CP Violation from New Physics in Radiative B Decays
Outline

• Motivation
• Oscillation in radiative B decays Part I
• Oscillation in radiative B decays Part II
• Angular analysis in $B \rightarrow \gamma \phi K$
• Conclusions
Motivation

• $b \rightarrow s \gamma$ is an important probe for new physics

• Inclusive measurements can give 2 parameters
  - Total rate $(3.55 \pm 0.24) \times 10^{-4}$ [HFAG]
  - CP asymmetry $(0.00 \pm 0.04)$ [HFAG]

• In exclusive decays it is possible to construct observables which are sensitive to all aspects of the polarization of the photon.

• This allows reasonably good null tests of the SM.
Radiative Penguins in Various Models

- Basic SM Penguin
- LR Symmetric
- SUSY
SM Quark Level Helicity Argument

- Must be left handed because it is touched by the W.
- Initial b must have this spin otherwise photon has 0 helicity.
- Must be left handed by helicity conservation.
A Null Test of the SM?

- On the quark level in the SM, the radiative decay $b \rightarrow s \gamma$ produces left polarized photons: $\text{right/left} = m_s / m_b$.

- If there is a significant right handed content, it may indicate New Physics: SUSY, LR symmetric etc.

- Consideration must be given to the SM contributions to right photons, in a meson decay it could be larger than the SM result above for a lone quark.

![Basic SM Penguin](image1)

![SM bkgd.](image2)

David Atwood (Iowa State University)
Oscillation in Radiative B Decays
Part I: $B \rightarrow K^{*}\gamma$

• The first proposed signal (Atwood Gronau Soni 1997) for right polarized photons in $B$ decay was to look for oscillations in $B \rightarrow K^{*}\gamma$.

• To have oscillation in $B^0 \rightarrow K^{0*}\gamma$, both $B$ and $\bar{B}$ need to decay to a common final state:

The following things must therefore happen:

1) $K^{0*}$ must decay in a flavor non-specific way, $K^{0*} \rightarrow K_S\pi^0$.

2) Both $B^0$ and $\bar{B}^0$ must produce both left and right polarized photons.

In the Standard Model $\bar{B}$ likes to decay to left photons while $B$ likes to decay to right photons so no oscillations.
The Experiment: $B^0 \rightarrow K^0\gamma$ Oscillation

- The $B$ factory experiment is similar to $\psi K_S$ except that the decay vertex is a little more challenging to detect.
- In addition one needs to trace back $K_S$ the decay to the vertex.
- This seems very challenging but none the less...

$\Upsilon(4s)$ $B^0$ $\gamma$ $\pi^0$ $\pi^+$ $\pi^-$

Note $\tau(K_S) = 40 \tau(B^0)$

cannot see this vertex directly
distance $\propto$ time

$Y(4s)$

$\tau(B^0)$
Measurement of Time-dependent $CP$-violating Asymmetries in $B^0 \to K^{*-0} \gamma(K^{*-0} \to K_s^0 \pi^0)$ Decays


We present a measurement of the time-dependent $CP$-violating asymmetries in $B^0 \to K^{*-0} \gamma(K^{*-0} \to K_s^0 \pi^0)$ decays based on 124 million $\Upsilon(4S) \to BB$ decays collected with the BABAR detector at the PEP-II asymmetric-energy B Factory at the Stanford Linear Accelerator Center. In a sample containing $105 \pm 14$ signal decays, we measure $S_{K^{*-} \gamma} = 0.25 \pm 0.63 \pm 0.14$ and $C_{K^{*-} \gamma} = -0.57 \pm 0.32 \pm 0.09$, where the first error is statistical and the second systematic.

OK for the first try I guess
How good a null test?

- Higher order graphs could ruin the two body helicity argument which works on the quark level.
- How bad is this contamination?
- Clearly it would be good to ultimately have more control over SM contamination.

