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Natural interpretation on the data of $\Lambda_c \to \Sigma\pi$

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Hong-Wei Ke and Xue-Qian Li, PRD 102, 113013 (2020), arXiv:2008.12163

Outline

1. Λ_c的实验数据
2. 以往理论研究回顾
3. pole model 计算
4. 末态相互作用的贡献

1. Λ_c实验数据

CHARMED BARYONS
$(C = +1)$

$\Lambda_c^+ = udc$, $\Sigma_c^{++} = uuc$, $\Sigma_c^+ = udc$, $\Sigma_c^0 = ddc$,
$\Xi_c^+ = usc$, $\Xi_c^0 = dsc$, $\Omega_c^0 = ssc$

Λ_c^+

$I(J^P) = 0(\frac{1}{2}^+)$

Mass $m = 2286.46 \pm 0.14$ MeV
Mean life $\tau = (202.4 \pm 3.1) \times 10^{-15}$ s (S = 1.7)
$c\tau = 60.7\ \mu$m

Decay asymmetry parameters

		Fraction (Γ_i/Γ)
$\Lambda\pi^+$	$\alpha = -0.84 \pm 0.09$	(1.30 ± 0.07) %
$\Sigma^+\pi^0$	$\alpha = -0.55 \pm 0.11$	(1.25 ± 0.10) %
α FOR $\Lambda_c^+ \to \Sigma^0\pi^+$	$= -0.73 \pm 0.18$	(1.29 ± 0.07) %

Parameters	$\Lambda_c^+ \to pK_S^0$	$\Lambda\pi^+$	$\Sigma^+\pi^0$	$\Sigma^0\pi^+$
α_{BP}^+	$0.18 \pm 0.43 \pm 0.14$	$-0.80 \pm 0.11 \pm 0.02$	$-0.57 \pm 0.10 \pm 0.07$	$-0.73 \pm 0.17 \pm 0.07$

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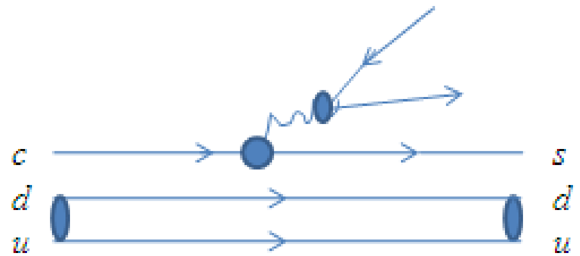
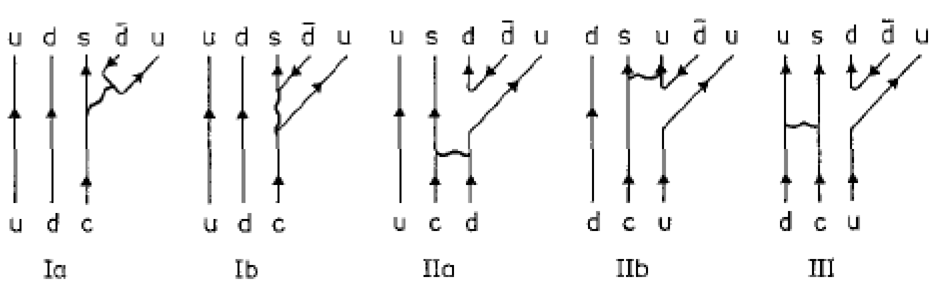
根据对重味介子的研究经验,一般可因子化的图起主要的贡献,这就无法解释 $\Lambda_c \to \Sigma\pi$ 和 $\Lambda_c^+ \to \Lambda\pi^+$ 的宽度接近



