Radiative B Decays – “Standard Candles” of Flavor Physics

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Matthias Neubert – Cornell University

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Outline

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• Inclusive $B \rightarrow X_s \gamma$ Decay Rate
• Implications for New Physics
• Inclusive CP Violation and Photon Polarization
• $B \rightarrow X_s \gamma$ Photon Spectrum and $|V_{ub}|$
• Exclusive $B \rightarrow K^* \gamma$ and $B \rightarrow \rho \gamma$ Decays
• Conclusions
1. Introduction

- $b \rightarrow s \gamma$ transitions are the prime example of flavor-changing neutral currents (FCNCs), which are forbidden in the Standard Model at tree level.
- Sensitivity to heavy particles in loops (penguins).
excellent probe for physics beyond the Standard Model (SM), since:

- SM rate is small, yet well measured experimentally
- SM rate can be calculated with high precision
- large generic sensitivity to non-standard sources of flavor violation and CP violation

⇒ powerful constraints on many New Physics scenarios, including SUSY
starting point of the most sophisticated calculation in flavor physics is the effective weak Hamiltonian:

\[ H_{\text{eff}} = -\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i(\mu) Q_i(\mu) \]

NLO calculation of Wilson coefficients requires:
- 3-loop anomalous dimensions [Chetyrkin, Misiak, Munz (96)]
2. Inclusive $B \rightarrow X_s \gamma$ Decay Rate

\[\hat{\gamma}^{(1)} = \begin{pmatrix}
\frac{-355}{9} & \frac{-502}{27} & \frac{-1412}{243} & \frac{-1369}{243} & \frac{134}{243} & \frac{-35}{162} & \frac{-818}{243} & \frac{3779}{324} \\
\frac{-35}{3} & \frac{-28}{3} & \frac{-416}{81} & \frac{1280}{81} & \frac{56}{81} & \frac{35}{27} & \frac{508}{81} & \frac{1841}{108} \\
0 & 0 & \frac{-4468}{81} & \frac{-31469}{81} & \frac{400}{81} & \frac{3373}{108} & \frac{22348}{243} & \frac{10178}{81} \\
0 & 0 & \frac{-8158}{243} & \frac{-59399}{243} & \frac{269}{486} & \frac{12899}{648} & \frac{-17584}{243} & \frac{-172471}{648} \\
0 & 0 & \frac{-251680}{81} & \frac{-128648}{81} & \frac{23836}{27} & \frac{6106}{243} & \frac{1183696}{729} & \frac{2901296}{243} \\
0 & 0 & \frac{58640}{243} & \frac{-26348}{243} & \frac{-14324}{243} & \frac{2551}{162} & \frac{2480344}{2187} & \frac{-3296257}{729} \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{4688}{27} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{-2192}{81} & \frac{4063}{27}
\end{pmatrix}\]
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- electroweak radiative corrections [Czarnecki, Marciano (98); Kagan, Neubert (98); Gambino, Haisch (01)]
2-loop matching coefficients at the weak scale, known for:

- **SM** [Adel, Yao (94); Greub, Hurth (97)]

![Diagrams](image-url)
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- constrained MSSM [Ciuchini et al. (98); Bobeth, Misiak, Urban (99)]
- constrained MSSM with large $\tan \beta$ [Degrassi, Gambino, Giudice (00); Carena et al. (00)]
matrix elements for the total inclusive rate are calculated using the operator product expansion:

\[ O(1) \]

\[ O(\alpha_s) \]

\[ O(1/m_b^2) \]

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- Power corrections calculable using heavy-quark effective theory
  [Falk, Luke, Savage (93); Voloshin (96)]
photon-energy cut $E_\gamma > 2.0$ GeV introduces sensitivity to the shape of the photon spectrum (“Fermi motion”), which can be analysed using the twist expansion

[Neubert (93); Bigi et al. (93)]

\[
\text{Data} \quad \text{Spectator Model}
\]

\[
\text{cut}
\]

\[
\text{CLEO '01}
\]

\[
\text{contained fraction} = (91\pm3\pm6)\%
\]

(sometimes included as part of the experimental uncertainty)
Recent Improvements

- use of running charm-quark mass $m_c(\mu)$ (rather than pole mass) in charm-penguin diagrams
  
  [Gambino, Misiak (01)]

  ⇒ sizeable enhancement by about 10% (!)

