P and CP VIOLATION IN B PHYSICS

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Outline

- Motivation
- Radiative decays
  - $B \to X_s\gamma,\ X_s \to K\pi\pi$
  - photon polarization provides precision test of Standard Model
- Hadronic decays
  - $B^0 \to D^{*-}a_1^+$
  - V-A test $\bar{c}\gamma_\mu(1-\gamma_5)b$
  - $2\beta+\gamma$ from CP asymmetry, no discrete ambiguity
- Conclusion

References

- hep-ph/0107254: M.G, Y. Grossman, D. Pirjol and A. Ryd, PRL 88, 051802 (2002)
- hep-ph/0205065: M.G. and D. Pirjol, PRD 66, 054008 (2002)
- hep-ph/0209230: M.G., D. Pirjol and D. Wyler

Talk will NOT REVIEW methods for measuring
$\beta \equiv \phi_1,\ \alpha \equiv \phi_2,\ \gamma \equiv \phi_3$

We are awaiting more precise measurements of
$B \to \pi\pi,\ B \to K\pi,\ B \to DK$

Motivation

b couplings $\Rightarrow$ CKM tests

- P violation $\leftrightarrow$ chiral structure
  - $|V_{cb}| \simeq 0.04 \quad \bar{c}\gamma_\mu(1-\gamma_5)b\ \ ?$
  - $|V_{ub}| \simeq 0.003 \quad \bar{u}\gamma_\mu(1-\gamma_5)b\ \ ?$
  - small $|V_{ib}|$ are sensitive to right-handed b couplings, in particular in loop (penguin) processes
- CP violation $\leftrightarrow$ weak phases
  - precise measurement of $\beta = \mathrm{Arg}V_{td}^* \quad *\,**$
  - measurements of $\gamma = \mathrm{Arg}V_{ub}^*,\ \ \alpha = \pi - \beta - \gamma\ \ ?$
  - CKM precision tests - if no new phase due to penguin amplitude

Motivation (cont.)

Beyond Standard Model

- Models
  - Left-right symmetry
  - Supersymmetry
- Signatures
  - Right-handed couplings
  - New CP phases

Photon helicity in $b \to s\gamma$

- $\mathcal{B}(\bar{B} \to X_s\gamma)$ agrees with SM within $10 - 20\%$
- In SM photon is left-handed up to m_s/m_b
- In Left-Right symmetric and SUSY models the photon may have a large right-handed component

$$\mathcal{H}_{\rm rad} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(C_{7L}\mathcal{O}_{7L} + C_{7R}\mathcal{O}_{7R} \right)$$

$$\mathcal{O}_{7L,R} \propto \bar{s}\sigma_{\mu\nu}\frac{1 \pm \gamma_5}{2} b F^{\mu\nu}$$

Standard Model: $C_{7R}/C_{7L} = m_s/m_b$

Fujikawa & Yamada; Cho & Misiak; Everett *et al.*

Earlier suggestions for measuring λ_γ

- CP asymmetries in $B^0(t) \to X_s^{(CP)}\gamma$

  Atwood, M.G., Soni

- angular correlations in $B \to K^*(\to K\pi)\ell^+\ell^-$

  Melikhov *et al.*; Krúger *et al.*; Kim *et al.*; Grossman & Pirjol

- Λ-Λ_b correlation in $\Lambda_b(\text{polarized}) \to \Lambda(\to p\pi)\gamma$

  Mannel & Recksiegel; Hiller & Kagan

may require very high luminosity B or Z factories

Photon helicity in $B \to K_{\text{resonance}}\,\gamma$

- Resonance states were observed

$$10^5\mathcal{B}(B \to K_2^*(1430)\gamma) = 1.66^{+0.59}_{-0.53} \pm 0.13 \quad \text{(CLEO)}$$
$$= 1.50^{+0.58+0.11}_{-0.53-0.13} \quad \text{(Belle)}$$

K_2^* are observed in $K_2^* \to K\pi$

- States decaying to $K\pi\pi$ were also observed (Belle)

helicity measurement requires 3-body recoil $K\pi_1\pi_2$

1. λ_γ is P-odd
2. no odd momentum correlation from 2-body
3. $\vec{p}_\gamma \cdot (\vec{p}_1 \times \vec{p}_2)$ is P-odd; T-odd requires FSI

λ_γ in $K_1(1400) \to K\pi\pi$

$$K_1^+(1400) \to \left\{ \begin{array}{c} K^{*+}\pi^0 \\ K^{*0}\pi^+ \end{array} \right\} \to K^0\pi^+\pi^0 \quad : \qquad K_1^0 \to K^+\pi^-\pi^0$$

$$\mathcal{B}(K_1 \to K^*\pi) = 0.94 \pm 0.06, \quad (D/S = 0.04 \pm 0.01)$$
$$\mathcal{B}(K_1 \to \rho K) = 0.03 \pm 0.03$$

$$|A(B \to K_1\gamma \to K\pi\pi\gamma)|^2 = |c_L|^2|\mathcal{M}_L|^2 + |c_R|^2|\mathcal{M}_R|^2$$

$$\lambda_\gamma \equiv \frac{|c_R|^2 - |c_L|^2}{|c_R|^2 + |c_L|^2} = \frac{|C_{7R}|^2 - |C_{7L}|^2}{|C_{7R}|^2 + |C_{7L}|^2}$$