非因子化的图的贡献在 $\Lambda_c \to \Sigma\pi$ 比较大



J. G. Korner and M. Kramer, Z. Phys. C **55**, 659 (1992)

2. 以往理论研究回顾

Decay	Körner, Krämer [8]	Xu, Kamal [9]	Cheng, Tseng [10] CA	Cheng, Tseng [10] Pole	Ivanov et al [11]	Żenczykowski [12]	Sharma, Verma [13]	
$\Lambda_c^+ \to \Lambda\pi^+$	input	1.62	1.46	0.88	0.79	0.52	1.12	$(1.30 \pm 0.07)\%$
$\Lambda_c^+ \to \Sigma^0\pi^+$	0.32	0.34	1.76	0.72	0.88	0.39	1.34	$(1.29 \pm 0.07)\%$
$\Lambda_c^+ \to \Sigma^+\pi^0$	0.32	0.34	1.76	0.72	0.88	0.39	1.34	$(1.25 \pm 0.10)\%$
$\Lambda_c^+ \to \Lambda\pi^+$	−0.70	−0.67	−0.99	−0.95	−0.95	−0.99	−0.99	-0.84 ± 0.09
$\Lambda_c^+ \to \Sigma^0\pi^+$	0.70	0.92	−0.49	0.78	0.43	0.39	−0.31	-0.73 ± 0.18
$\Lambda_c^+ \to \Sigma^+\pi^0$	0.70	0.92	−0.49	0.78	0.43	0.39	−0.31	-0.55 ± 0.11

[8] J.G. Körner and M. Krämer, “Exclusive nonleptonic charm baryon decays,” Z. Phys. C 55, 659 (1992).

[9] Q. P. Xu and A. N. Kamal, “Cabibbo favored nonleptonic decays of charmed baryons,” Phys. Rev. D 46, 270 (1992).

[10] H. Y. Cheng and B. Tseng, “Cabibbo allowed nonleptonic weak decays of charmed baryons”, Phys. Rev. D 48, 4188 (1993) [hep-ph/9304286].

[11] M.A. Ivanov, J.G. Körner, V.E. Lyubovitskij, and A.G. Tusetsky, “Exclusive nonleptonic decays of bottom and charm baryons in a relativistic three quark model: Evaluation of nonfactorizing diagrams,” Phys. Rev. D 57, 5632 (1998).

[12] P. Żenczykowski, “Nonleptonic charmed baryon decays: Symmetry properties of parity violating amplitudes,” Phys. Rev. D 50, 5787 (1994).

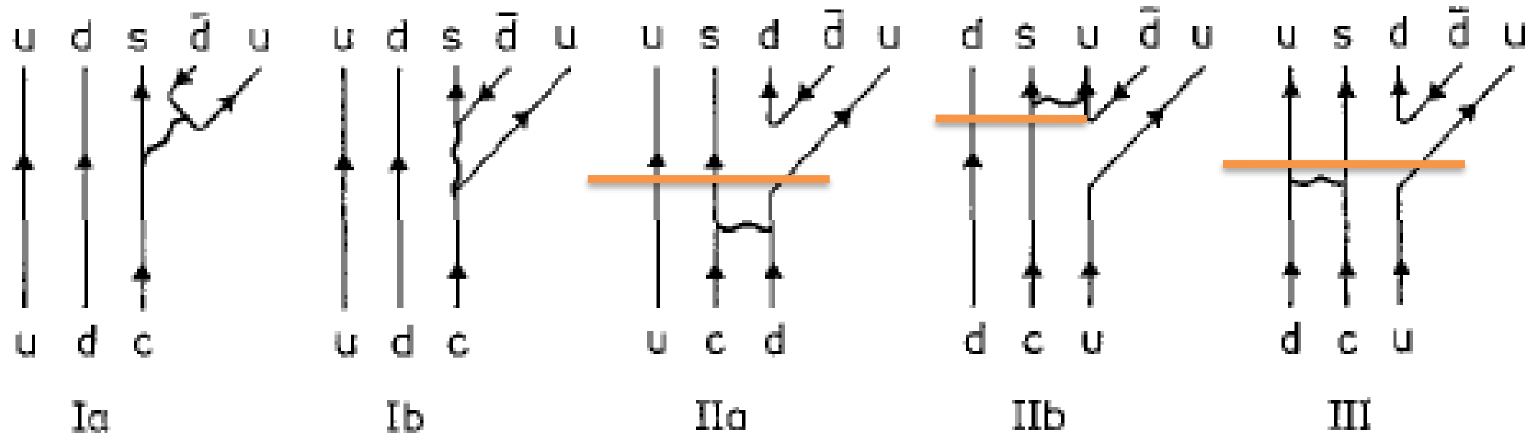
[13] K.K. Sharma and R.C. Verma, “A Study of weak mesonic decays of Λ_c and Ξ_c baryons on the basis of HQET results,” Eur. Phys. J. C 7, 217 (1999).

