Challenges in Hyperon Decays

DC at pbar 2000
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IIT

* Nonleptonic Decays
  1. $\Delta I = \frac{1}{2}$ rule
  2. Nonleptonic enhancement
  3. S-wave/P-wave puzzle
* CP-violation —— see Valencia
* Semi-leptonic Decays —— see Swallow
* Radiative Decays
  1. Hara theorem ⟶ asymmetry
  2. Relative rates
* magnetic momentum

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* Theory :

(a) Models ⟶ [Quark models, Bag models, QCD Sumrules, Chiral model

(b) Testing "theory" : Heavy baryon chiral perturbation theory (HBCPT)

L'

(4) Nonleptonic decay

$\Lambda \to p\pi^-$ $\Sigma^+ \to n\pi^+$ $\Xi \to \Lambda\pi^0$

$\Lambda \to n\pi^0$ $\Sigma^+ \to p\pi^0$ $\Xi^- \to \Lambda\pi^-$

$\Sigma^- \to n\pi^-$

$B \to B'\pi$ $$\mathcal{M} = \bar{u}(p')\left(\overset{\text{P violating, S-wave}}{A} + \underset{\text{P conserving, P-wave}}{B\gamma_5}\right)u(p)$$

(1) $\Delta I = \frac{1}{2}$ rule

* Isospin decomposition

$$A(\Lambda \to p\pi^-) = \sqrt{2}\, A_\Lambda^{(1)} - A_\Lambda^{(3)} \quad \text{etc.}$$

Similarly for B

$\Rightarrow$ $\Delta I = \frac{1}{2}$ rule

$A(3/2)/A(1/2)$	S	P
Λ	0.014	0.006
Σ	-0.017	-0.047
Ξ	0.034	0.023

$\longrightarrow$ about the same level as kaon $\Delta I = \frac{1}{2}$ rule

* $\Delta I = \frac{1}{2}$ rule may be something general about nonlepton physics

* kaon $\Delta I = \frac{1}{2}$ rule not completely understood yet

* For hyperon

① QCD short distance enhancement of $H_W^{\Delta I = \frac{1}{2}}$

→ factor of 3–4 enhancement

② Pati-Woo (1971), Miura-Minamikawa (1967) mechanism

If baryon ≡ (3 quarks) then antisymmetry of color wavefunction and the color property of $\Delta I = 3/2$ operator ⇒ only the $\Delta I = 1/2$ operator can mediate the transition $\langle B' | H_W | B \rangle$

$$\Rightarrow \langle B' | O^{\Delta I = 3/2} | B \rangle = 0$$

* $B \to B'$ matrix elements are not the only mechanism for $B \to B'\pi$ decay
* baryon ≡ (3 quark) may be too naive
* Same mechanism does not apply to kaon

* Overall, $\Delta I = 1/2$ rule is less of a problem for hyperon theoretically than for kaon.

(2) Non leptonic enhancement

Why $\Gamma(\Lambda \to p\pi^-)$ is about 10^3 larger than

$\Gamma(\Lambda \to p e^- \bar{\nu}_e)$

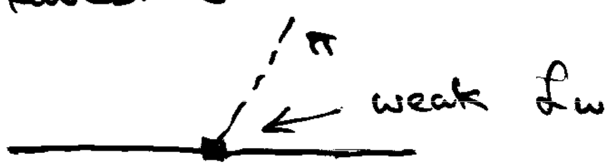
* Quark model + QCD
* Not too much recent attention

(3) S-wave / P wave problem

In chiral model or current algebra approach

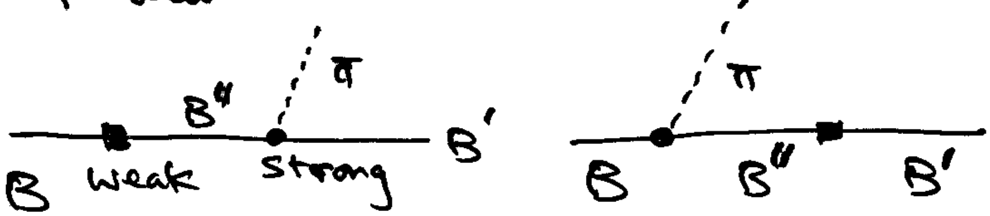
S-wave (A) is due to a contact term or

the lowest order term in Chiral Lagrangian



* same vertex does not contribute to P-wave (B)

