Nonleptonic decays of heavy baryons

– the perspective of theory –

Stefan Groote

Institute of Physics, University of Tartu, Estonia

March 6th, 2023

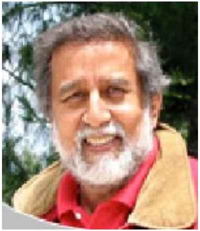
Nonleptonic decays of hyperons

1966: F. Hussain and P. Rotelli

Semi-phenomenological analysis
of nonleptonic hyperon decays
Il Nuovo Cimento A **44** (1966) 1047–1054

1972: J.G. Körner and T. Gudehus

Nonleptonic hyperon decays in a
current–current quark model
Il Nuovo Cimento **11A** (1972) 597–617



Nonleptonic decays of charmed baryons

1979: J.G. Körner, G. Kramer, J. Willrodt

Exploratory quark model calculation of two-body and quasi-two-body non-leptonic charm baryon decays
Z. Phys. C **2** (1979) 117

1992: J.G. Körner and M. Krämer

Updated and improved quark model analysis of two-body Cabibbo favoured non-leptonic decays of charmed baryons
Z. Phys. C **55** (1992) 659

A review of 196 nonleptonic baryonic decays

Eur. Phys. J. C (2022) 82:297
https://doi.org/10.1140/epjc/s10052-022-10224-0

THE EUROPEAN PHYSICAL JOURNAL C

Review

Topological tensor invariants and the current algebra approach: analysis of 196 nonleptonic two-body decays of single and double charm baryons – a review

Stefan Groote[1,a], **Jürgen G. Körner**[2]

[1] Füüsika Instituut, Tartu Ülikool, W. Ostwaldi 1, 50411 Tartu, Estonia
[2] PRISMA Cluster of Excellence, Institut für Physik, Johannes-Gutenberg-Universität, Staudinger Weg 7, 55099 Mainz, Germany

Received: 29 December 2021 / Accepted: 7 March 2022

The research presented in this paper was begun while JGK was visiting the Quaid-y-Azam University in Islamabad in 2006. His thanks go to Jamil Aslam, Alimjian Kadeer and the late Faheem Hussain† for their participation in the early stages of this work. ... The almost finished manuscript was finalized by SG in thankful remembrance of his deceased collaborator and friend JGK.

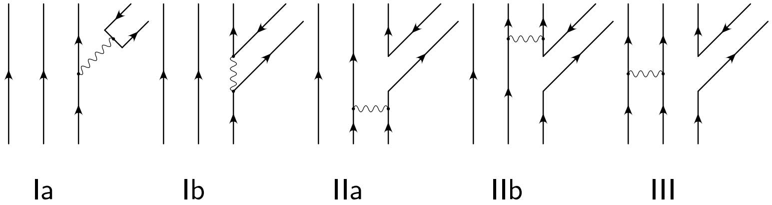
BESIII collaboration at the Beijing e^+e^- collider BEPCII

- 2015: detection of Λ_c^+ pair production opened new era
  BESIII Collaboration, Phys. Rev. Lett. **116** (2016) 052001
- asymmetry parameters for $\Lambda_c^+ \to pK_S^0, \Lambda^0\pi^+, \Sigma^+\pi^0, \Sigma^0\pi^+$
  BESIII Collaboration, Phys. Rev. D **100** (2019) 072004
- measurement of the SCS processes $\Lambda_c^+ \to p\eta, p\pi^0$
  BESIII Collaboration, Phys. Rev. D **95** (2017) 111102
- identification of $\Lambda_c^+ \to nK_s^0\pi^+$ raised hope
  to measure also decays with neutrons
  BESIII Collaboration, Phys. Rev. Lett. **118** (2017) 112001
- upgrade of BEPCII: Λ_c^+ production rate by factor 16
  BESIII Collaboration, Chin. Phys. C **44** (2020) 040001
- energy increase up to $4.9\,\mathrm{GeV}$: Σ_c pairs
- energy increase up to $4.95\,\mathrm{GeV}$: Ξ_c^+ and Ξ_c^0 pairs