夸克模型 ← [8], [11]

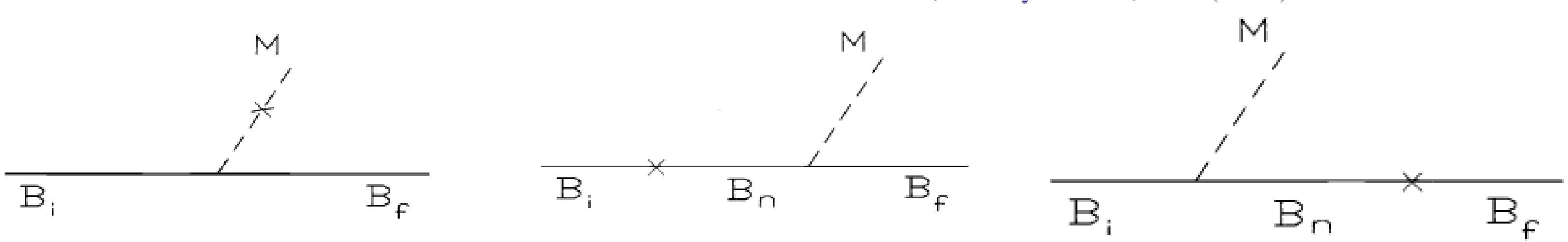
Pole model (+current algebra) ← [9], [10], [12], [13]

H. Y. Cheng, X. W. Kang, and F. Xu, Phys. Rev. D 97, 074028 (2018).

3. pole model 计算



J. G. Korner and M. Kramer, Z. Phys. C **55**, 659 (1992).



Bn是共振态或连续态

H. Y. Cheng and B. Tseng, Phys. Rev. D **46**, 1042 (1992)

$B_i \to B_f + P$ 跃迁矩阵元

$$M(B_i \to B_f + P) = i\bar{u}_f (A + B\gamma_5) u_i$$

where A and B are the s- and p-wave decay amplitudes

只考虑 the low-lying $B_n(\frac{1}{2}^+), B_n^*(\frac{1}{2}^-)$ and $B_n^*(\frac{1}{2}^+)$ poles

$$A = \sum_{B_n} \left[\frac{g_{B_f B_n P} b_{ni}}{m_i + m_n} + \frac{b_{fn} g_{B_n B_i P}}{m_f + m_n} \right] - \sum_{B_n^*(1/2^-)} \left[\frac{g_{B_f B_{n^*} P} b_{n^* i}}{m_i - m_{n^*}} + \frac{b_{fn^*} g_{B_{n^*} B_i P}}{m_f - m_{n^*}} \right]$$

$$B = -\sum_{B_n} \left[\frac{g_{B_f B_n P} a_{ni}}{m_i - m_n} + \frac{a_{fn} g_{B_n B_i P}}{m_f - m_n} \right] - \sum_{B_n^*(1/2^+)} \left[\frac{g_{B_f B_{n^*} P} a_{n^* i}}{m_i - m_{n^*}} + \frac{a_{fn^*} g_{B_{n^*} B_i P}}{m_f - m_{n^*}} \right]$$

where a_{ij}, a_{i^*j}, and b_{i^*j} are the baryon-baryon matrix elements defined by

$$\langle B_i | \mathcal{H}_W | B_j \rangle = \bar{u}_i (a_{ij} + b_{ij}\gamma_5) u_j \,,$$

$$\langle B_i^*(\tfrac{1}{2}^-) | \mathcal{H}_W^{PV} | B_j \rangle = i b_{i^*j} \bar{u}_i u_j \,,$$

$$\langle B_i^*(\tfrac{1}{2}^+) | \mathcal{H}_W^{PC} | B_j \rangle = a_{i^*j} \bar{u}_{i^*} \gamma_5 u_j \,.$$

