Radiative Penguins at BaBar

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The origin of penguins
Told by John Ellis:

“Mary K. [Gaillard], Dimitri [Nanopoulos], and I first got interested in what are now called penguin diagrams while we were studying CP violation in the Standard Model in 1976... The penguin name came in 1977, as follows.

In the spring of 1977, Mike Chanowitz, Mary K. and I wrote a paper on GUTs [Grand Unified Theories] predicting the $b$ quark mass before it was found. When it was found a few weeks later, Mary K., Dimitri, Serge Rudaz and I immediately started working on its phenomenology.

That summer, there was a student at CERN, Melissa Franklin, who is now an experimentalist at Harvard. One evening, she, I, and Serge went to a pub, and she and I started a game of darts. We made a bet that if I lost I had to put the word penguin into my next paper. She actually left the darts game before the end, and was replaced by Serge, who beat me. Nevertheless, I felt obligated to carry out the conditions of the bet.

For some time, it was not clear to me how to get the word into this $b$ quark paper that we were writing at the time.... Later...I had a sudden flash that the famous diagrams look like penguins. So we put the name into our paper, and the rest, as they say, is history.”

John Ellis in Mikhail Shifman’s “ITEP Lectures in Particle Physics and Field Theory”, hep-ph/9510397
Observables of the $b \rightarrow s \gamma$ transition

Charmless Baryonic Modes

\[ \mathcal{B}(B \to X_{s d} \gamma) \]

HFAG
April 2008

Branching Ratio \( \times 10^6 \)

\[ \begin{array}{c}
pp \\
\Delta^{++}p \\
\Sigma^+p \\
\Delta^0\Lambda \\
p\Xi^-
\end{array} \]

CLEO
Belle
BABAR
PDG2006
New Avg.

\[ \begin{array}{c}
p\Sigma(1385)^- \\
p\Sigma(1385)^0 \\
p\Lambda(1520) \\
\Delta^+\Lambda \\
p\Xi^0K^- \\
\Lambda\Lambda K^+ \\
\Lambda\Lambda\pi^+ \\
p\Sigma^0\pi^- \\
p\Lambda\pi^- \\
p\Lambda\pi^0 \\
pp\pi^+ \\
ppK^0 \\
\Theta^+p \\
\Theta^{++}p \\
f_J(2221)K^+ \\
f_J(2221)K^0 \\
f_J(2221)K^{++} \\
f_J(2221)K^{+0} \\
\end{array} \]
BaBar data

Most data collected at \( \Upsilon(4S) \) resonance (10.58 GeV)

10 % @ 10.54 for background studies

recent addition of other resonances to broaden physics spectrum
The Detector

1.5 T solenoid

Electromagnetic Calorimeter

e^+ (3.1 GeV)

e^- (9 GeV)

Čerenkov Detector (DIRC)

Drift Chamber

Instrumented Flux Return

Silicon Vertex Tracker
Cross sections at 10.58 GeV

<table>
<thead>
<tr>
<th>$e^+e^-$ →</th>
<th>$u\bar{u}$</th>
<th>$d\bar{d}$</th>
<th>$s\bar{s}$</th>
<th>$c\bar{c}$</th>
<th>$\tau^+\tau^-$</th>
<th>$b\bar{b}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>cross section (nb)</td>
<td>1.39</td>
<td>0.35</td>
<td>0.35</td>
<td>1.30</td>
<td>0.94</td>
<td>1.05</td>
</tr>
</tbody>
</table>
Fighting “continuum background”

- B meson pair is produced almost at rest
  - spherical event shape

- lighter quarks have larger phasespace
  - more jet-like

- we don’t want to find jets
Fighting backgrounds from other B decays

- main ingredient: kinematic variables in a likelihood fit
  \[ m_{\text{rec.}} := |q_{\text{rec}}| \]
  \[ m_{\text{miss.}} := |q_{e^+e^-} - q_{\text{rec}}| \]

- or, equivalently, mES, deltaE

- Flat / Argus for background

- Peaking for signal
Analysis tradeoffs

- **fully inclusive**
  - minimal experimental constraints

- **sum-of-exclusive**
  - analysis of multiple final states

- **exclusive**
  - analysis of only a single decay

To the left:
- theoretical uncertainties

To the right:
- experimental uncertainties
**b \rightarrow s \gamma** challenges

- **Task:** find the signal
- **Note:** This is a log scale...