<table>
<thead>
<tr>
<th>Paper</th>
<th>$S_{K^*\gamma}(SM)$</th>
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</thead>
<tbody>
<tr>
<td>Ball and Zwicky</td>
<td>$-2.2 \pm 1.5%$</td>
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<tr>
<td>hep-ph/0609037</td>
<td></td>
</tr>
<tr>
<td>Matsumori and Sanda</td>
<td>$-3.5 \pm 1.7%$</td>
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<tr>
<td>Grinstein and Pirjol</td>
<td>$| \leq 10%$</td>
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<tr>
<td>Grinstein, Grossman, Ligeti, Pirjol</td>
<td>$| \leq 10%$</td>
</tr>
<tr>
<td>PRD71:011504(2005)</td>
<td></td>
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In (Atwood Gershon Hazumi Soni 2005) it was pointed out that the K* can be replaced by any X_s of definite charge conjugation.

The simplest such generalization is to $X_s = K_s \pi^0$

- That is you can throw together all $K_s \pi^0$, not just at the K* peak.

The sign of the oscillation depends only on the $C$ eigenvalue of $X_s$.

This approach gives potentially more statistics.

The dependence on $X_s$ gives a handle on the degree of SM contamination.
**H_{eff} for New Physics**

- Assuming that the dimension 5 dipole operator dominates, the effective Hamiltonian is:

\[
H_{eff} = -\sqrt{8} \frac{G_F e m_b}{16\pi^2} \int F_{\mu\nu} \left[ F_L \bar{q} \sigma^{\mu\nu 1+\gamma_5} b + F_R \bar{q} \sigma^{\mu\nu 1-\gamma_5} b \right] 
\]

- If this model is true, then the photon polarization should not depend on the invariant mass or composition of the hadrons. An important point to test.

- In the SM $F_L$ dominates because of the left coupling of the $W$

- New physics will contribute to both $F_L$ and $F_R$. 

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NP versus SM Contamination

• If radiative decays are controlled by this $H_{\text{eff}}$, then the amplitude, $S$, of the oscillations will not depend on $X_s$.

• SM contamination will depend on the kinematics of $X_s$.

• To check for SM contamination, look for variations in $S$ as a function of:
  - The particles in $X_s$.
  - The invariant mass of $X_s$.
  - Other kinematic variables inside $X_s$
    • e.g. Dalitz plot variables in $B \rightarrow \pi^0 K_s \gamma$. 
Angular Analysis in $B \to \gamma \phi K$

- Let us now consider the decay $B \to \gamma \phi K$ as a probe of photon polarization in $b \to s \gamma$. (WIP Atwood Gershon Hazumi and Soni).
- The following points make it particularly desirable (the same methods can be applied more generally to any $\gamma PV$ final state):
  - The large branching ratio measured at BABAR and BELLE
    $$B(B^- \to \phi K^- \gamma) = (3.46 \pm 0.6) \times 10^{-6} \quad \text{(HFAG)}$$
  - The neutral version of this final state makes an excellent choice for the time dependent analysis: the prompt $\phi$ decay allows the vertex to be better located.
  - The time independent angular distribution of the $\phi$ decay allows the measurement of additional polarization dependent observables, some of which are even more suppressed in the SM than the oscillation amplitude.
  - An easy decay mode to reconstruct even at hadronic machines (LHCB)
- This is somewhat similar to the analysis of $B \to \gamma [K^{**} \to K \pi \pi]$ considered by (Gronau Pirjol PRD 054008(02) and Gronau Grossman, Pirjol and Ryd PRL88 0510802(02))
Features of $B \rightarrow \gamma \phi K$

- **Time Dependent analysis**
  - Only applies in neutral case
  - Requires tagging and time measurement
  - Can integrate over angular variables
  - Extracts only one observable (oscillation amplitude)
  - Subject to an unknown amount of SM contamination; can check Dalitz variable dependence.

- **Angular Analysis**
  - Neutral and charged cases can be used
  - No time measurement
  - No tagging for $C$-even $P$-odd observables
  - Charged case self tagging.
  - Extracts 4 observables
  - Some observables (ie $C$-even $P$-odd) have reduced $[O(1\%)]$ SM contamination.
  - Complicated angular distributions require lots of data to untangle (super B or LHCB)
Angular Distribution

B frame

Kφ frame

φ frame

Helicity = ±1, 0

J^P = 1^+, 1^−, 2^+, 2^−, ...

