Chen, L. Meng, and S. L. Zhu, Phys. Rev. D 109, 034027 (2024)

➢ Threshold effect

- R. Molina and E. Oset, EPJ Web Conf. 291 (2024) 03010

1.3 Molecular explanations to Tcs(2900) and Ds0(2317)/Ds1(2460)

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

Review papers:

H.-X. Chen, W. Chen, X. Liu, Y.-R. Liu, and S.-L. Zhu, Rept. Prog. Phys. 80, 076201 (2017)

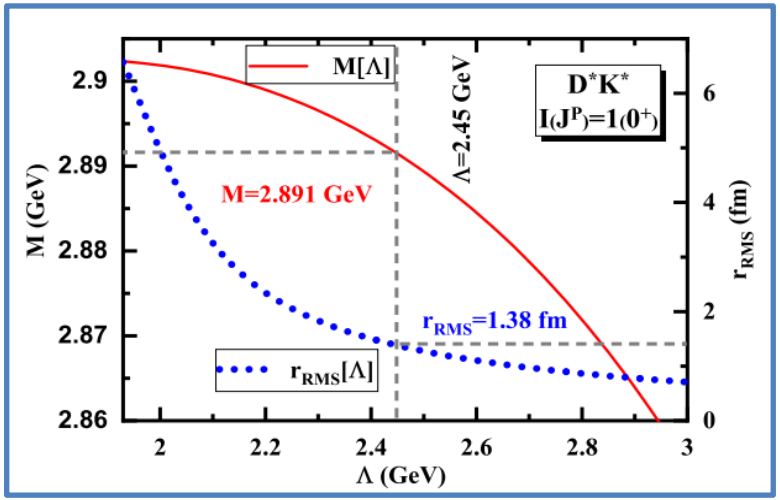
Y. Dong, A. Faessler, and V. E. Lyubovitskij, Prog. Part. Nucl. Phys. 94, 282 (2017)

F.-K. Guo, C. Hanhart, U.-G. Mei ner, Q. Wang, Q. Zhao, and B.-S. Zou, Rev. Mod. Phys. 90, 015004 (2018)

D.-L. Yao, L.-Y. Dai, H.-Q. Zheng, and Z.-Y. Zhou, Rept. Prog. Phys. 84, 076201 (2021)

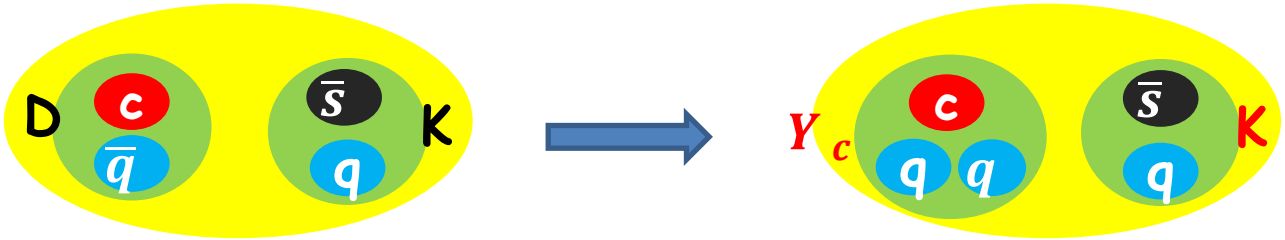
One-boson-exchange (OBE) effective potentials

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



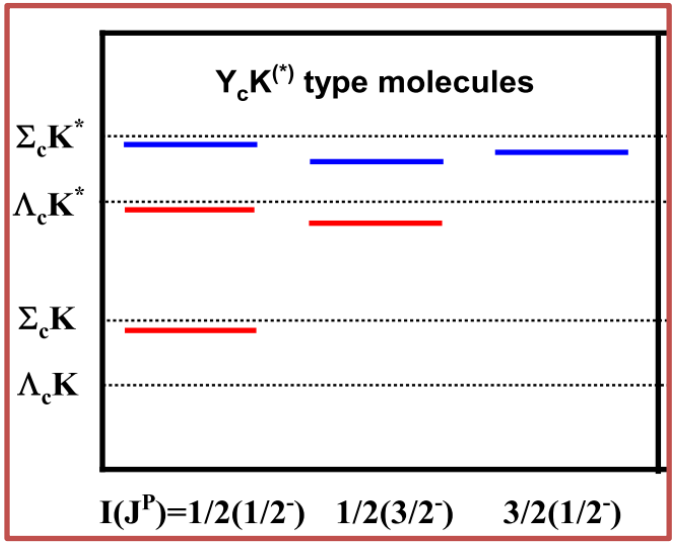
1.4 Other possible charm-strange molecular pentaquarks