Belle Collaboration, LHCb Collaboration

- tagging techniques allow for absolute branching ratios
  Belle Collaboration, Phys. Rev. Lett. **113** (2014) 042002
- measurements of absolute branching ratios of Ξ_c^0, Ξ_c^+
  Belle Collaboration, Phys. Rev. Lett. **122** (2019) 082001
  Belle Collaboration, Phys. Rev. D **100** (2019) 031101
- confirmation of $\Lambda_c^+ \to p\eta, p\pi^0$
  Belle Collaboration, Phys. Rev. D **103** (2021) 072004
- possibility to measure DCS decay $\Xi_c^+ \to p\phi$
  LHCb Collaboration, JHEP **1904** (2019) 084
- charm conserving SCS decay $\Xi_c^0 \to \Lambda_c^+\pi^-$
  LHCb Collaboration, Phys. Rev. D **102** (2020) 071101
- double charmed baryon two-body decay $\Xi_{cc}^{++} \to \Xi_c^+\pi^+$
  LHCb Collaboration, Phys. Rev. Lett. **121** (2018) 162002

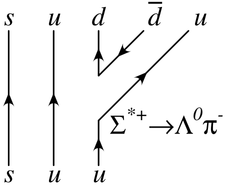
Contributing diagrams



current × current quark model

Description of nonleptonic two-body decays by five generic quark diagrams. To compare with: decay $\Sigma^{*+} \to \Lambda^0 + \pi^+$ with SU(3) coupling $B_{10} \to B_8 + M_8$ described by invariants

$$\tilde{I}_1 = B^{a[bc]} B_{a[bc']} M^{c'}_c , \quad \tilde{I}_2 = B^{a[bc]} B_{b[c'a]} M^{c'}_c$$



Effective weak current–current Hamiltonian

- $\Delta C = 1$ Cabibbo favoured (CF) decays

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{2\sqrt{2}} V_{cs} V_{ud}^* (c_+ \mathcal{O}_+ + c_- \mathcal{O}_-) + H.c.$$

$$\mathcal{O}_\pm = (\bar{s}c)(\bar{u}d) \pm (\bar{u}c)(\bar{s}d),\ (\bar{q}_1 q_2) \equiv \bar{q}_1 \gamma^\mu (1 - \gamma_5) q_2$$

- $\Delta C = 1$ singly Cabibbo suppressed (SCS) decays

$$\mathcal{H}_{\text{eff}}(a) = \frac{G_F}{2\sqrt{2}} V_{cs} V_{us}^* (c_+ \mathcal{O}_+(a) + c_- \mathcal{O}_-(a)) + H.c.$$

$$\mathcal{H}_{\text{eff}}(b) = \frac{G_F}{2\sqrt{2}} V_{cd} V_{ud}^* (c_+ \mathcal{O}_+(b) + c_- \mathcal{O}_-(b)) + H.c.$$

$$\mathcal{O}_\pm(a) = (\bar{s}c)(\bar{u}s) \pm (\bar{u}c)(\bar{s}s),\ \mathcal{O}_\pm(b) = (\bar{d}c)(\bar{u}d) \pm (\bar{u}c)(\bar{d}d)$$

Effective weak current–current Hamiltonian (cont.)

- $\Delta C = 1$ doubly Cabibbo suppressed (DCS) decays

$$\mathcal{H}_{\rm eff}(c) = \frac{G_F}{2\sqrt{2}} V_{cd} V_{us}^* (c_+ \mathcal{O}_+(c) + c_- \mathcal{O}_-(c)) + H.c.$$

$\mathcal{O}_\pm(c) = (\bar{d}c)(\bar{u}s) \pm (\bar{u}c)(\bar{d}s)$

- $\Delta C = 0$ singly Cabibbo suppressed (SCS) decays

$$\mathcal{H}_{\rm eff}(a') = \frac{G_F}{2\sqrt{2}} V_{us} V_{ud}^* (c_+ \mathcal{O}_+(a') + c_- \mathcal{O}_-(a')) + H.c.$$

$$\mathcal{H}_{\rm eff}(b') = \frac{G_F}{2\sqrt{2}} V_{cd} V_{cs}^* (c_+ \mathcal{O}_+(b') + c_- \mathcal{O}_-(b')) + H.c.$$

