Exclusive Baryonic B Decays

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- History
- Two-body baryonic B decays
- Three-body baryonic B decays
- Radiative baryonic B decays
- Conclusions

History

Hadronic B decays can contain a baryon pair in the final state.

ARGUS ('87): $\mathcal{B}(B^- \to p\bar{p}\pi^-) = (3.7 \pm 1.9) \times 10^{-4}$

$$\mathcal{B}(\overline{B}^0 \to p\bar{p}\pi^+\pi^-) = (6.0 \pm 1.9) \times 10^{-4}$$

$\Rightarrow$ stimulate extensive studies (16 theory papers) during the years of 1988-92.

- pole model: Deshpande, Trampetic, Soni; Jarfi et al.
- QCD sum rule: Chernyak, Zhitnitsky
- diquark model: Ball, Dosch
- symmetry: He, McKeller, Wu; Sheikholeslami, Khanna

After 92' experimental and theoretical studies in baryonic B decays fade away; revived in recent years

Experimental status

Except for recently measured $\overline{B}^0 \to \Lambda_c^+ \bar{p}$ by Belle,

$$\mathcal{B}(\overline{B}^0 \to \Lambda_c^+ \bar{p}) \;=\; (2.19^{+0.56}_{-0.49} \pm 0.32 \pm 0.57) \times 10^{-5}$$

none of two-body baryonic B decays has been observed. The upper limits are:

Decay	CLEO	Belle	BaBar
$\overline{B}^0 \to p\bar{p}$	1.4×10^{-6}	1.2×10^{-6}	2.7×10^{-7}
$\overline{B}^0 \to \Lambda\bar{\Lambda}$	1.2×10^{-6}	1.0×10^{-6}	
$B^- \to \Lambda\bar{p}$	1.5×10^{-6}	2.2×10^{-6}	
$B^- \to \Sigma_c^0(2455)\bar{p}$	8.0×10^{-5}	9.3×10^{-5}	
$B^- \to \Sigma_{c1}^0(2520)\bar{p}$		4.6×10^{-5}	

Charmful Baryonic B Decays

Mode	Belle (10^{-4})	CLEO (10^{-4})
$\overline{B}^0 \to D^{*+} n\bar{p}$		$14.5^{+3.4}_{-3.0} \pm 2.7$
$\overline{B}^0 \to D^{*+} p\bar{p}\pi^-$		$6.5^{+1.3}_{-1.2} \pm 1.0$
$\overline{B}^0 \to D^{*0} p\bar{p}$	$1.20^{+0.33}_{-0.29} \pm 0.21$	
$\overline{B}^0 \to D^0 p\bar{p}$	$1.18 \pm 0.15 \pm 0.16$	
$B^- \to \Lambda_c^+ \bar{p}\pi^-\pi^0$		$18.1 \pm 2.9^{+2.2}_{-1.6} \pm 4.7$
$\overline{B}^0 \to \Lambda_c^+ \bar{p}\pi^+\pi^-$	$11.0 \pm 1.2 \pm 1.9 \pm 2.9$	$16.7 \pm 1.9^{+1.9}_{-1.6} \pm 4.3$
$B^- \to \Lambda_c^+ \bar{p}\pi^-$	$1.87^{+0.43}_{-0.40} \pm 0.28 \pm 0.49$	$2.4 \pm 0.6^{+0.19}_{-0.17} \pm 0.6$
$B^- \to \Sigma_c^{++} \bar{p}\pi^-\pi^-$	$\Sigma_c = \Sigma_c(2455)$	$2.8 \pm 0.9 \pm 0.5 \pm 0.7$
$B^- \to \Sigma_c^0 \bar{p}\pi^+\pi^-$		$4.4 \pm 1.2 \pm 0.5 \pm 1.1$
$\overline{B}^0 \to \Sigma_c^{++} \bar{p}\pi^-$	$2.38^{+0.63}_{-0.55} \pm 0.41 \pm 0.62$	$3.7 \pm 0.8 \pm 0.7 \pm 0.8$
$\overline{B}^0 \to \Sigma_c^0 \bar{p}\pi^+$	$0.84^{+0.42}_{-0.35} \pm 0.14 \pm 0.22 < 1.59$	$2.2 \pm 0.6 \pm 0.4 \pm 0.5$
$B^- \to \Sigma_c^0 \bar{p}\pi^0$		$4.2 \pm 1.3 \pm 0.4 \pm 1.0$
$\overline{B}^0 \to \Sigma_{c1}^{++} \bar{p}\pi^-$	$1.63^{+0.57}_{-0.51} \pm 0.28 \pm 0.42$	$\Sigma_{c1} = \Sigma_c(2520)$
$\overline{B}^0 \to \Sigma_{c1}^0 \bar{p}\pi^+$	$0.48^{+0.45}_{-0.40} \pm 0.08 \pm 0.12 < 1.21$	