- Diquark has the same color structure with the antiquark



$$Y_c K^{(*)} (Y_c = \Lambda_c, \Sigma_c)$$

- OBE effective potentials
- S -D wave mixing effects and the coupled channel effects
- Predicting six possible molecular candidates: 3 single channel molecules and 3 coupled channel molecules



R. Chen and Q. Huang, Phys. Rev. D108, 054011(2024)

1.5 Exploring two-body strong decay properties of YcK* molecules

- Providing more valuable information.
- **Decay behaviors:** sensitive to the inner structures of molecules, reflecting the constituent hadrons interacting or decaying.
- Employing the effective Largrangians approach, considering the coupled channel effects.

Decay channels

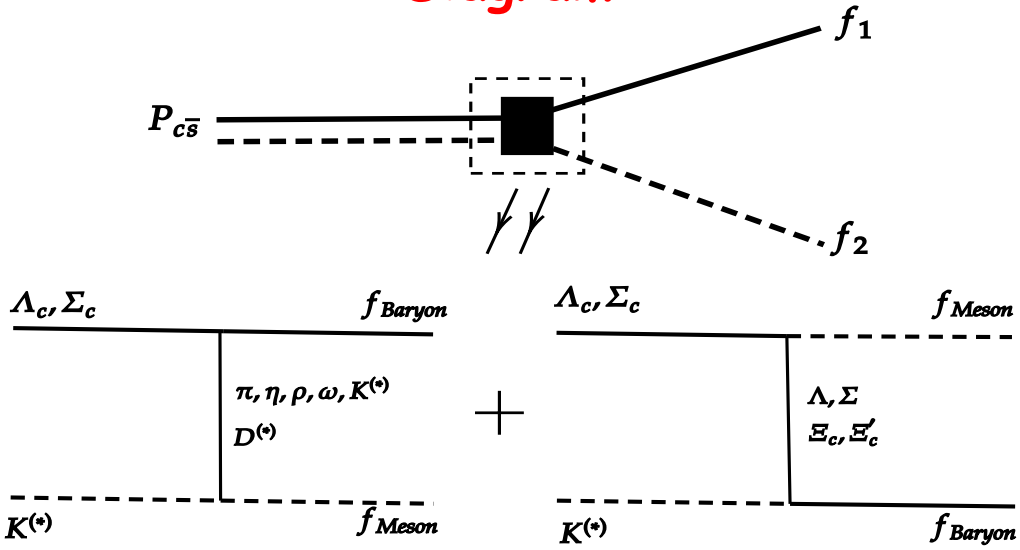
$$\Sigma_c K/\Lambda_c K^*/\Sigma_c K^*[1/2(1/2^-)] \to \{D_s N, \Lambda_c K\},$$
$$\Lambda_c K^*/\Sigma_c K^*[1/2(1/2^-)] \to \{D_s^{(*)} N, \Lambda_c K, \Sigma_c K\},$$
$$\Lambda_c K^*/\Sigma_c K^*[1/2(3/2^-)] \to \{D_s^* N\},$$
$$\Sigma_c K^*[1/2(1/2^-)] \to \{D_s^{(*)} N, \Lambda_c K^{(*)}, \Sigma_c K\},$$
$$\Sigma_c K^*[1/2(3/2^-)] \to \{D_s^* N, \Lambda_c K^*, \Sigma_c^* K\},$$
$$\Sigma_c K^*[3/2(1/2^-)] \to \{D_s^* \Delta, \Sigma_c K\}.$$

2. Two-body strong decay interactions

2.1 Interactions

- Exchanged particles: $\pi, \eta, \rho, \omega, K, D, D^*, \Lambda, \Sigma, \Xi_c, \Xi_c'$