$\mathcal{O}_\pm(a') = (\bar{u}s)(\bar{d}u) \pm (\bar{d}s)(\bar{u}u)$, $\mathcal{O}_\pm(b') = (\bar{d}c)(\bar{c}s) \pm (\bar{c}c)(\bar{d}s)$

Körner–Pati–Woo (KPW) theorem

- Because of unitarity, with Wolfenstein parametrisation one has $V_{cs}V_{us}^* = -V_{cd}V_{ud}^* + O(\lambda^4)$ and $V_{cd}V_{cs}^* = -V_{us}V_{ud}^* + O(\lambda^4)$ $\Rightarrow$ SCS = SCSa − SCSb
- diagrams Ia and Ib factorisable, remaining (IIa, IIb, III) nonfactorisable W-exchange diagrams
- W-exchange contributions are related to the operator $\mathcal{O}_- = (\bar{q}_1 q_2)(\bar{q}_3 q_4) - (\bar{q}_3 q_2)(\bar{q}_1 q_4)$ only (KPW theorem)
  J. G. Körner, Nucl. Phys. B **25** (1971) 282–290
  J. C. Pati and C. H. Woo, Phys. Rev. D **3** (1971) 2920
- ground state transitions $1/2^+ \to 1/2^+ + 0^-(1^-)$ in $\mathcal{H}_{\rm eff}(\mathcal{O}_-)$ induced by antisymmetric flavour-changing tensor $H_{[q_1 q_3]}^{[q_2 q_4]}$
- diagrams Ia, Ib $\to (I_1^-, I_2^-)$, diagram IIa $\to (I_3, I_4)$, diagram IIb $\to (\hat{I}_3, \hat{I}_4)$, diagram III $\to I_5$.

Seven topological tensor invariants

$$I_1^-(\ell,\ell') = B_\ell^{a[bc]} B^{\ell'}_{a[bc']} M^d_{d'} H^{[c'd']}_{[cd]}$$

$$I_2^-(\ell,\ell') = B_\ell^{a[bc]} B^{\ell'}_{b[c'a]} M^d_{d'} H^{[c'd']}_{[cd]}$$

$$I_3(\ell,\ell') = B_\ell^{a[bc]} B^{\ell'}_{a[b'c']} M^d_c H^{[c'b']}_{[db]}$$

$$I_4(\ell,\ell') = B_\ell^{b[ca]} B^{\ell'}_{a[b'c']} M^d_c H^{[c'b']}_{[db]}$$

$$\hat{I}_3(\ell,\ell') = B_\ell^{a[bc]} B^{\ell'}_{a[b'c']} M^{c'}_d H^{[db']}_{[cb]}$$

$$\hat{I}_4(\ell,\ell') = B_\ell^{a[bc]} B^{\ell'}_{b'[c'a]} M^{c'}_d H^{[db']}_{[cb]}$$

$$I_5(\ell,\ell') = B_\ell^{a[bc]} B^{\ell'}_{a'[b'c']} M^{c'}_c H^{[a'b']}_{[ab]}$$

for baryonic transition $\ell' \to \ell$

- u, d, s, c $= 1, 2, 3, 4$
- summation over quark labels
- Jacobi identity used: $B^\ell_{a[bc]} + B^\ell_{b[ca]} + B^\ell_{c[ab]} = 0$
- rearrangement of indices
- $I_5'(\ell,\ell') = B_\ell^{a[bc]} B^{\ell'}_{b'[c'a']} M^{c'}_c H^{[a'b']}_{[ab]}$ equal to $I_5(\ell,\ell')$
- tadpole-type $B_\ell^{a[bc]} B^{\ell'}_{a[bc]} M^d_{d'} H^{[cd']}_{[cd]}$ vanishes for $\Delta C = 1$

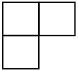
Ground state charmed baryon states $J^P = 1/2^+$