- reduction of renormalization-scale dependence by keeping $m_b(m_W)$ in the top sector normalized at a high scale
  
  [Gambino, Misiak (01)]

- completion of two-loop matrix elements for penguin operators (tiny effect)
  
  [Buras et al. (02)]

- avoid normalization to semileptonic rate (using $m_b^{\text{pole}} \rightarrow m_b^{1S}$ conversion)
  
  [Becher et al. (02)]
Results for total branching ratio

energy cut $E_\gamma > 1.6$ GeV:

$$\text{Br}(B \to X_s \gamma) = \begin{cases} (3.57 \pm 0.30) \cdot 10^{-4} ; \\ (3.54 \pm 0.30) \cdot 10^{-4} ; \end{cases}$$

[Becher et al. (02)]

extrapolation to $E_\gamma > 2.0$ GeV: [Becher et al. (02)]

$$\text{Br}(B \to X_s \gamma) = (3.26 \pm 0.27^{+0.09}_{-0.18}) \cdot 10^{-4}$$

compares well with CLEO measurement of

$$(2.94 \pm 0.39 \pm 0.25) \cdot 10^{-4}$$
extrapolation to total branching ratio:

\[ \text{Br}(B \rightarrow X_s \gamma) = (3.64 \pm 0.31) \cdot 10^{-4} \]

-compares well with Belle measurement of

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Models with minimal flavor violation:

- CKM matrix is the only source of quark-flavor mixing (e.g., type-II 2HDM, CMSSM, . . .)
- typically only moderate FCNC effects allowed after constraints from EW precision data are included
- phenomenologically “preferred”, since data show no evidence for non-standard flavor (or CP) violation
- theoretically somewhat ad hoc (naturalness?)
Models with new sources of flavor violation:

- e.g., generic SUSY extensions of the SM, models with new quark generations, etc.
- more “natural”, since we expect some physics beyond the SM to explain the origin of flavor
- generically, these models can have drastic effects on FCNC processes!
  \[(K-\bar{K} \text{ mixing, } B \rightarrow X_s \gamma, K \rightarrow \pi \nu \bar{\nu}, \ldots)\]
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SUSY flavor problem
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- in a generic model, each flavor-changing process receives its own, characteristic New-Physics effects
- adjusting flavor parameters in an ad hoc way leads to correlations between observables that are strongly model dependent

\[ (K \leftrightarrow \bar{K} \leftrightarrow B \rightarrow X_s \gamma \leftrightarrow K \rightarrow \pi \nu \bar{\nu} \leftrightarrow \ldots) \]
charged-Higgs contribution adds constructively to SM contribution  \( \Rightarrow \) obtain a strong bound on \( m_{H^+} \)

complete NLO analysis [Ciuchini et al. (97); Borzumati, Greub (98)]

most recent update yields \( m_{H^+} > 350 \) GeV at 99% CL

[Gambino, Misiak (01)]
more generally, expect constructive or destructive interference with SM contribution: [Kagan, Neubert (98)]

\[ 10^4 \text{Br}(B \rightarrow X_s \gamma) \approx 3.26 + 1.40 \text{Re} \xi_7 + 0.14 \text{Re} \xi_8 \\
+ 0.37 (|\xi_7|^2 + |\xi_7^R|^2) + 0.08 \text{Re} (\xi_7 \xi_8^* + \xi_7^R \xi_8^{R*}) \]

where the New Physics contributions are

\[ \xi_{7,8} = \frac{C_{7,8}^{NP}(m_W)}{C_{7,8}^{SM}(m_W)}, \quad \xi_{7,8}^R = \frac{C_{7,8}^{R,NP}(m_W)}{C_{7,8}^{SM}(m_W)} \]

possible to have large New Physics contributions if \( \text{Re} \xi_{7,8} < 0 \) (destructive interference), and if one is willing to accept some fine-tuning.
CMSSM with minimal flavor violation

three types of contributions:

\[ C_{7,8}(m_W) = C_{7,8}^{SM}(m_W) + C_{7,8}^{H}(m_W) + C_{7,8}^{X}(m_W) \]

- \( C_{7,8}^{SM}(m_W) \): SM
- \( C_{7,8}^{H}(m_W) \): type-II 2HDM
- \( C_{7,8}^{X}(m_W) \): chargino-stop
several recent analyses, including novel higher-order terms enhanced by large $\tan\beta$:

[Carena et al. (00); Degrassi et al. (00); Demir, Olive (01); Boz, Pak (02)]

⇒ strongly favors negative values of $\mu A_t$ (with positive $\mu$ preferred)
important finding that large-$\tan \beta$ corrections can weaken the bound on the charged Higgs mass even in the decoupling limit:

[Degrassi, Gambino, Giudice (00); Carena et al. (00)]
new SUSY flavor-changing quark-squark-gluino couplings can be parameterized in terms of off-diagonal entries in the squark mass matrix, e.g.

\[ \delta_{23}^{LR} = \frac{(m_{LR}^2)_{23}}{m_{\tilde{q}}} \] etc. (naively of \( O(1) \))

many analyses based on the mass insertion approximation [Gabbiani et al. (96); Hagelin, Kelley, Tanaka (94); ...]
recent, more complete analysis includes interplay of contributions from gluinos, neutralinos, charginos, and charged Higgs [Besmer, Greub, Hurth (01)]

only 2 flavor-violating parameters

4 flavor-violating parameters

⇒ find that constraints on $\delta_{23}^{LR,RL}$ can be significantly relaxed due to interference effects
Flavor violation from light $\tilde{b}$ squarks

presence of a light $\tilde{b}$ squark (mass $\sim 2$–$4$ GeV) and gluino (mass $\sim 15$ GeV) could explain the observed excess of $b$-production at the Tevatron [Berger et al. (00)]

$\bullet$ this would give rise to new sources of $b \to s$ FCNC transitions
flavor-violations can be parameterized in terms of 
\[ \epsilon_{sb}^{LR} = \Gamma_{s3}^{L} \Gamma_{b3}^{R} \text{ etc. (naively of } O(1)) \]

complete NLO analysis gives extremely tight constraints on these couplings [Becher et al. (02)]
4. CP Asymmetry in $B \rightarrow X_s \gamma$

- additional, powerful probe for New Physics
- basically a null effect in the SM, since:

  \begin{align*}
  A_{CP}(B \rightarrow X_s \gamma) & \sim \alpha_s(m_b) \times \frac{V_{ub}}{V_{cb}} \times \frac{m_c^2}{m_b^2} \\
  & \approx 0.5\%
  \end{align*}

and

\begin{align*}
A_{CP}(B \rightarrow X_{s/d} \gamma) & = 0
\end{align*}

- large asymmetries are possible in extensions of the SM with new CP-violating couplings entering the Wilson coefficients
approximate expression (without new operators):

\[ A_{CP} \approx 1.3\% \, \text{Im}(C_2/C_7) - 9.5\% \, \text{Im}(C_8/C_7) \]
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- second term is important for models with enhanced chromo-magnetic dipole transitions (\(C_8\)) and new CP-violating couplings, and can lead to CP asymmetries exceeding 10–20%
An example: [Kagan, Neubert (98)]

\[(\frac{C8}{C7})_{NP} = 6\]

Allowed range: [0, 1.5]
two recent analyses in MSSM with minimal flavor violation but explicit CP violation ($\phi_\mu, \phi_A \neq 0$)

[Demir, Olive (01); Boz, Pak (02)]

including large-$\tan \beta$ enhanced contributions beyond leading order, they find significant (complex) contributions to $C_{7,8}$, e.g.:
this can lead to $A_{CP}(B \rightarrow X_s \gamma)$ of order 10% without spoiling the SM prediction for the branching ratio:
radiative $B$ decays in the SM have helicity structure $b_R \rightarrow s_L\gamma_L$; however, in many extensions of the SM (e.g., left-right symmetric models, SUSY) there can be couplings with opposite helicity ($\rightarrow$ parameters $\xi_{7,8}^R$ above) photon polarization can be measured in $B \rightarrow K_{\text{res}}\gamma$ decays (followed by $K_{\text{res}} \rightarrow K^*\pi \rightarrow K\pi\pi$), by studying the up-down asymmetry of the photon direction relative to the $K\pi\pi$ decay plane [Gronau et al. (01)] asymmetry can be calculated reliably to be $(34 \pm 5)\%$ for $K_1(1400)$ gross deviations from this prediction would signal the presence of opposite-chirality transitions from New Physics
5. Photon Spectrum as a QCD Tool

$B \to X_s \gamma$ photon energy spectrum is insensitive to New Physics and therefore a great QCD laboratory:

- moments $\langle E_\gamma \rangle$ and $(\langle E_\gamma^2 \rangle - \langle E_\gamma \rangle^2)$ provide a precise determination of the $b$-quark mass and other HQET parameters
  \[ \Rightarrow \] helps in the determination of $|V_{cb}|$