K^+   K^−
What can we learn from angular distributions

- If there are 2 different $J^P$ partial waves, then the left photon can interfere with the right photon.
- Components of the angular distribution will be proportional to:

$$\text{Re}(F_R F_L^*) \quad \text{Im}(F_R F_L^*) \quad \text{Re}(F_\perp F_\parallel^*) = |F_R|^2 - |F_L|^2$$

NB: 2x sign ambiguity

- This is separately true for the $B^+$ and $B^-$.
- In general, you can take the components of the angular distribution and solve for the magnitude and phase of $F_R/F_L$, both for $B^+$ and $B^-$. 
- Here I would like to highlight the part of the distribution proportional to $\text{Im}(F_R F_L^*)$
C-even P-odd

• Generally you will get a parity odd distribution proportional to $\text{Im}(F_R F_L^*)$.
• If you add this coefficient of $B$ and anti-$B$ distributions, the result is C-even P-odd ($\therefore$ CP-odd).
• P-odd means it is proportional to $\sin \phi$ (ie triple product).
• It is small in the SM for two reasons:
  - It is proportional to $F_R / F_L$: to produce an non-zero result the SM must make photons of the suppressed helicity.
  - It is proportional to $\sin(\text{arg}(F_R F_L^*))$, the wrong handed photons must have a different $CP$ phase ($O(\lambda^2)$)
• Signals of this type will therefore be $O(1\%)$ in the SM.
Key Points

- For the C-even P-odd distribution, no tagging is required: particle and anti-particle distributions are added together.

- If a C-odd P-even distribution is found, there must be new physics.
Toy Model

- As a toy model, I will assume that only the two channels $J^p=1^+$ and $1^-$ participate and that the $1^+$ happens to decay in such a way that the $\phi$ has only helicity=$\pm 1$. 
The angular distribution in this case is
\[ \Gamma^+(\eta, \theta, \phi) = \sin^2 \theta \left[ \lambda_0 + \lambda_1 \cos^2 \eta + \lambda_2 \cos \eta ight. \\
+ \lambda_3 \cos(2\phi) + \lambda_4 \sin(2\phi) + \lambda_5 \cos \eta \cos(2\phi) \\
\left. + \lambda_6 \cos \eta \sin(2\phi) + \lambda_7 \cos^2 \eta \cos(2\phi) + \lambda_8 \cos^2 \eta \sin(2\phi) \right] \]

The following information may be extracted from these parameters:

\[
\begin{align*}
\text{C-even P-odd} \\
\lambda_4 + \overline{\lambda_4} \\
\lambda_6 + \overline{\lambda_6} \\
\lambda_8 + \overline{\lambda_8}
\end{align*}
\]

\[
\begin{align*}
\text{Im}(F_R F_L^*) / |F_R|^2 + |F_L|^2 &= \frac{1}{2} \left( \lambda_6 \overline{\lambda_0 + \lambda_1} \right) \\
|F_R|^2 - |F_L|^2 &= \pm \frac{(\lambda_8 - \lambda_4)}{\sqrt{(\lambda_0 + \lambda_1)^2 - (\lambda_7 + \lambda_3)^2 - \lambda_2^2}} \\
\text{(note: 2× ambiguity)}
\end{align*}
\]
Inventory of polarization observables

In $B^0$ decay there are 4 rates and 3 phases

1. $b \to s\gamma_R$
2. $b \to s\gamma_L$
3. $\bar{b} \to \bar{s}\gamma_L$
4. $\bar{b} \to \bar{s}\gamma_R$

In $B^\pm$ decay there are 4 rates and 2 phases

1. $b \to s\gamma_R$
2. $b \to s\gamma_L$
3. $\bar{b} \to \bar{s}\gamma_L$
4. $\bar{b} \to \bar{s}\gamma_R$
Conclusions

- Oscillations in $B \rightarrow K^* \gamma$ and more generally $B \rightarrow X_s \gamma$ provide a good ($\lesssim 10\%$) null test for New Physics beyond the SM.

- The consistency of a NP signal versus SM contamination can be tested by checking the variation with $X_s$ and Dalitz variables.

- The decay $B \rightarrow \phi K \gamma$ is an excellent choice for oscillation studies

- Angular distributions in $B \rightarrow \phi K \gamma$ can elucidate all the polarization observables of the photon.

- In particular, $C$-even $P$-odd observables are an excellent null test of the SM, only $O(1\%)$ SM contamination.