Notation	content	SU(3)	(I, I_3)	S	C	Mass [MeV]
Λ_c^+	$c[ud]$	$\bar{\mathbf{3}}$	$(0,0)$	0	1	2286.46 ± 0.14
Ξ_c^+	$c[su]$	$\bar{\mathbf{3}}$	$(1/2, 1/2)$	-1	1	2467.95 ± 0.19
Ξ_c^0	$c[sd]$	$\bar{\mathbf{3}}$	$(1/2, -1/2)$	-1	1	2470.99 ± 0.40
Σ_c^{++}	cuu	$\mathbf{6}$	$(1,1)$	0	1	2453.97 ± 0.14
Σ_c^+	$c\{ud\}$	$\mathbf{6}$	$(1,0)$	0	1	2452.9 ± 0.4
Σ_c^0	cdd	$\mathbf{6}$	$(1,-1)$	0	1	2453.75 ± 0.14
$\Xi_c^{\prime +}$	$c\{su\}$	$\mathbf{6}$	$(1/2, 1/2)$	-1	1	2578.4 ± 0.5
$\Xi_c^{\prime 0}$	$c\{sd\}$	$\mathbf{6}$	$(1/2, -1/2)$	-1	1	2579.2 ± 0.5
Ω_c^0	css	$\mathbf{6}$	$(0,0)$	-2	1	2695.2 ± 1.7
Ξ_{cc}^{++}	ccu	$\mathbf{3}$	$(1/2, 1/2)$	0	2	3621.2 ± 0.7
Ξ_{cc}^+	ccd	$\mathbf{3}$	$(1/2, -1/2)$	0	2	3621
Ω_{cc}^+	ccs	$\mathbf{3}$	$(0,0)$	-1	2	3710

SU(4) representations

- not concerned with the 20 $J^P = 3/2^+$ $(C = 0, 1, 2, 3)$ ground state baryons belonging to the **20** representation of $SU(4)$, as these are prevented from contributing as intermediate states by the KPW theorem.

- Together with light baryons p, n, Λ^0, Σ^+, Σ^0, Σ^-, Ξ^+, Ξ^0 the $8 + 12 = 20$ $J^P = 1/2^+$ ground state baryons belong to the **20'** representation of $SU(4)$



HQET decays

- nine antitriplet and sextet single charmed baryons in **21** representation of spin–flavour $SU(6) \supset SU(2) \times SU(3)$,

$$\mathbf{21} \subset \mathbf{1} \otimes \overline{\mathbf{3}} \oplus \mathbf{3} \otimes \mathbf{6}$$

- Σ_c^{++}, Σ_c^{+}, Σ_c^{0} decay dominantly via one-pion emission
- $\Xi_c^{\prime +}$, $\Xi_c^{\prime 0}$ decay dominantly via one-photon emission
- remaining Λ_c^+, Ξ_c^+, Ξ_c^0, Ω_c^0, Ξ_{cc}^{++}, Ξ_{cc}^{+}, Ω_{cc}^{+} decay via weak interactions, mostly to $J^P = 1/2^+$ baryons and $J^P = 0^-$ mesons.

This is the main concern of this talk.

$$\mathcal{M}(B_i \xrightarrow{H} B_f M_k) = \mathcal{M}_{fki} = \sum_j I_{fki}^j \mathcal{T}_j \qquad j = 1^-, 2^-, 3, 4, \hat{3}, \hat{4}, 5$$

SU(3) properties of $\mathcal{H}_{\rm eff}(\mathcal{O}_-)$

		Y	I_3	$SU(3)$	ΔI	ΔU	ΔU_3	ΔV
CF	$H^{[su]}_{[cd]}$	$2/3$	-1	$\mathbf{6}$	1	1	1	0
SCS	$H^{[su]}_{[cs]}$	$-1/3$	$-1/2$	$\mathbf{6}\oplus\overline{\mathbf{3}}$	$1/2$	$1,0$	$0,\ 0$	$1/2$
	$H^{[du]}_{[cd]}$	$-1/3$	$-1/2$	$\mathbf{6}\oplus\overline{\mathbf{3}}$	$1/2$	$1,0$	$0,0$	$1/2$
	$H^{[su]}_{[cs]}-H^{[du]}_{[cd]}$	$-1/3$	$-1/2$	$\mathbf{6}$	$1/2$	1	0	$1/2$
DCS	$H^{[du]}_{[cs]}$	$-4/3$	0	$\mathbf{6}$	0	1	-1	1
$\Delta C=0$	$H^{[ud]}_{[su]}$	-1	$1/2$	$\mathbf{8}$	$1/2$	1	-1	$1/2$
	$H^{[dc]}_{[cs]}$	-1	$1/2$	$\mathbf{8}$	$1/2$	1	-1	$1/2$