$\mathcal{B}(B^- \to J/\psi \Lambda \bar{p}) = (12^{+9}_{-6}) \times 10^{-6}$ by BaBar and $< 4.1 \times 10^{-5}$ by Belle

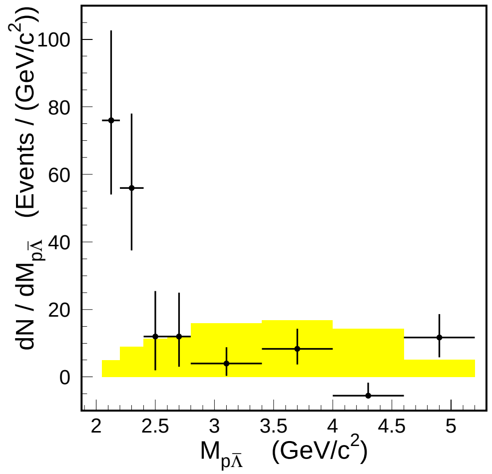
Charmless Baryonic B Decays

Belle measurements (in units of 10^{-6}):

$\overline{B}^0 \to \Lambda\bar{p}\pi^+$	$3.97^{+1.00}_{-0.80} \pm 0.56$
$B^- \to p\bar{p}K^-$	$4.89^{+0.59}_{-0.55} \pm 0.54$
$B^- \to p\bar{p}K^{*-}$	$6.70^{+2.36+0.87}_{-1.95-1.07}$
$\overline{B}^0 \to p\bar{p}K_S$	$1.56^{+0.84}_{-0.82} \pm 0.19$
$B^- \to p\bar{p}\pi^-$	$1.76^{+0.42}_{-0.37} \pm 0.21$

first observation of charmless baryonic B decay (for $B^- \to p\bar{p}K^-$)

Spectrum for $B \to \mathcal{B}_1\overline{\mathcal{B}}_2 M$ (e.g. $\overline{B}^0 \to \Lambda\bar{p}\pi^+$) shows threshold enhancement behavior of baryon pairs



Expt. $\Rightarrow$

$$\mathcal{B}(B^- \to \Lambda_c^+ \bar{p} \pi^-) \gg \mathcal{B}(\overline{B}^0 \to \Lambda_c^+ \bar{p}),$$
$$\mathcal{B}(B^- \to p\bar{p}K^-) \gg \mathcal{B}(\overline{B}^0 \to p\bar{p}),$$
$$\mathcal{B}(B^- \to \Sigma_c^0 \bar{p} \pi^0) \gg \mathcal{B}(B^- \to \Sigma_c^0 \bar{p})$$

In many cases, $\Gamma(B \to \mathcal{B}_1 \overline{\mathcal{B}}_2 M M') \gg \Gamma(B \to \mathcal{B}_1 \overline{\mathcal{B}}_2 M) \gg \Gamma(B \to \mathcal{B}_1 \overline{\mathcal{B}}_2)$

This phenomenon can be understood in terms of threshold effect: the invariant mass of baryon pairs is preferred to be close to threshold

The question is why the $\mathcal{B}_1 \overline{B}_2$ pair prefers to have an invariant mass near threshold ?