H. Y. Cheng and B. Tseng, Phys. Rev. D **46**, 1042 (1992)

As for the decay $B_i \to B_f + V$, its general amplitude is of the form

$$M(B_i \to B_f + V) = i\bar{u}_f(p_f)\epsilon^{*\mu}(A_1\gamma_\mu\gamma_5 + A_2 p_{f\mu}\gamma_5 + B_1\gamma_\mu + B_2 p_{f\mu})u_i(p_i)$$

The vector part of the BBV coupling constant leads to

$$A_1 = -\sum_{B_n^*(1/2^-)} \left[\frac{g_{B_f B_{n^*} V} b_{n^* i}}{m_i - m_{n^*}} + \frac{b_{f n^*} g_{B_{n^*} B_i V}}{m_f - m_{n^*}} \right],$$

$$B_1 = -\sum_{B_n} \left[\frac{g_{B_f B_n V} a_{ni}}{m_i - m_n} + \frac{a_{fn} g_{B_n B_i V}}{m_f - m_n} \right],$$

$$A_2 = B_2 = 0,$$

neglect the tensor BBV coupling

H. Y. Cheng and B. Tseng, Phys. Rev. D **46**, 1042 (1992)

有关的两个过程具体计算

$\Lambda_c^+ \to \Sigma^0 \pi^+$. This decay does not receive factorizable contributions and hence provides a measure of the non-spectator diagrams. The pole amplitudes are

$$A^{\text{pole}} = -\sum_{\Sigma^{*+}(1/2^-)} \frac{g_{\Sigma^0 \Sigma^{*+}\pi^+} b_{\Sigma^{*+}\Lambda_c^+}}{m_{\Lambda_c^+} - m_{\Sigma^{*+}}} - \sum_{\Sigma_c^{*0}(1/2^-)} \frac{b_{\Sigma^0 \Sigma_c^{*0}} g_{\Sigma_c^{*0}\Lambda_c^+ \pi^+}}{m_{\Sigma^0} - m_{\Sigma_c^{*0}}} = 2.44 \times 10^{-2} h ,$$

$$B^{\text{pole}} = -\left(\frac{g_{\Sigma^0 \Sigma^+ \pi^+} a_{\Sigma^+ \Lambda_c^+}}{m_{\Lambda_c^+} - m_{\Sigma^+}} + \frac{a_{\Sigma^0 \Sigma_c^0} g_{\Sigma_c^0 \Lambda_c^+ \pi^+}}{m_{\Sigma^0} - m_{\Sigma_c^0}} \right) = 0.146 h$$

$$h \equiv G_F \cos^2\theta_C$$

$\Lambda_c^+ \to \Lambda \rho^+$ 非因子化部分

$$A_1^{\text{pole}} = -\sum_{\Sigma^{*+}} \frac{g_{\Sigma^+ \Lambda \rho^+} b_{\Sigma^{*+} \Lambda_c^+}}{m_{\Lambda_c^+} - m_{\Sigma^{*+}}} - \sum_{\Sigma_c^{*0}} \frac{b_{\Lambda \Sigma_c^{*0}} g_{\Lambda_c^+ \Sigma_c^{*0} \rho^+}}{m_\Lambda - m_{\Sigma_c^{*0}}}$$

$$B_1^{\text{pole}} = -\left(\frac{g_{\Sigma^+ \Lambda \rho^+} a_{\Sigma^+ \Lambda_c^+}}{m_{\Lambda_c^+} - m_{\Sigma^*}} + \frac{a_{\Lambda \Sigma_c^0} g_{\Lambda_c^+ \Sigma_c^0 \rho^+}}{m_\Lambda - m_{\Sigma_c^0}} \right)$$

H. Y. Cheng and B. Tseng, Phys. Rev. D **46**, 1042 (1992)

TABLE I. Numerical values of the predicted s- and p-wave amplitudes of $\Lambda_c^+ \to B + P$ decays in units of $G_F \cos^2\theta_C \times 10^{-2}$ GeV^2. The theoretical and experimental branching ratios (in percent) and the predicted α asymmetry parameter are given in the last three columns. The lifetime of the charmed baryon Λ_c^+ is taken to be 1.91×10^{-13} s (Ref. [25]).