T. A. Kaeding, "Tables of SU(3) isoscalar factors,"
Atom. Data Nucl. Data Tabl. **61** (1995) 233

Weight diagrams

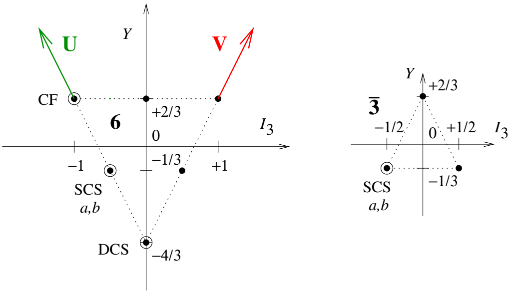


Figure: Weight diagrams of the sextet (left) and antitriplet (right) representation of the effective weak Hamiltonian. The locations of the CF, SCS and DCS transitions are marked by a circle dot symbol $\odot$.

An example

Charmed baryon decays $B_c(\overline{\mathbf{3}}) \xrightarrow{H(\mathbf{6})} B(\mathbf{8}) + M(\mathbf{8},\mathbf{1})$

SU(3) decomposition of the transitions

$$\overline{\mathbf{3}} \to \mathbf{6} \otimes \mathbf{8} \otimes \mathbf{8} = 3 \cdot \overline{\mathbf{3}} \oplus 4 \cdot \mathbf{6} \oplus 5 \cdot \overline{\mathbf{15}} \oplus \overline{\mathbf{15}}' \oplus \overline{\mathbf{21}} \oplus \overline{\mathbf{24}} \oplus 2 \cdot \overline{\mathbf{42}} \oplus \overline{\mathbf{60}}$$

represents decays of antitriplet charmed baryons Λ_c^+, Ξ_c^+ and Ξ_c^0

- SCS: cancellation of $\mathcal{H}_{\rm eff}(c \to s;\, s \to u)$ and $\mathcal{H}_{\rm eff}(c \to d;\, d \to u)$ leads to sextet $\mathbf{6}$
- $\overline{\mathbf{3}}$ appears three times (Kaeding notation) $\Rightarrow$
- three SU(3) invariant amplitudes, $7 - 3 = 4$ linear relations

$$I_1^- = I_2^- \qquad 2\hat{I}_3 + \hat{I}_4 = 0 \qquad I_3 + I_4 = 2I_5 \qquad 2I_1^- = I_3 + \hat{I}_3$$

An example (cont.)

				I_1^-	I_2^-	I_3	I_4	$\hat{I}_3$	$\hat{I}_4$	I_5
CF	$12\,\Lambda_c^+$	$\to$	$\Lambda^0\pi^+$	-2	-2	-2	$+4$	-2	$+4$	$+1$
	$4\sqrt{3}\,\Lambda_c^+$	$\to$	$\Sigma^0\pi^+$	0	0	$+2$	0	-2	$+4$	$+1$
	$4\sqrt{3}\,\Lambda_c^+$	$\to$	$\Sigma^+\pi^0$	0	0	-2	0	$+2$	-4	-1
	$4\sqrt{3}\,\Lambda_c^+$	$\to$	$\Sigma^+\eta_\omega$	0	0	-2	0	-2	$+4$	-1
	$2\sqrt{6}\Lambda_c^+$	$\to$	$\Sigma^+\eta_\phi$	0	0	-2	$+2$	0	0	0
	$12\Lambda_c^+$	$\to$	$\Sigma^+\eta_8$	0	0	$+2$	-4	-2	$+4$	-1
	$6\sqrt{2}\Lambda_c^+$	$\to$	$\Sigma^+\eta_1$	0	0	-4	$+2$	-2	$+4$	-1
	$2\sqrt{6}\,\Lambda_c^+$	$\to$	$p\bar{K}^0$	$+1$	$+1$	$+2$	-2	0	0	0
	$2\sqrt{6}\,\Lambda_c^+$	$\to$	Ξ^0K^+	0	0	0	-2	0	0	-1