Recent Theoretical Studies

Two-body baryonic decays: dominated by nonfactorizable contributions

- Pole model with matrix elements being evaluated by MIT bag model (HYC, Yang 01)
- Diquark model: Chang and Hou (01) have generalized the diquark model of Ball and Dosch (91) to include penguin effects
- Quark-diagram approach: model independent analysis
  charmless baryonic B decay (Chua 03); charmful decay (Luo, Rosner 03)

Three-body baryonic decays: two different types of factorizable contributions

$\langle M|(\bar{q}_3 q_2)|0\rangle\langle\mathcal{B}_1\overline{\mathcal{B}}_2|(\bar{q}_1 b)|B\rangle$: transition process

$\langle\mathcal{B}_1\overline{\mathcal{B}}_2|(\bar{q}_1 q_2)|0\rangle\langle M|(\bar{q}_3 b)|B\rangle$: current-produced process

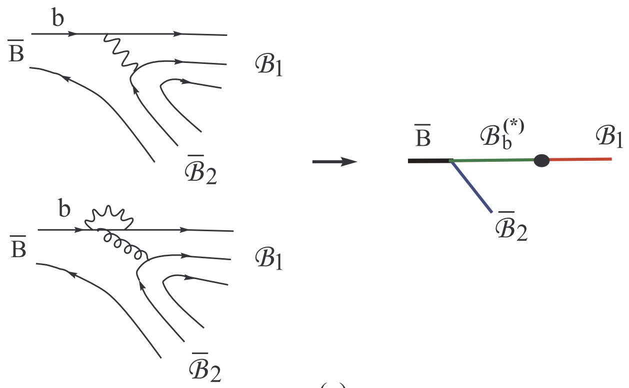
The matrix element $\langle\mathcal{B}_1\overline{\mathcal{B}}_2|(\bar{q}_1 q_2)|0\rangle$ can be related to some measurable quantities for octet baryon pair

- Current-induced process can be evaluated under factorization and QCD counting rule for form factors (Chua, Hou, Tsai 01,02) (Chua, Hou 02) (HYC, Yang 01,02)
- Pole model is suitable for dealing with transition process (HYC, Yang 01)

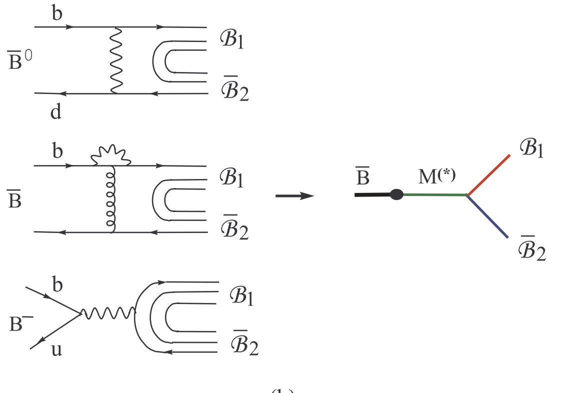
2-body baryonic B decays

$B \to \mathcal{B}_1\overline{\mathcal{B}}_2$: via internal W-emission, $b \to d(s)$ penguin transition and weak annihilation.

need two-pair creation $\Rightarrow B \to \mathcal{B}_1\overline{\mathcal{B}}_2 < B \to M_1M_2$



(a)



(b)

The nonfactorizable amplitude is difficult to evaluate. We shall consider the pole contribution and assume that the decay amplitude is saturated by one-particle low-lying intermediate states.

$$\mathcal{A}(B \to \mathcal{B}_1\overline{\mathcal{B}}_2) = \bar{u}_1(A + B\gamma_5)v_2$$

Pole model $\Rightarrow$ parity-conserving (pc) amplitude is governed by $\frac{1}{2}^+$ ground-state baryon states, pv one by $\frac{1}{2}^-$ low-lying baryon resonances.

$$A = -\sum_{\mathcal{B}_b^*} \frac{g_{\mathcal{B}_b^* \to B\mathcal{B}_2}\, b_{\mathcal{B}_b^*\mathcal{B}_1}}{m_1 - m_{\mathcal{B}_b^*}}, \qquad B = \sum_{\mathcal{B}_b} \frac{g_{\mathcal{B}_b \to B\mathcal{B}_2}\, a_{\mathcal{B}_b\mathcal{B}_1}}{m_1 - m_{\mathcal{B}_b}}$$

Two unknown quantities need to be determined:

• Weak matrix elements $\langle \mathcal{B}|H_{\rm eff}^{PV(PC)}|\mathcal{B}_b^{(*)}\rangle$: apply MIT bag model to compute weak baryon-baryon transition.

• Strong couplings: two distinct models for quark pair creation

1. $^3P_0$ model: $q\bar{q}$ pair is created from the vacuum with vacuum quantum numbers. Presumably it works in the nonperturbative low energy regime.
2. $^3S_1$ model: quark pair is created perturbatively via one gluon exchange with one-gluon quantum numbers $^3S_1$. May be more relevant for $B \to \mathcal{B}_1\overline{\mathcal{B}}_2$ where pQCD is presumably applicable.