Reaction	$A^{\rm fac}$	$A^{\rm pole}$	$A^{\rm tot}$	$B^{\rm fac}$	$B^{\rm pole}$	$B^{\rm tot}$	α	(BR)$_{\rm theory}$	(BR)$_{\rm expt}$
$\Lambda_c^+ \to p\bar{K}^0$	-5.73	3.91	-1.82	14.33	3.23	17.56	-0.49	1.2	2.1 ± 0.6
$\Lambda_c^+ \to \Lambda\pi^+$	-5.40	1.95	-3.45	18.09	-4.87	13.22	-0.96	0.87	0.8 ± 0.3
$\Lambda_c^+ \to \Sigma^0\pi^+$	0	2.44	2.44	0	14.63	14.63	0.83	0.72	0.80 ± 0.35
$\Lambda_c^+ \to \Sigma^+\pi^0$	0	-2.44	-2.44	0	-14.63	-14.63	0.83	0.72	

TABLE II. Same as Table I except for $\Lambda_c^+ \to B + V$ decays. The upper (lower) entry is for $\beta = 0(\frac{3}{4})$.

Reaction	$A_1^{\rm fac}$	$A_1^{\rm pole}$	$A_2^{\rm fac}$	$A_2^{\rm pole}$	$B_1^{\rm fac}$	$B_1^{\rm pole}$	$B_2^{\rm fac}$	$B_2^{\rm pole}$	α	(BR)$_{\rm theory}$
$\Lambda_c^+ \to \Lambda\rho^+$	-8.64	0	-0.71	0	-13.33	0	2.99	0	-0.19	2.6
	-8.64	0.36	-0.71	0	-13.33	0.40	2.99	0	-0.19	2.3

current algebra

$$B(\Lambda_c^+ \to \Sigma^0\pi^+) = 1.7\%\ ,\quad \alpha = -0.49$$

H. Y. Cheng and B. Tseng, Phys. Rev. D **46**, 1042 (1992).

H. Y. Cheng, X. W. Kang, and F. Xu, Phys. Rev. D 97, 074028 (2018).

baryon poles, respectively. It is known that the pole model is reduced to current algebra in the soft pseudoscalar-meson limit. The great advantage of current algebra is that the evaluation of

resonances which are not well understood in the quark model. Nevertheless, the use of the pole model is very general and is not limited to the soft meson limit and to the pseudoscalar-meson final state. For example, current algebra is not applicable to the decays $\mathcal{B}_c \to \mathcal{B} + V$. However,

knowledge of the negative-parity baryon resonances. The empiric fact that current algebra seems to work reasonably well for $\Lambda_c^+ \to \mathcal{B} + P$ is a bit surprising and annoying since the pseudoscalar meson produced in Λ_c^+ decays is generally far from being soft. We plan to examine this important issue and the pole model in a separate work.

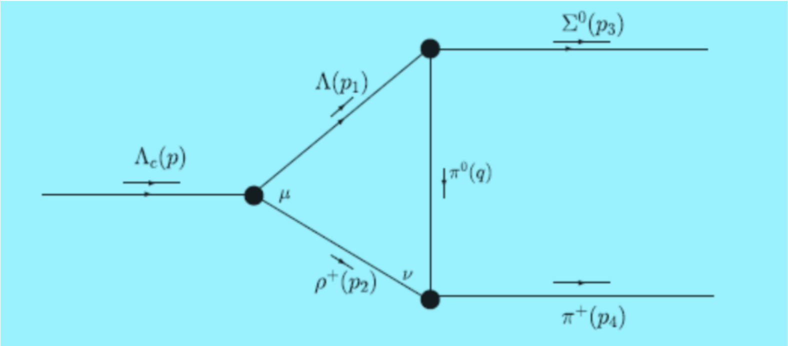
既然pole model更合理，那我们是否还有别的办法让不对称参数α的符号改变，而分支比基本不变