Diagram



A coupled channel molecule composed of several channels

$$i \rightarrow f_1 + f_2$$

$$|i\rangle = \sum_n |A_n B_n\rangle$$

$$A_n + B_n \rightarrow f_1 + f_2$$

2.1 Interactions

$$i \to f_1 + f_2 \quad \Longrightarrow \quad A_n + B_n \to f_1 + f_2$$

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

Wave functions for the n-th channels

Considering the different normalization conventions used for the scattering amplitude, one have

$$\langle f_1 f_2 | V | i \rangle = -\frac{\mathcal{M}(i \to f_1 + f_2)}{\sqrt{2E_i}\sqrt{2E_{f_1}}\sqrt{2E_{f_2}}} \qquad \langle f_1 f_2 | V | A_n B_n \rangle = -\frac{\mathcal{M}(A_n(\boldsymbol{k}) + B_n(-\boldsymbol{k}) \to f_1(\boldsymbol{p}) + f_2(-\boldsymbol{p}))}{\sqrt{2E_{A_n}}\sqrt{2E_{B_n}}\sqrt{2E_{f_1}}\sqrt{2E_{f_2}}}$$

2.2 Decay width

In the rest frame of the molecular state

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

$$|\boldsymbol{p}| = \sqrt{\left(m_i^2 - (m_{f_1} + m_{f_2})^2\right)\left(m_i^2 - (m_{f_1} - m_{f_2})^2\right)}/(2m_i)$$

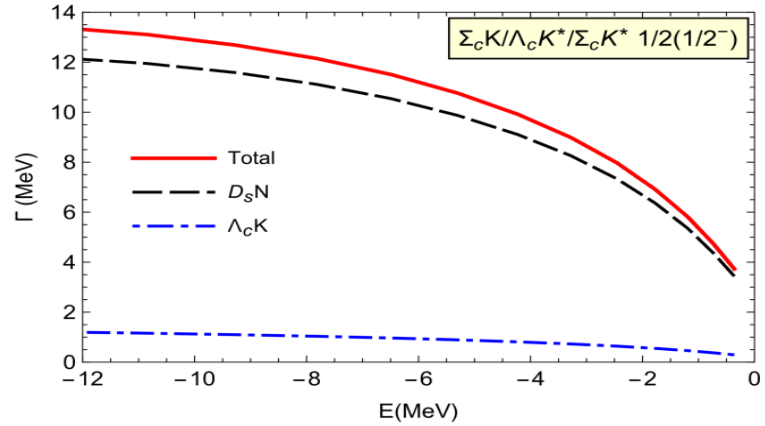
2.3 Effective Lagrangians in SU(4) symmetry

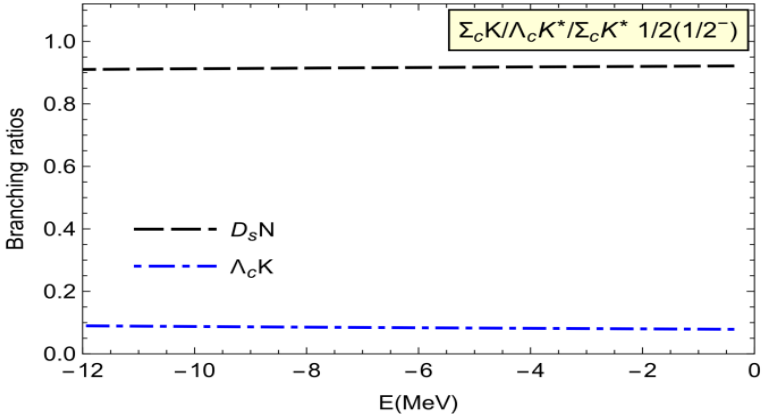
$$\mathcal{L} = \mathcal{L}_{PPV} + \mathcal{L}_{VVP} + \mathcal{L}_{VVV}$$