Results for charmful $B \to \mathcal{B}_c\overline{\mathcal{B}}$

	CZ	Jarfi et al.	This work	Expt.
$\overline{B}^0 \to \Lambda_c^+\bar{p}$	4×10^{-4}	1.1×10^{-3}	1.1×10^{-5}	$(2.19\pm0.84)\times10^{-5}$
$B^- \to \Sigma_c^0\bar{p}$		1.5×10^{-2}	6.0×10^{-5}	$<8.0\times10^{-5}$
$\overline{B}^0 \to \Sigma_c^0\bar{n}$		5.8×10^{-3}	6.0×10^{-7}	
$B^- \to \Lambda_c^+\bar{\Delta}^{--}$		3.6×10^{-2}	1.9×10^{-5}	

(CZ=Chernyak & Zhitnitsky)

All earlier predictions based on sum-rule analysis, pole model and diquark model are too large compared to experiment.

$B^- \to \Sigma_c^0\bar{p}$ proceeds via Λ_b pole, while $\overline{B}^0 \to \Lambda_c^+\bar{p}$ via Σ_b pole. Since $\Lambda_b N\bar{B}$ coupling $> \Sigma_b N\bar{B}$ one $\Rightarrow$ $\Sigma_c^0\bar{p}$ has a larger rate than $\Lambda_c\bar{p}$.

An earlier measurement by Belle : $\mathcal{B}(B^- \to \Sigma_c^0\bar{p}) = (4.5^{+2.6}_{-1.9}\pm0.7\pm1.2)\times10^{-5}$

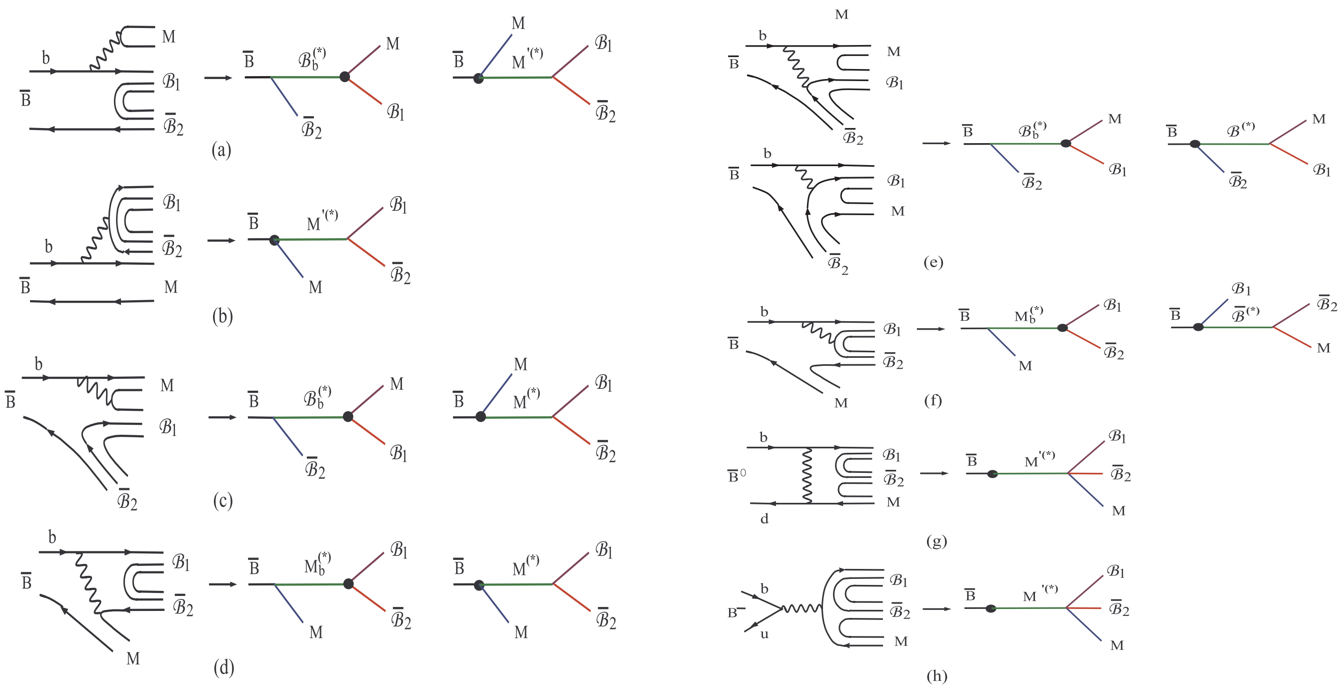
Results for charmless $B \to \mathcal{B}_1\overline{\mathcal{B}}_2$