* P-wave due to pole diagram



lowest order weak Lagrangian

$$\mathcal{L}_W^{(0)} = h_D \,\mathrm{Tr}\left(\bar{B}\{\lambda, B\}\right) + h_F \,\mathrm{Tr}\left(\bar{B}[\lambda, B]\right)$$

$\lambda \equiv \xi^{+}\lambda_6\,\xi$ $\qquad \xi^2 \equiv \Sigma$ = Goldstone matrix

* $\mathcal{L}_W^{(0)}$ contribute to A but not to B, directly
* h_D and h_F can be used to fit

  S-wave amplitudes quite well

  Especially $iA_{\Sigma^+ \to n\pi^+} = 0$ at this order

  while experimentally $A_{\Sigma^+ \to n\pi^+} \ll$ others
* Fit to A can be used to predict B (P-wave)

  amplitudes $\longrightarrow$ poor fit for many of $B \to B'\pi$
* One can also use h_D, h_F to fit P-wave

  then S-wave is poorly fit

Potential way out

* next order effective Lagrangian

  — too many parameters, non-unique fit
* $(\frac{1}{2})^-$ resonance or $(\frac{1}{2})^+$ Roper resonance

  as intermediate baryon B''

  — model dependence

Radiative decays

$* \quad \Sigma^+(uus) \rightarrow p^+(uud)\, \gamma$ BF $\sim (1.23 \pm 0.05) \times 10^{-3}$

neutral modes:

$\Sigma^0 \rightarrow n\, \gamma$ too hard to see due to $\Sigma^0 \rightarrow \Lambda^0 \gamma$

$\Xi^0 \rightarrow \Sigma^0 \gamma$ $(3.5 \pm 0.4) \times 10^{-3}$

$\Xi^0 \rightarrow \Lambda^0 \gamma$ $(1.06 \pm 0.16) \times 10^{-3}$

$\Lambda^0 \rightarrow n\, \gamma$ $(1.75 \pm 0.15) \times 10^{-3}$

$* \quad \Xi^- \rightarrow \Sigma^- \gamma$ $(1.27 \pm 0.23) \times 10^{-4}$

$\Sigma^0 \rightarrow \Lambda^0 \gamma$ 100% electromagnetic

$*$ are charged modes, between U spin doublets

General
$$A = \frac{-e}{M_B + M_{B'}} \underbrace{i \epsilon^{*\mu} q^\nu}_{\sim F^{\mu\nu}} \bar{u}(p') \sigma_{\mu\nu} (C + D\gamma_5) u(p)$$

C: P-conserving magnetic dipole transition M

D: P-violating electric dipole transition E1

$$\Gamma \propto |C|^2 + |D|^2$$

Asymmetry $A_\gamma = \dfrac{2 \,\mathrm{Re}(C^* D)}{|C|^2 + |D|^2}$ $\rightarrow$ need both C & D

6

Hara
PRL (1964)

Hara Theorem :

Assuming that the amplitudes are not singular in the $SU(3)_F$ limit, parity violating D amplitudes must vanish for decay between states of a U spin doublet in SU(3) limit !

$$\Rightarrow D_{\Sigma^+\to p^+\gamma} = D_{\Xi^-\to\Sigma^-\gamma} = 0$$

$$\Rightarrow A_\gamma(\Sigma^+\to p^+\gamma) = A_\gamma(\Xi^-\to\Sigma^-\gamma) = 0$$

* When SU(3) breaking are taken into account A_γ may be small and positive

Problem : Experimentally $A_\gamma(\Sigma^+\to p^+\gamma) = -0.76 \pm 0.08$
large and negative !!