... and a lot more decays (in total: 196)

S- and P-wave amplitudes

Current algebra approach

$$\langle B_f M_k | \mathcal{H}_{\rm eff} | B_i \rangle = \bar{\psi}_f (\mathcal{A}_{fki} - \mathcal{B}_{fki} \gamma_5) \psi_i$$

parity violating S-wave amplitude

$$\mathcal{A}_{fki} = \mathcal{A}_{fki}^{\rm fac} + \mathcal{A}_{fki}^{\rm pole} + \mathcal{A}_{fki}^{\rm com}$$

parity conserving P-wave amplitude

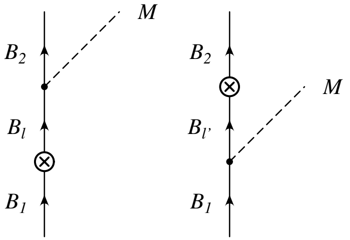
$$\mathcal{B}_{fki} = \mathcal{B}_{fki}^{\rm fac} + \mathcal{B}_{fki}^{\rm pole} + \mathcal{B}_{fki}^{\rm com}$$

- factorising contributions related to invariants I_1^- and I_2^-
- nonfactorising pole and commutator contributions related to the remaining invariants I_3, I_4, $\hat{I}_3$, $\hat{I}_4$ and I_5

Parity violating S-wave amplitude $\mathcal{A}^{\rm com}_{fki}$

$$\begin{aligned}
\mathcal{A}^{\rm com}_{fki} &= \frac{\sqrt{2}}{f_k}\langle B_f|[M_k,\mathcal{H}^{\rm pc}_{\rm eff}]|B_i\rangle \\
&= \frac{\sqrt{2}}{f_k}\Big(\sum_\ell\langle B_f|M_k|B_\ell\rangle\langle B_\ell|\mathcal{H}^{\rm pc}_{\rm eff}|B_i\rangle \\
&\qquad -\sum_{\ell'}\langle B_f|\mathcal{H}^{\rm pc}_{\rm eff}|B_{\ell'}\rangle\langle B_{\ell'}|M_k|B_i\rangle\Big) \\
&= \mathcal{A}^{\rm com}_{fki}(s)-\mathcal{A}^{\rm com}_{fki}(u) \\
&\sim \sum_\ell I^f_{fk\ell}I^{\rm pc}_{\ell i}-\sum_{\ell'}I^{\rm pc}_{f\ell'}I^f_{\ell' ki}
\end{aligned}$$

(f_k pseudoscalar coupling)



s-channel contribution (left)
u-channel contribution (right)

f-type matrix element $I^f_{\ell' k\ell}=\langle B_{\ell'}|M_k|B_\ell\rangle=4(\tilde I_1)_{\ell' k\ell}+2(\tilde I_2)_{\ell' k\ell}$
composed of strong tensor invariants $\tilde I_1$ and $\tilde I_2$ (cf. before)

Orthonormality and completeness

Orthonormality relation

$$\sum_{k,m,n} B_\ell^{k[mn]} B^{\ell'}_{k[mn]} = \delta_\ell^{\ell'}$$

Completeness relation

$$\sum_\ell B^\ell_{k[mn]} B_\ell^{b[cd]} = \frac{2}{6}(\delta_k^b \delta_m^c \delta_n^d - \delta_k^b \delta_m^d \delta_n^c)$$
$$-\frac{1}{6}(\delta_m^b \delta_n^c \delta_k^d - \delta_m^b \delta_n^d \delta_k^c) - \frac{1}{6}(\delta_n^b \delta_k^c \delta_m^d - \delta_n^b \delta_k^d \delta_m^c)$$

used in order to expand s- and u-channel into tensor invariants, e.g.

$$(\tilde{I}_1)_{fk\ell} I^{\rm pc}_{\ell\, i} = B_f^{a[bc]} (M_k)_c^{c'} B^\ell_{a[bc']} B_\ell^{r[st]} B^i_{r[a'b']} H^{[a'b']}_{[st]} = \tfrac{2}{3} I_3 - \tfrac{1}{3} I_4 + \tfrac{2}{3} I_5$$