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

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

3. Numerical results

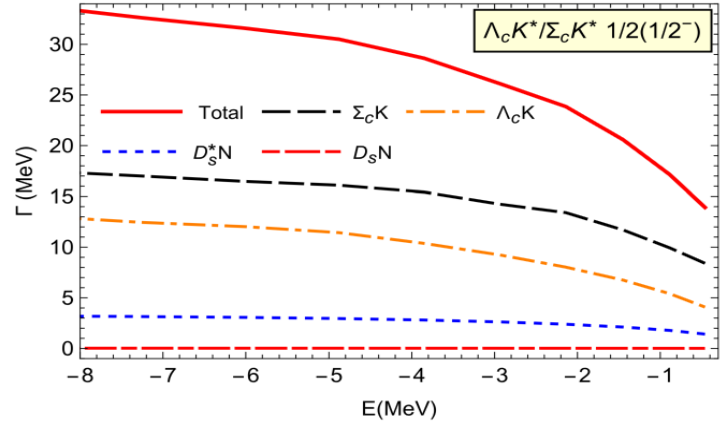


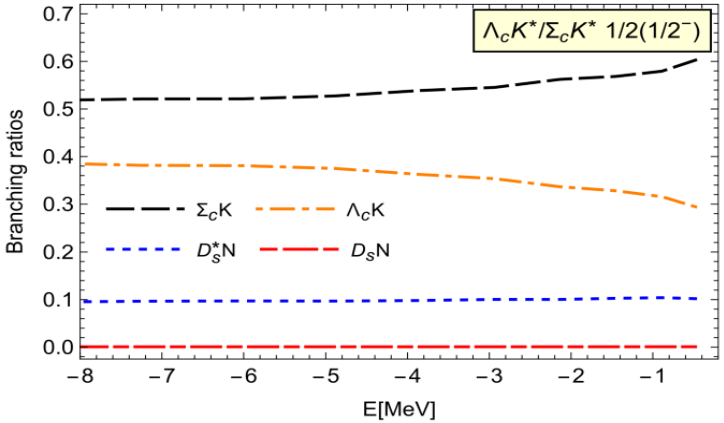


$\Sigma_c K/\Lambda_c K^*/\Sigma_c K^*$ 1/2(1/2⁻)

- Total decay width: 10 MeV.
- Dominant decay mode: DsN.
- $\Lambda_c K$: suppressed by Ξ_c exchanging, ρ exchanging in the tensor terms.
- The coupled channel effects play an important role.
- **Branching ratios:** almost independent with the binding energy.

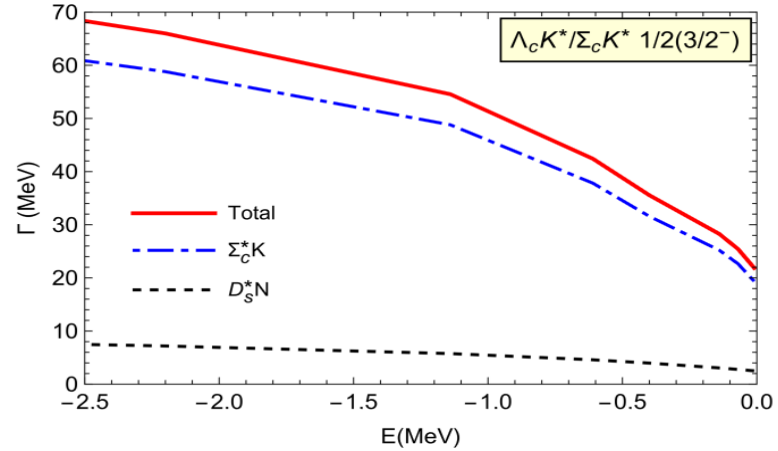
$\Lambda_c K^*/\Sigma_c K^*$ 1/2(1/2⁻)

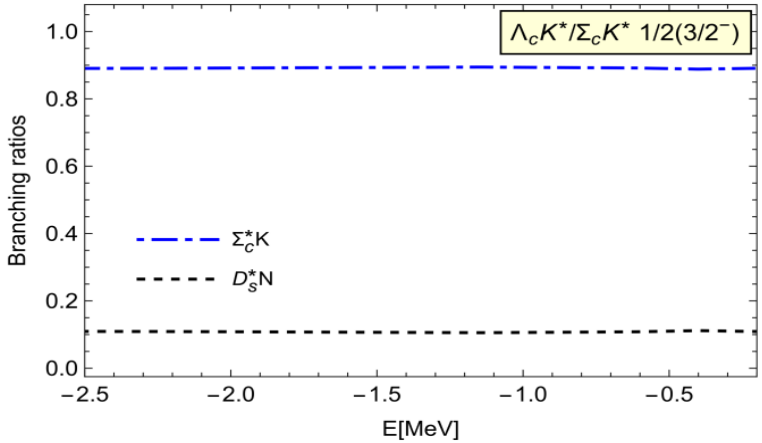




- Total decay width: 15~30 MeV.
- Dominant decay mode: $\Sigma_c K(50\%)$, followed by $\Lambda_c K$ (40%) and Ds*N (10%).
- **Branching ratios:** almost independent with the binding energy.
- $\Sigma_c K^*$: very important due to the pion exchange interaction.