Many papers questioned the validity of the assumptions that go into Hara theorem

Li & Liu, P.L.B (1987)
Gaillard, P.L.B (1988)
Lach & Zenczkowski, Int.J.M.P A (1995)
hep-ph/9911267
hep-ph/0003295

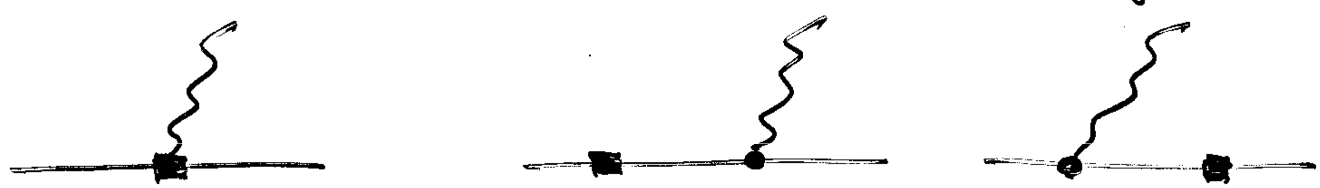
e.g. D may be singular in SU(3) limit.

Issues

① How to get large and <u>negative</u> A_γ for $\Sigma^+ \to p^+ \gamma$

② Relative rates

In lowest order Chiral model: diagram



(a)
direct emission

pole diagrams (b)

* (a) doesnot contribute at either C or D at lowest order

* (b) does not contribute to D (Lee-Swift theorem)

* (b) contribute to C but only to neutral modes

$\Rightarrow$ all $D = 0$

$C = D = 0$ for $\Sigma^+ \to p^+ \pi$ $\Xi^- \to \Sigma^- \pi$

* higher order Lagrangian may get the asymmetry but not likely to get the correct relative rate

* Look for new leading contribution

8

New leading contribution by resonance

① Decuplet $\frac{3}{2}^+$ $\subset$ $(\underset{SU(6)}{56}, \underset{\ell}{0^+})$

⟶ can contribute at loop level

⟶ higher order effect

→ negligible

② $\frac{1}{2}^-$ octet in $(70(SU(6)), \underset{\ell=1}{1^-})$

e.g. N(1535)
Λ(1405)

⟶ contribute to ~~B~~ D

LeYaouanc et. al. N.P.B(1979)
Gavela et. al P.L.B(1981)
Borasoy + Holstein P.R. D59 (1999) 054019
hep-ph/0005205
Zenczykowski hep-ph/9911267

③ Roper octet $\frac{1}{2}^+$
$N^*(1440)$ $\Lambda^*(1600)$
$\Sigma^*(1660)$ $\Xi^*(1620)$

⟶ Contribute to ~~A~~ C

⟶ correct the rate — fit relative rate

Chiral Perturbation Theory (ChPT)

* Use only the low energy (light mass) degrees of freedom to describe low energy scattering phenomena
* light mass particles → pseudo-Goldstone bosons
  → Lagrangian dictated by symmetry and spontaneously broken approximate $\underset{\text{chiral}}{\text{symmetry}}$
* Write down the most general Lagrangian consistent with symmetries
* Expansion in momentum and symmetry breaking parameters → infinite # of terms

  Perturbative expansion in $\frac{p}{\Lambda_\chi}$ and $\frac{m_s}{\Lambda_\chi}$
* Assume that only the first few terms in the expansion is important
* Fit the coupling constants of these terms using data → derive prediction

* ChPT works pretty well for mesons which are Goldstone boson and therefore light.
* Application to baryon present new problem. Baryons remain massive even in the chiral symmetric limit with $m_B \simeq \Lambda_\chi$ chiral symmetry breaking scale

⇒ In relativistic form

$$\frac{D_\mu B}{\Lambda_\chi} \text{ is of order one}$$

$$\Rightarrow \quad [D_{\mu_1}, [D_{\mu_2}, [D_{\mu_3} \cdots [D_{\mu_n} B] \cdots] \frac{1}{\Lambda_\chi^n} \sim 1 \quad \forall_n$$