### Inclusive approach:
- Tag one semileptonic B decay,
- reconstruct $X_s$ from the other
- + no dependence on $X_s$
- - fragmentation function
- - no B rest frame

### Semi-inclusive approach:
- reconstruct a large number of channels
- + good resolution of photon energy
- - missing decays
- - $X_s$ fragmentation dependence
$b \rightarrow s \gamma$ inclusive

- New approach: Full hadronic reconstruction of the tag $B$
- Better identification of signal
- Low efficiency of the tag $B$ (0.3 %)

b \rightarrow s \gamma \text{ results}

Charge asymmetry ACP = 0.10 ± 0.18 ± 0.05
Isospin asymmetry Δ0− = −0.06 ± 0.15 ± 0.07
BF = (3.66 ± 0.85 ± 0.60) \times 10^{−6}
incl. $b \rightarrow s\gamma$ summary

- Sensitivity to many faces of new physics
- Excellent agreement with SM
- Still an active area, experimentally as well as theoretically

Baryonic B decays

- Inclusive search has to cut hard on the photon energy - baryons, on the other hand reduce the available phase space.

- Invariant mass of the baryon pair peaks at threshold.

- Semi-inclusive studies completely neglect the decays.

- Additional observables could open windows to new physics.
Current measurements

Cleo (9.1 / fb)
\[ B(B^- \rightarrow \Lambda^0 \bar{p} \gamma) + 0.3B(B^- \rightarrow \Sigma^0 \bar{p} \gamma) < 3.3 \times 10^{-6} \]
\[ B(B^- \rightarrow \Sigma^0 \bar{p} \gamma) < 7.9 \times 10^{-6} \]

Belle (140 / fb)
\[ B(B^- \rightarrow \Lambda^0 \bar{p} \gamma) = 2.16^{+0.58}_{-0.53} \times 10^{-6} \]
\[ B(B^- \rightarrow \Sigma^0 \bar{p} \gamma) < 4.6 \times 10^{-6} \]

Belle (414 / fb)
\[ B(\bar{B}^0 \rightarrow \Lambda^0 \bar{p} \pi^-) = (3.23^{+0.33}_{-0.29} \pm 0.29) \times 10^{-6} \]
\[ B(B^- \rightarrow \Lambda^0 \bar{p} \gamma) = (2.45^{+0.44}_{-0.38} \pm 0.22) \times 10^{-6} \]
\[ B(B^- \rightarrow \Lambda^0 \bar{p} \pi^0) = (3.00^{+0.61}_{-0.53} \pm 0.33) \times 10^{-6} \]

BaBar (210 / fb)
\[ B(\bar{B}^0 \rightarrow \Lambda^0 \bar{p} \pi^-) = (3.30 \pm 0.53 \pm 0.31) \times 10^{-6} \]
Event generation

Model: Cheng, Yang
pole model approach

Model: Geng, Hsiao
factorization / QCD counting rules
Candidate reconstruction

- Combine two oppositely charged tracks to make the Lambda
- (Add photon to make a Sigma)
- Add a proton and a high energy photon to make the B
- Fit the decay chain
- Two main variables

\[ m_{\text{rec.}} := |q_{\text{rec}}| \]
\[ m_{\text{miss.}} := |q_{e^+e^-} - q_{\text{rec}}| \]
\[ m_{\text{rec.}} = m_{B}^{\text{PDG}} \]
Reconstructed mass

$B^- \rightarrow \Lambda \bar{p} \gamma$

$B^- \rightarrow \Sigma^0 \bar{p} \gamma$

$B^- \rightarrow \Lambda \bar{p} \pi^0$

$B^- \rightarrow \Sigma^0 \bar{p} \pi^0$

Background
Missing mass

\[ B^- \rightarrow \Lambda \bar{p} \gamma \]

\[ B^- \rightarrow \Sigma^0 \bar{p} \gamma \]

\[ B^- \rightarrow \Lambda \bar{p} \pi^0 \]

\[ B^- \rightarrow \Sigma^0 \bar{p} \pi^0 \]