- combination of $B \to X_s \gamma$ photon spectrum and $B \to X_u l \nu$ charged-lepton spectrum provide the currently best route to measuring $|V_{ub}|$ (immensely important for unitarity-triangle physics at the $B$ factories)
non-perturbative effects in endpoint region of $B \to X_s \gamma$ and $B \to X_u l \nu$ can be related to a universal shape function (up to $1/m_b$ corrections): [Neubert (93)]

- measure the $B \to X_s \gamma$ photon spectrum $S(E_\gamma)$
- predict the fraction of events with charged-lepton energy $E_l > E_0$ via

$$
F_u(E_0) = \frac{4}{m_b} \int_{E_0}^{m_B/2} dE_\gamma w(E_\gamma, E_0) S(E_\gamma)
$$

where the weight function $w(E_\gamma, E_0)$ is known including perturbative and $1/m_b$ corrections

[Neubert (93); Leibovich, Low, Rothstein (99); Bauer, Luke, Mannel (02)]
extract $|V_{ub}|$ from a measurement of the $B \rightarrow X_u l \nu$ decay rate in the region above 2.2 GeV

theoretical uncertainty on $|V_{ub}|$ is of order 10% or less

experimental result (CLEO ’01):

$$|V_{ub}| = (4.08 \pm 0.56_{\text{exp}} \pm 0.29_{\text{th}})$$
6. Exclusive Radiative Decays

- significant recent progress in theory of exclusive hadronic $B$ decays based on QCD factorization theorems [Beneke et al. (99)]

- factorization formula for $B \rightarrow V \gamma$ ($V = K^*$ or $\rho$):
  [Bosch, Buchalla (01); Beneke, Feldmann, Seidel (01)]

\[
\langle V \gamma(\epsilon) | Q_i | B \rangle = \left[ F_{B \rightarrow V} (0) T^I_i + \int_0^1 d\xi \, dx \, T^{II}_i (\xi, x) \, \Phi_B (\xi) \, \Phi_V (x) \right] \cdot \epsilon^*
\]

- opens up novel probes for New Physics, since e.g. CP asymmetries can be enhanced w.r.t. inclusive decays
particularly important for $b \to d\gamma$ transitions, where inclusive measurements are hindered by the large $b \to s\gamma$ background.

SM prediction is that $b \to d\gamma$ decays are about 20 times smaller than $b \to s\gamma$ decays, but CP asymmetries are predicted to be 20 times larger!
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expectation is supported by tight experimental bounds $\text{Br}(B^- \to \rho^-\gamma) < 2.8 \cdot 10^{-6}$ and $\text{Br}(B^0 \to \rho^0\gamma) < 1.5 \cdot 10^{-6}$, which imply (BaBar ’02):

$$\frac{\text{Br}(B^- \to \rho^-\gamma)}{\text{Br}(B^- \to K^{*-}\gamma)} < 0.07, \quad \frac{2\text{Br}(B^0 \to \rho^0\gamma)}{\text{Br}(B^0 \to K^{*0}\gamma)} < 0.07$$
Isospin Violation in $B \rightarrow K^{*}\gamma$

in SM, the leading contribution to isospin asymmetry

$$\Delta_{0-} = \frac{\Gamma(B^0 \rightarrow K^{*0}\gamma) - \Gamma(B^- \rightarrow K^{*-}\gamma)}{\Gamma(B^0 \rightarrow K^{*0}\gamma) - \Gamma(B^- \rightarrow K^{*-}\gamma)} = (8 \pm 2)\%$$

is due to the 4-quark penguin operator

$$Q_6 = (\bar{s}_i b_j) V_{-A} \sum_q (\bar{q}_j q_i) V_{+A}$$

$\Rightarrow$ direct probe of sign and magnitude of the ratio

$\text{Re}(C_6/C_7)$ of Wilson coefficients [Kagan, Neubert (01)]
new window to New Physics; for instance, a positive value for the asymmetry would exclude a large region of MSSM parameter space at large $\tan \beta$, where $\text{Re}(C_7) > 0$:

![Graph showing the relation between Re($C_7$) and tan(β)]

- present experimental situation is inconclusive, since $\Delta_0^- = (3 \pm 6)\%$
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- had no time to discuss related processes such as $b \rightarrow s l^+ l^-$, $b \rightarrow s\nu\bar{\nu}$, $K \rightarrow \pi\nu\bar{\nu}$, which are equally rich
only a pessimist would take the absence of non-standard contributions (within present errors) in radiative and other rare $B$ decays as an argument against low-energy SUSY . . .
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. . . . . while the optimist looks forward to SUSY 2003