⇒ infinite term at each order

* Way out: Heavy Baryon ChPT: do non-relativistic reduction such that the remaining momentum are all small momentum: expand in $\frac{1}{m_B}$

⇒ Become a double expansion in $\frac{1}{\Lambda_\chi}$ and $\frac{1}{m_B}$

Procedure:

* Start with a relativistic Lagrangian for baryons
* define $B_v \equiv e^{imv\cdot x} B \qquad v^\mu v_\mu = 1$
* define projections $H \equiv P_v^+ B_v \qquad h \equiv P_v^- B_v$

$$P_v^\pm \equiv \frac{1 \pm \not{v}}{2}$$

H: large component
h: small component

$p^\mu \equiv$ 4-momentum of B is decomposed into

$p^\mu = k^\mu - m v^\mu$ $\qquad$ m = average SU(3) singlet baryon mass

k^μ is the derivative on H
↳ small

* Expand $\mathcal{L}(B) \equiv \mathcal{L}(H, h)$ in H and h and integrate out h, expand the result in k

Reparametrization inv.

① p^μ is over-represented by k^μ and v^μ
⟶ arbitrariness

② Each relativistic term is expanded as many terms in $\left(\frac{1}{m}\right)^n$ ⟶ hidden relationship betw' terms

(3) reparametrization invariant makes sure that the non-relativistic Lagrangian still retains Lorentz invariant

<u>Two approaches</u> in constructing HBChPT Lagrangian

(1) Start with relativistic Lagrangian and do the reduction

$\longrightarrow$ have to make sure terms such as

$\mathrm{Tr}\left[B\,[D_{\mu_1}\cdots\ [D_{\mu_n}B]\cdots]\right]$ do not produce new relevant terms

(2) Start with non-relativistic form constructing the most general $\frac{1}{\Lambda_\chi}$ and $\frac{1}{M_B}$ expansion

$\longrightarrow$ have to check reparametrization inv.

— a mixed procedure may be best.

Application of HBChPT to radiative decays

Jenkin et. al. Nucl Phy B399 (1993) 69
Neufeld NP B403 (93) 166

→ use higher order loop effect to achieve a better fit of the relative rates

→ still can not explain $A_\gamma(\Sigma^+ \to p^+ \gamma)$

Bos et. al PR D51 (95) 6308
D54 (96) 3321
D57 (98) 4101

→ consider next order terms in HBChPT that contribute at tree level but was ignored before

→ can not get the relative rate

Borasoy + Holstein PRD59 (99) 054019
Borasoy + Muller hep-ph/0005262

→ Use lowest order chiral Lagrangian
But introduce new resonances into the chiral Lag.

$\frac{1}{2}^-$ octet $\in (70, 1^-)$

$\frac{1}{2}^+$ octet $\in$ Roper-type

$\frac{1}{2}^-$ octet resonance $\rightarrow$ contribute to D terms

$\frac{1}{2}^+$ octet resonances $\rightarrow$ ① contribute to C terms of charge modes

② correct the C terms of neutral modes

$\Rightarrow$ can fit all the relative rate and asymmetry of $\Sigma^+ \rightarrow p^+ \pi$

* Introduce resonances of $\Delta M_B \sim 400$ MeV $\sim m_s$ and new contribution of order $\frac{m_s}{\Delta M_B} \sim 1$

$\rightarrow$ ruin the nice property of the general ChPT

$\rightarrow$ downgrade the "theory" of HBChPT to a model.

$\rightarrow$ what is the proper way of including higher resonances into ChPT ? not clear yet

Summary

* There are many unsolved puzzles or unsatisfactory loose-ends still in hyperon physics
* HBChPT is a nice idea but may not work in some cases
* Effect of higher resonance may be needed to account for data
* How to consistently incorporate these resonances into the theory is still unknown ...