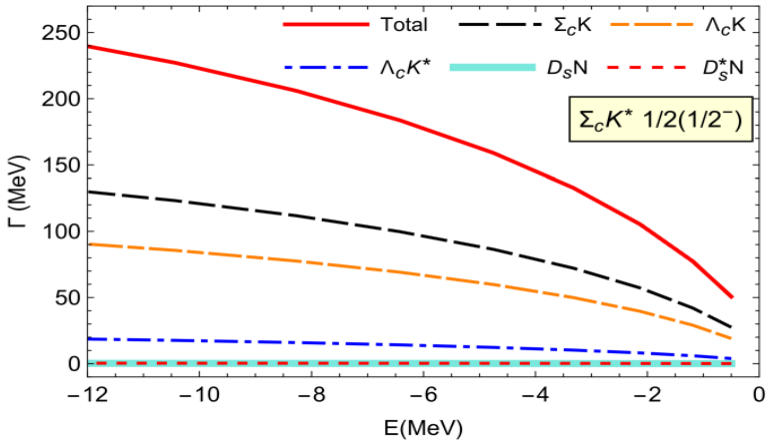
$\Lambda_c K^*/\Sigma_c K^*$ 1/2(3/2$^-$)

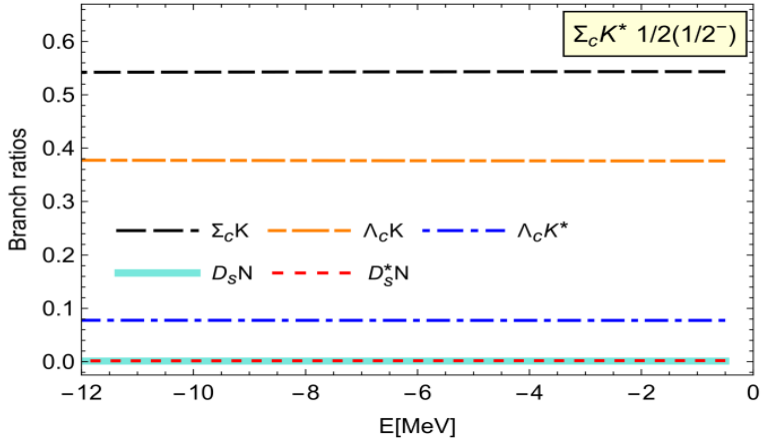




- Total decay width: in the order of several tens MeV.
- $\Sigma_c^* K$: dominant decay channel (90%), resulting from the significant pion exchange interaction.
- **Branching ratios:** almost independent with the binding energy.
- Coupled channel effects: important, a coherent growth existing in the different initial channels.

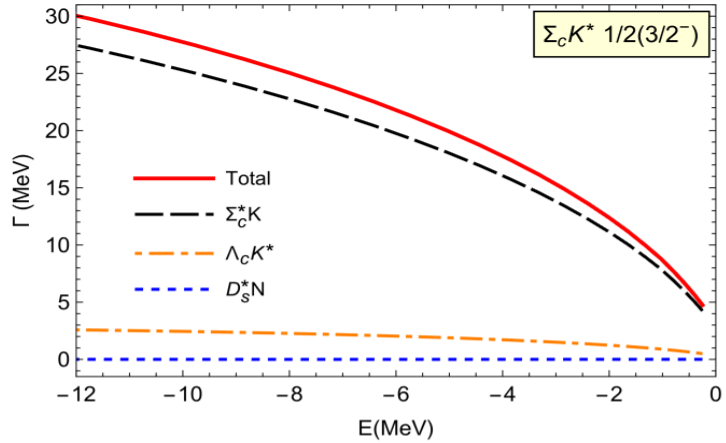
$\Sigma_c K^*$ 1/2(1/2⁻)