	CZ	Jarfi et al.	This work	Expt.
$\overline{B}^0 \to p\bar{p}$	1.2×10^{-6}	7.0×10^{-6}	$1.1\times10^{-7\dagger}$	$< 2.7\times10^{-7}$
$\overline{B}^0 \to n\bar{n}$	3.5×10^{-7}	7.0×10^{-6}	$1.2\times10^{-7\dagger}$	
$B^- \to n\bar{p}$	6.9×10^{-7}	1.7×10^{-5}	5.0×10^{-7}	
$\overline{B}^0 \to \Lambda\bar{\Lambda}$		2×10^{-7}	$0^\dagger$	$< 1.0\times10^{-6}$
$B^- \to p\bar{\Delta}^{--}$	2.9×10^{-7}	3.2×10^{-4}	1.4×10^{-6}	$< 1.5\times10^{-4}$
$\overline{B}^0 \to p\bar{\Delta}^-$	7×10^{-8}	1.0×10^{-4}	4.3×10^{-7}	
$B^- \to n\bar{\Delta}^-$		1×10^{-7}	4.6×10^{-7}	
$\overline{B}^0 \to n\bar{\Delta}^0$		1.0×10^{-4}	4.3×10^{-7}	
$B^- \to \Lambda\bar{p}$	$\lesssim 3\times10^{-6}$		$2.2\times10^{-7\dagger}$	$< 2.2\times10^{-6}$
$\overline{B}^0 \to \Lambda\bar{n}$			$2.1\times10^{-7\dagger}$	
$\overline{B}^0 \to \Sigma^+\bar{p}$	6×10^{-6}		$1.8\times10^{-8\dagger}$	
$B^- \to \Sigma^0\bar{p}$	3×10^{-6}		$5.8\times10^{-8\dagger}$	
$B^- \to \Sigma^+\bar{\Delta}^{--}$	6×10^{-6}		2.0×10^{-7}	
$\overline{B}^0 \to \Sigma^+\bar{\Delta}^-$	6×10^{-6}		6.3×10^{-8}	
$B^- \to \Sigma^-\bar{\Delta}^0$	2×10^{-6}		8.7×10^{-8}	

† only PC part is considered here

Observation of $\overline{B}^0 \to \Lambda_c^+\bar{p} \Rightarrow$ charmless $B \to \mathcal{B}_1\overline{\mathcal{B}}_2 \sim 10^{-7}$

3-body baryonic B decays



There are 9 distinct quark diagrams. Six of them are factorizable, but only two, Figs.(b) and (d), are directly calculable in practice

$$\text{Figs. (a), (c)}: \quad \mathcal{A} \propto \langle M|(\bar{q}_3 q_2)|0\rangle\langle \mathcal{B}_1\overline{\mathcal{B}}_2|(\bar{q}_1 b)|B\rangle,$$
$$\text{Figs. (b), (d)}: \quad \mathcal{A} \propto \langle \mathcal{B}_1\overline{\mathcal{B}}_2|(\bar{q}_1 q_2)|0\rangle\langle M|(\bar{q}_3 b)|B\rangle,$$
$$\text{Figs. (g), (h)}: \quad \mathcal{A} \propto \langle \mathcal{B}_1\overline{\mathcal{B}}_2 M|(\bar{q}_1 q_2)|0\rangle\langle 0|(\bar{q}_3 b)|B\rangle.$$

Two remarks:

1. For Figs. (b) and (d) the two-body matrix element $\langle \mathcal{B}_1\overline{\mathcal{B}}_2|(\bar{q}_1 q_2)|0\rangle$ for octet baryons can be related to the e.m. form factors of the nucleon.