Background
## Expected yields

<table>
<thead>
<tr>
<th>Sample/candidates</th>
<th>Expected yield in</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Lambda\bar{p}\gamma$</td>
<td>$\Sigma^0\bar{p}\gamma$</td>
</tr>
<tr>
<td>Only $B^- \rightarrow \Lambda\bar{p}\gamma$</td>
<td>64</td>
<td>&lt;21</td>
</tr>
<tr>
<td>Only $B^- \rightarrow \Sigma^0\bar{p}\gamma$</td>
<td>4</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Both</td>
<td>88</td>
<td>&lt;131</td>
</tr>
</tbody>
</table>

90 % confidence interval

Phys.Rev.Lett.95:061802,2005
Likelihood fit

- Selection of fit variables
- find appropriate shape \( f(x, \theta) \)
- minimize

\[
\mathcal{L} = \sum_{e=1}^{N} \ln \left( \sum_{i=1}^{N_s} N_i f_i(y_e) \right) - \sum_{i=1}^{N_s} N_i
\]

- Get yields and errors

\[
V_{ij} = \frac{\partial^2 \mathcal{L}(\theta)}{\partial \theta_i \partial \theta_j}
\]
Fit Validation

pull distributions

signal yield in 1000 embedded toy Monte Carlo experiments
## Yields

### Events with One Candidate

<table>
<thead>
<tr>
<th></th>
<th>Yield</th>
<th>+</th>
<th>-</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^- \rightarrow \Lambda \bar{p} \gamma$</td>
<td>26.45</td>
<td>12.40</td>
<td>11.26</td>
<td>2.57</td>
</tr>
<tr>
<td>$B^- \rightarrow \Sigma^0 \bar{p} \gamma$</td>
<td>63.21</td>
<td>18.20</td>
<td>16.98</td>
<td>4.41</td>
</tr>
</tbody>
</table>

### Events with Two Candidates

<table>
<thead>
<tr>
<th></th>
<th>Yield</th>
<th>+</th>
<th>-</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^- \rightarrow \Lambda \bar{p} \gamma$</td>
<td>75.61</td>
<td>11.61</td>
<td>11.09</td>
<td>8.88</td>
</tr>
<tr>
<td>$B^- \rightarrow \Sigma^0 \bar{p} \gamma$</td>
<td>57.45</td>
<td>14.34</td>
<td>13.65</td>
<td>4.62</td>
</tr>
</tbody>
</table>
sPlots

- Each event is assigned a weight

\[ sP_n(y_e) = \frac{\sum_{j=1}^{N_s} V_{nj} f_j(y_e)}{\sum_{j=1}^{N_s} N_j f_j(y_e)} \]

- Sum over all events in bins of a new variable \( x \) to get the distribution of one sample

- Needs validation, because this can be proven only in the limit of infinite yields
sPlots validation

red - input distribution taken from generated model

green - distribution reconstructed with the sPlots method. Each bin is the average of 1000 experiments
Analysis strategy
Baryonic Penguins

Summary

\[ \mathcal{B}(B^- \to \Lambda \bar{p} \gamma) = (2.63 \pm 0.28) \times 10^{-6} \]
\[ \mathcal{B}(B^- \to \Sigma^0 \bar{p} \gamma) = (4.97 \pm 0.52) \times 10^{-6} \]
\[ \mathcal{B}(B^- \to \Sigma^0 \bar{p} \pi^0) + \mathcal{B}(B^- \to \Lambda \bar{p} \pi^0) < 6.3 \times 10^{-6} \]

First measurement of \( \mathcal{B}(B^- \to \Sigma^0 \bar{p} \gamma) \) and the shape of the invariant mass

Results are preliminary, statistical error only
Radiative Penguins ($b \rightarrow s \gamma$, $b \rightarrow sll$) are sensitive to physics beyond the SM on many fronts.

BaBar has stopped taking data, but the analysis program is still going strong.

Theoretical and experimental progress is continuing to set severe constraints on new (and old) physics models.
$B^- \rightarrow \Lambda \bar{p} \gamma$

$B^- \rightarrow \Sigma^0 \bar{p} \gamma$

$B^- \rightarrow \Lambda \bar{p} \pi^0$

$B^- \rightarrow \Sigma^0 \bar{p} \pi^0$

Background