Parity conserving P-wave amplitude $\mathcal{B}^{\rm pole}_{fki}$

- Parity violating pole contribution neglected,

$$\mathcal{A}^{\rm pole}_{fki} = -\sum_{\ell} \frac{g_{fk\ell}\, b_{\ell\, i}}{m_i - m_\ell} - \sum_{\ell'} \frac{b_{f\ell'}\, g_{\ell' ki}}{m_f - m_{\ell'}} = \mathcal{A}^{\rm pole}_{fki}(s) + \mathcal{A}^{\rm pole}_{fki}(u)$$

as $b_{\ell\ell'} = \langle B_\ell | \mathcal{H}^{\rm pv}_{\rm eff} | B_{\ell'} \rangle \ll \langle B_\ell | \mathcal{H}^{\rm pc}_{\rm eff} | B_{\ell'} \rangle = a_{\ell\ell'}$

- For the same reason, partity conserving commutator skipped,

$$\mathcal{B}^{\rm com}_{fki} \sim \left(\sum_{\ell} I^f_{fk\ell} I^{\rm pv}_{\ell i} - \sum_{\ell'} I^{\rm pv}_{f\ell'} I^f_{\ell' ki} \right)$$

- Remaining is parity conserving P-wave amplitude

$$\mathcal{B}^{\rm pole}_{fki} = \sum_{\ell} \frac{g_{fk\ell}\, a_{\ell\, i}}{m_i - m_\ell} + \sum_{\ell'} \frac{a_{f\ell'}\, g_{\ell' ki}}{m_f - m_{\ell'}} = \mathcal{B}^{\rm pole}_{fki}(s) + \mathcal{B}^{\rm pole}_{fki}(u)$$

(Goldberger–Treiman relation $g_{fk\ell} = \sqrt{2}(m_f + m_\ell) g^A_{fk\ell}/f_k$)

$$= \frac{\sqrt{2}}{f_k} \left(\sum_{\ell} g^A_{fk\ell} \frac{m_f + m_\ell}{m_i - m_\ell} a_{\ell\, i} + \sum_{\ell'} a_{f\ell'} \frac{m_i + m_{\ell'}}{m_f - m_{\ell'}} g^A_{\ell' ki} \right)$$

Conclusions

- Further calculations done with quark models
- Calculation of branching ratios feasible from algebra
- Statments about forbidden decays (within the model)
- Development of sum rules

Problem

$\Xi_c^+ \to \Xi'^0(1530)\pi^+$ forbidden by KPW theorem if Ξ_c^+ belongs strictly to the antitriplet $\overline{\mathbf{3}}$ but measured by Belle with clear signal

M. Sumihama *et al.* [Belle Coll.], Phys. Rev. Lett. **122** (2019) 072501

C.-Q. Geng, C.-W. Liu, T.-H. Tsai, Phys. Rev. D **99** (2019) 114022

Solution

Substancial portion of Ξ_c^+ made of the sextet **6**

C.-Q. Geng, X.-N. Jin, C.-W. Liu, Phys. Lett. B **838** (2023) 137736

(correspondence with Chia-Wei Liu, Nov. 2022)

- Refine the covariantized constituent quark model and extend it to include also SCS and DCS decays of single charmed baryons

  J. G. Körner and M. Krämer, Z. Phys. C **55** (1992) 659

- Work on charmed baryon pair production in e^+e^- collisions
- Charmed baryon production via Intrinsic Charm (IC) mechanism

  S. J. Brodsky, S. Groote, S. Koshkarev, Eur. Phys. J. C **78** (2018) 483

- Low energy interactions and baryonic states calculated with the non-local Nambu–Jona-Lasinio model derived from QCD

  M. Frasca, A. Ghoshal, S. Groote, Phys. Rev. D **104** (2021) 114036
  – ¨ – , Nucl. Part. Phys. Proc. **318–323** (2022) 138–141
  – ¨ – , Nucl. Part. Phys. Proc. **324–329** (2023) 85–89
  – ¨ – , 2202.14023 [hep-ph]

  A. Chatterjee, – ¨ – , 2302.10944 [hep-ph]

Thank you for your interest!