4. 末态相互作用的贡献

我们建议末态相互作用和直接过程（可因子化和不可因子化）的干涉

the direct transition of $\Lambda_c \to \Sigma\pi$

the portal $\Lambda_c \to \Lambda\rho \to \Sigma\pi$



理论计算$\Lambda_c \to \Lambda\rho$的分支比接近3%,实验的上限小于6%

The total amplitude of the practical transition $\Lambda_c \to \Sigma\pi$

$$\begin{aligned} M &= M^{\rm DIR} + M^{\rm FSI}, \\ &= i\bar{U}_\Sigma[A^{\rm DIR} - B^{\rm DIR}\gamma_5]U_{\Lambda_c} + i\bar{U}_\Sigma[A^{\rm FSI} - B^{\rm FSI}\gamma_5]U_{\Lambda_c} \\ &= i\bar{U}_\Sigma[A - B\gamma_5]U_{\Lambda_c}, \end{aligned}$$

直接衰变的结果我们用pole model计算的结果，末态相互作用需要计算一下

$$M_a^{\rm FSI} = \frac{1}{2}\int \frac{d\mathbf{p}_1}{(2\pi)^3 2E_1}\frac{d\mathbf{p}_2}{(2\pi)^3 2E_2}(2\pi)^4\delta(p - p_1 - p_2)\mathcal{M}^{\rm DIR}[\Lambda_c \to \Lambda\rho]\mathcal{M}[\Lambda\rho \to \Sigma\pi]$$

The relevant effective interactions are

$$\mathcal{L}_{\Lambda\Sigma\pi} = g_{\Lambda\Sigma\pi}\bar{\psi}_\Sigma\gamma_5\psi_\Lambda\pi,$$
$$\mathcal{L}_{\rho\pi\pi} = g_{\rho\pi\pi}(\partial_\mu\pi^0\pi^+\rho^{-\mu} - \partial_\mu\pi^+\pi^0\rho^{-\mu})$$

C. W. Shen, F. K. Guo, J. J. Xie, and B. S. Zou, Nucl. Phys. **A954**, 393 (2016).

顶点处的形状因子

$$F(q^2, m_P^2) = \frac{\Lambda_1^2 - m_P^2}{\Lambda_1^2 - q^2},$$

TABLE IV. $A^{\rm FSI}$ and $B^{\rm FSI}$ in $M_a^{\rm FSI}$ (in units of $G_F V_{cs} V_{ud} \times 10^{-2}$ GeV^2).

Λ_1	$A^{\rm FSI}$	$B^{\rm FSI}$
0.8 GeV	−3.26 (−3.12)	2.75 (2.63)
1.0 GeV	−4.68 (−4.48)	5.17 (4.95)

Reaction	$A^{\rm fac}$	$A^{\rm pole}$	$A^{\rm tot}$	$B^{\rm fac}$	$B^{\rm pole}$	$B^{\rm tot}$	α
$\Lambda_c^+ \to \Sigma^0 \pi^+$	0	2.44	2.44	0	14.63	14.63	0.83
$\Lambda_c^+ \to \Sigma^+ \pi^0$	0	−2.44	−2.44	0	−14.63	−14.63	0.83

TABLE V. Theoretical total results of $\Lambda_c \to \Sigma^0\pi^+$ where A and B are in units of $G_F V_{cs} V_{ud} \times 10^{-2}$ GeV^2 and Γ is in units of 10^{-14} GeV.

Λ_1	A	B	α	Γ
0.8 GeV	−1.02 (−0.88)	17.38 (17.26)	−0.29 (−0.25)	2.95 (2.89)
1.0 GeV	−2.44 (−2.24)	19.80 (19.58)	−0.64 (−0.60)	4.24 (4.07)

实验分宽度的中心值是4.08×10^{-14}GeV

Parameters	$\Lambda_c^+ \to pK_S^0$	$\Lambda\pi^+$	$\Sigma^+\pi^0$	$\Sigma^0\pi^+$
α_{BP}^+	$0.18 \pm 0.43 \pm 0.14$	$-0.80 \pm 0.11 \pm 0.02$	$-0.57 \pm 0.10 \pm 0.07$	$-0.73 \pm 0.17 \pm 0.07$

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讨论：

1. 实验上测得 $\Lambda_c \to \Sigma^+\pi^0$ 和 $\Lambda_c \to \Sigma^0\pi^+$ 的中心值在分开，而理论计算目前还没有差异
2. 是否 Λ_c 其它类似的衰变过程的也可以用同样的机制来解释

谢谢大家！