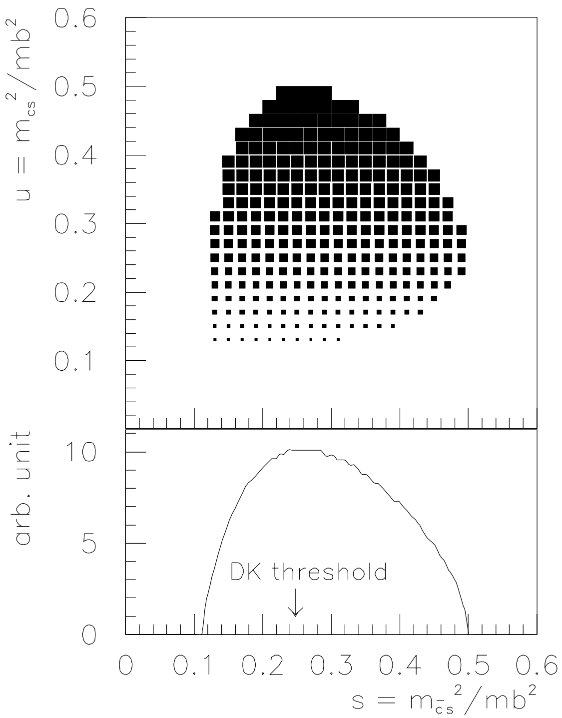
2. For Figs. (a) and (c) we will consider the pole diagrams to evaluate 3-body matrix elements.The 3-body matrix element $\langle \mathcal{B}_1\overline{\mathcal{B}}_2|(\bar{q}_1 b)|B\rangle$ receives contributions from point-like contact interaction (i.e. direct weak transition) and pole diagrams.

Why is $\Gamma(B \to \mathcal{B}_1\overline{\mathcal{B}}_2 M) \gg \Gamma(B \to \mathcal{B}_1\overline{\mathcal{B}}_2)$?

• Hou and Soni (01): Smallness of $B \to \mathcal{B}_1\overline{\mathcal{B}}_2$ has to do with the large energy release. They conjectured that in order to have larger baryonic B decays, one has to reduce the energy release and allow for baryonic ingredients to be present in the final state. $\Rightarrow$ $\Gamma(B \to \rho p\bar{n}) > \Gamma(B \to p\bar{p})$ since the ejected ρ meson in the former decay carries away much energies and the configuration is more favorable for baryon production.

• Dunietz (95): Invariant mass of diquark ud peaks at the highest possible values in a Dalitz plot for $b \to ud\bar{d}$ transition due to its $V-A$ feature. (Buchalla, Dunietz, Yamamoto)

$\Rightarrow$ Very massive udq objects will intend to form a highly excited baryon state such as Δ and N^* and will be seen as $Nn\pi(n \geq 1)$. This explains the non-observation of the $N\overline{N}$ final states, the large BR of $\overline{B} \to N\bar{\Delta}$ and why the three-body mode $N\overline{N}\pi(\rho)$ is favored.

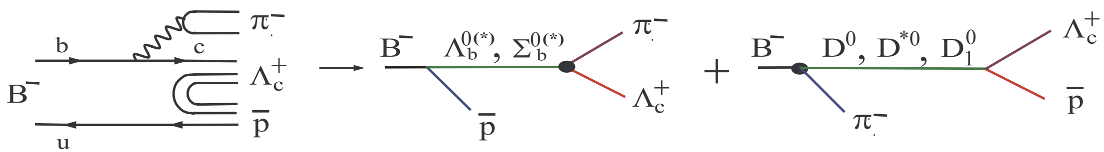


Dalitz plot of $b \to c\bar{c}s$ as a function of $u = m_{cs}^2/m_b^2$ and $s = m_{\bar{c}s}^2/m_b^2$ (from Buchalla, Dunietz, Yamamoto, PL, B364, 188 (1995)).

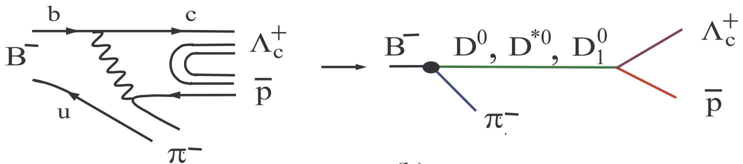
$B \to \mathcal{B}_1 \overline{\mathcal{B}}_2 M$ in Pole Model