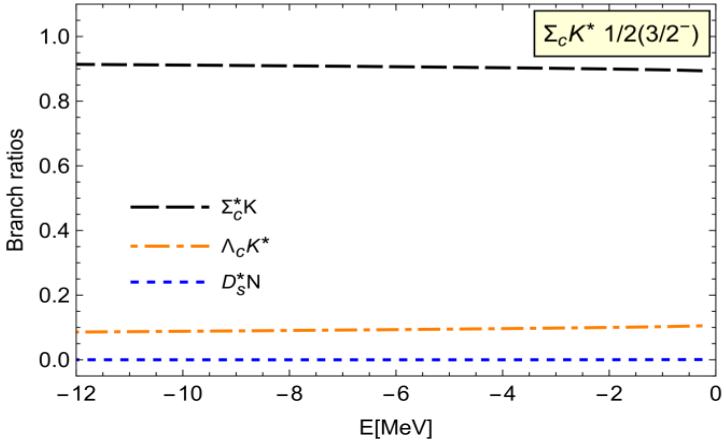




- Total decay width: around 200 MeV or larger.
- Dominant decay mode: $\Sigma_c K$(54%), ΛcK (38%), ΛcK*(8%); resulting from **light meson exchange** interactions.
- ΛcK*(8%) : smaller phase space than $\Sigma_c K$ and ΛcK.
- Branching ratios: almost independent with the binding energy.

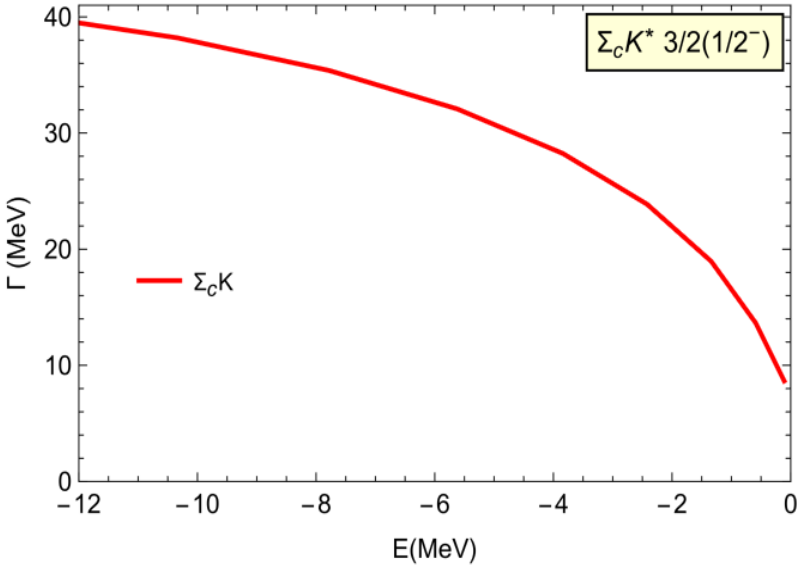
$\Sigma_c K^*$ 1/2(3/2⁻)





- Total decay width: 10~20 MeV.
- ΛcK and $\Sigma_c K$ channel: suppressed by D-wave interactions, smaller decay width than $\frac{1}{2}$ (1/2-).
- $\Sigma_c^* K$: dominant decay mode, 90% of total decay width due to the pion exchange interaction.
- ΛcK*: smaller phase space, strong coherent cancellation between the meson exchange and baryon exchange interactions.

$\Sigma_c K^*$ 3/2(1/2⁻)



- Total decay width: 10~40 MeV.
- $\Sigma_c K$: the only two-body strong decay mode via S-wave interaction.
- **Smaller width than 1/2(1/2-): three times smaller isospin factor** existing in pion and rho exchange interactions

4. Summary

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

States	$I(J^P)$	Order of decay width	Channels (Branch ratios)			
$\Sigma_c K/\Lambda_c K^*/\Sigma_c K^*$	$1/2(1/2^-)$	~ 10 MeV	$D_s N(91\%)$	$\Lambda_c K(9\%)$		
$\Lambda_c K^*/\Sigma_c K^*$	$1/2(1/2^-)$	~ 20 MeV	$\Sigma_c K(54\%)$	$\Lambda_c K(36\%)$	$D_s^* N(10\%)$	$D_s N(< 1\%)$
	$1/2(3/2^-)$	~ 50 MeV	$\Sigma_c^* K(90\%)$	$D_s^* N\ (10\%)$		
$\Sigma_c K^*$	$1/2(1/2^-)$	~ 150 MeV	$\Sigma_c K(54\%)$	$\Lambda_c K(38\%)$	$\Lambda_c K^*(8\%)$	$D_s^{(*)} N(< 1\%)$
	$1/2(3/2^-)$	~ 20 MeV	$\Sigma_c^* K(91\%)$	$\Lambda_c K^*(9\%)$	$D_s^* N(< 1\%)$	
	$3/2(1/2^-)$	~ 30 MeV	$\Sigma_c K(100\%)$			

Thank you

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