Consider $B^- \to \Lambda_c^+ \bar{p} \pi^-$ as an example

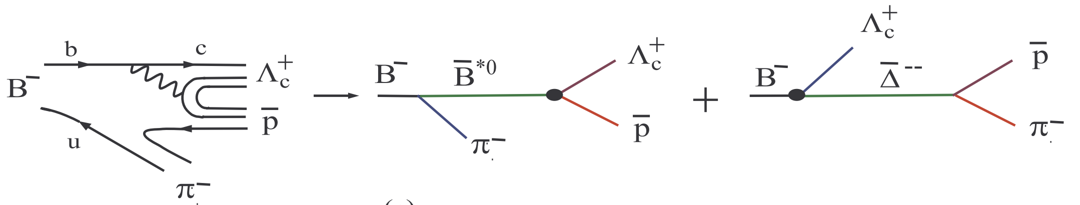
$$\begin{aligned} \Gamma(B^- \to \Lambda_c^+ \bar{p}\pi^-) &= \Gamma(B^- \to \Lambda_c^+ \bar{p}\pi^-)_{\rm nonr} + \Gamma(B^- \to \Sigma_c^0 \bar{p} \to \Lambda_c^+ \bar{p}\pi^-) \\ &+ \Gamma(B^- \to \Lambda_c^+ \bar{\Delta}^{--} \to \Lambda_c^+ \bar{p}\pi^-) \end{aligned}$$



(a)



(b)



(c)

$$A(B^- \to \Lambda_c \bar{p}\pi^-)_{\rm fact} = \frac{G_F}{\sqrt{2}} V_{cb}V_{ud}^* \Big\{ a_1 \langle \pi^-|(\bar{d}u)|0\rangle\langle \Lambda_c^+ \bar{p}|(\bar{c}b)|B^-\rangle + a_2 \langle \pi^-|(\bar{d}b)|B^-\rangle\langle \Lambda_c^+ \bar{p}|(\bar{c}u)|0\rangle \Big\} \equiv A_1 + A_2$$

Factorizable amplitude A_2 can be directly calculated. For amplitude A_1 we evaluate the baryon and meson pole diagrams.

$$\Lambda_b \text{ propagator}: \qquad \frac{1}{m_{\Lambda_b}^2 - m_{\Lambda_c\pi}^2}$$

not $1/m_b^2$ suppressed at the region where invariant mass of $\Lambda_c\pi$ is large (e.g. π carries away much energy)

$$D \text{ propagator}: \qquad \frac{1}{m_D^2 - m_{\Lambda_c\bar{p}}^2}$$

not small if invariant mass of $\Lambda_c\bar{p}$ is near threshold

This explains the threshold effect in spectrum and why $\mathcal{B}(B^- \to \Lambda_c^+ \bar{p}\pi^-) \gg \mathcal{B}(\overline{B}^0 \to \Lambda_c^+ \bar{p})$

Some Highlights

• $\mathcal{B}(B^- \to \Lambda_c^+ \bar{p}\pi^-) \approx 2.4 \times 10^{-4}$, in agreement with CLEO and Belle. About 1/4 of the rate comes from resonant contributions

• Factorization $\Rightarrow \frac{\Gamma(B \to D^{*+} n\bar{p})}{\Gamma(B \to D^+ n\bar{p})} \sim 3$ should be tested experimentally by measuring $D^+ n\bar{p}$ production.

• Charmless decays $B^- \to p\bar{p}K^-(K^{*-})$ are penguin-dominated

$$\begin{aligned} \mathcal{B}(B^- \to p\bar{p}K^-) &\approx 4.0 \times 10^{-6} \qquad (4.89^{+0.59}_{-0.55} \pm 0.54) \times 10^{-6} \\ \mathcal{B}(B^- \to p\bar{p}K^{*-}) &\approx 2.3 \times 10^{-6} \qquad (6.70^{+2.36+0.87}_{-1.95-1.07}) \times 10^{-6} \end{aligned}$$

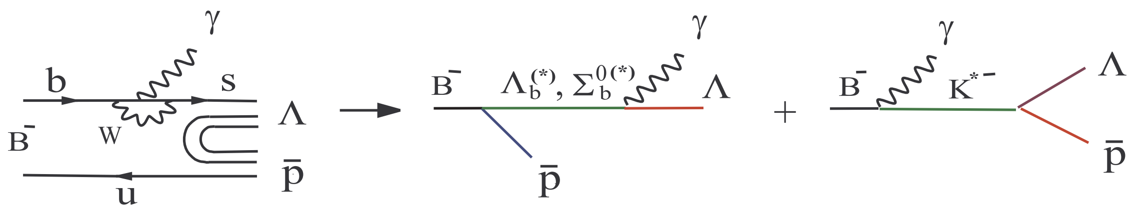
Naively it is expected that $p\bar{p}K^{*-} < p\bar{p}K^-$ due to absence of penguin contributions of a_6 and a_8 to the former. This is not borne out by experiment, why ?

• $B \to \Lambda\bar{p}\pi$ was previously argued to be small $< 10^{-6}$. Its sizable BR $\sim 4.0 \times 10^{-6}$ now can be understood as a proper treatment of pseudoscalar form factor arising from penguin matrix element (Chua, Hou 02).

Radiative baryonic B decays

Naively it is expected that $\Gamma(B \to \mathcal{B}_1\overline{\mathcal{B}}_2\gamma) \sim \mathcal{O}(\alpha_{\rm em})\Gamma(B \to \mathcal{B}_1\overline{\mathcal{B}}_2) \Rightarrow$ it is difficult to observe radiative baryonic B decays via bremsstrahlung.

Owing to large m_t, $b \to s\gamma$ penguin transition is neither quark mixing nor loop suppressed.



Consider Λ_b pole diagram and apply heavy quark spin symmetry and static b quark limit to evaluate tensor matrix element in

$$\langle \Lambda(p_\Lambda)\gamma(\varepsilon,k)|\mathcal{H}_W|\Lambda_b(p_{\Lambda_b})\rangle = -i\frac{G_F}{\sqrt{2}}\frac{e}{8\pi^2}V_{ts}^*V_{tb}\,2c_7^{\rm eff}m_b\varepsilon^\mu k^\nu \times\langle\Lambda|\bar{s}\sigma_{\mu\nu}(1+\gamma_5)b|\Lambda_b\rangle$$

which can be related to $\Lambda_b \to \Lambda$ form factors.

The decay rate depends on $g_{\Lambda_b \to B^- p}$ and form factors of $\Lambda_b \to \Lambda$:

$$\mathcal{B}(B^- \to \Lambda \bar{p} \gamma) \approx 1.1 \times 10^{-6}$$

For comparison,

$$\mathcal{B}(\Lambda_b \to \Lambda \gamma) = 1.9 \times 10^{-5}$$

CLEO $\Rightarrow [\mathcal{B}(B^- \to \Lambda \bar{p} \gamma) + 0.36 \mathcal{B}(B^- \to \Sigma^0 \bar{p} \gamma)]_{E_\gamma > 1.5\,\mathrm{GeV}} < 3.9 \times 10^{-6}$

Penguin-induced radiative baryonic B decay modes should be readily accessible by B factories.

Summary

1. $B \to \mathcal{B}_1\overline{\mathcal{B}}_2$ receives main contributions from internal W-emission diagram. The predicted branching ratios are in general very small, typically less than 10^{-7}.
2. As predicted, many of charmless three-body final states have a larger rate than their two-body counterparts.
3. Three-dominated modes $\bar{B}^0 \to n\bar{p}\pi^+(\rho^+)$ have BR of order of $(1 \sim 4) \times 10^{-6}$ for π^+ production and $(3 \sim 5) \times 10^{-6}$ for ρ^+ production. Moreover, $\mathcal{B}(\bar{B}^0 \to p\bar{n}\pi^-) \sim 3 \times 10^{-6}$ and $\mathcal{B}(\bar{B}^0 \to p\bar{n}\rho^-) \sim 8 \times\ 10^{-6}$ are predicted.
4. For penguin-dominated modes we predict that $\mathcal{B}(B^- \to p\bar{p}K^-) \sim 4 \times 10^{-6}$, and the decays $B^- \to p\bar{p}K^{*-}$, $\overline{B}^0 \to p\bar{n}K^-$ and $\overline{B}^0 \to p\bar{n}K^{*-}$ all have the branching ratio of order 2×10^{-6}. Therefore, several $B \to N\overline{N}K^{(*)}$ decays should be easily seen by B factories at the present level of sensitivity.
5. The rates of $B^- \to \Lambda\bar{p}\gamma$ and $B^- \to \Xi^0\bar{\Sigma}^-\gamma$ are sizable, of order 1×10^{-6}.