Standard Model: $\lambda_\gamma = -1 + \mathcal{O}(m_s^2/m_b^2)$ for $B^-, \bar{B}^0$

Calculate $\langle \vec{p}_\gamma \cdot (\vec{p}_1 \times \vec{p}_2) \rangle_{K_1(1400)}$

$$\mathcal{M} \propto \varepsilon^\mu \left[p_{1\mu}\left(1 - \frac{m_K^2 - m_\pi^2}{m^2(K^*)}\right) + 2p_{2\mu} \right] BW(s_{23}) - (p_1 \leftrightarrow p_2) \equiv \varepsilon \cdot J$$

$$\frac{d\Gamma}{ds_{13}ds_{23}d\cos\theta} \propto |\vec{J}|^2(1+\cos^2\theta) + \lambda_\gamma 2\mathrm{Im}\left(\hat{n}\cdot(\vec{J}\times\vec{J}^*)\right)\cos\theta$$

$$\text{up down asymmetry } \mathcal{A} = \frac{\int_0^{\pi/2} d\Gamma - \int_{\pi/2}^{\pi} d\Gamma}{\int_0^{\pi} d\Gamma} = (0.33 \pm 0.05)\lambda_\gamma$$

$\hat{n} =$ normal to decay plane

$\theta =$ angle between normal to decay plane and γ

$BW(s) = \left[s - m(K^*)^2 - im(K^*)\Gamma(K^*)\right]^{-1}$

Precision

Theoretical assumptions

- Lorentz invariance
- Isospin symmetry

Hadronic uncertainties

- D wave in $K_1 \to K^*\pi$: $D/S = 0.04 \pm 0.01$
- $\mathcal{B}(K_1 \to \rho K) = 0.03 \pm 0.03$

$$\Rightarrow \quad \mathcal{A} = (0.33 \pm 0.05)\lambda_\gamma$$

15% measurement of $\lambda_\gamma = -1 + \mathcal{O}(m_s^2/m_b^2)$
better measurement by full energy and angular distribution

Feasibility

- Standard Model Signature: In B^- and $\bar{B}^0$ decays the photon prefers to move in the hemisphere of $\vec{p}^{\,\pi}_{\rm slow} \times \vec{p}^{\,\pi}_{\rm fast}$
- Assume $\mathcal{B}(B \to K_1(1400)\gamma) = 0.7 \times 10^{-5}$
  $\Rightarrow \mathcal{A}(3\sigma)$ can be measured with 10^8 $B^0/\bar{B}^0, B^+/B^-$ pairs
  15% measurement of λ_γ require 10^9 pairs
- Energy and angle distributions can distinguish $K_1(1400)$ from other resonances

Belle and BABAR: Please, study $B \to K\pi\pi\gamma$

Helicity amplitudes in hadronic decays

$B \to VV$, e.g. $B^0 \to D^{*-}(\to D\pi)\rho^+(\to \pi\pi)$

- Final particle distribution determines V-polarization
- Measure rates $\Gamma_i,\ i = 0, \|, \perp$ and certain interference
- Factorization $\&$ HQ prediction ($\Gamma_0/\Gamma = 0.884$) agrees well with experiment ($\Gamma_0/\Gamma = 0.878 \pm 0.034 \pm 0.030$)
- Time-dependence measures $2\beta + \gamma$ with discrete ambiguity

Measurements cannot

- distinguish between Left- and Right-polarization
- determine the sign of $\sin(2\beta + \gamma)$

Advantage of $B \to VA$

$$B^0 \to D^{*-}(\to D\pi)a_1^+(\to 3\pi)$$

Will show:

1. 3-body decay distinguishes between Left and Right polarization and enables measurements of Γ_L and Γ_R
2. Tests $\bar{c}\gamma_\mu(1-\gamma_5)b$
3. Time-dependence measures $2\beta+\gamma$ without discrete ambiguity

Cannot be achieved with 3-body decays of V in $B \to VV$

Calculate $B^0 \to D^{*-} a_1^+$ in helicity amps

$$A(B^0 \to D^{*-}\pi^+(p_1)\pi^+(p_2)\pi^-(p_3)) = \sum_{i=0,+,-} H_i A_i$$

$$A_i = A_i(a_1^+ \to \rho^0\pi^+(p_2)) + A_i(a_1^+ \to \rho^0\pi^+(p_1))$$

$$A(a_1^+(\varepsilon) \to \pi_1^+\pi_2^+\pi_3^-) = \varepsilon \cdot J$$

$J =$ symmetric under $p_1 \leftrightarrow p_2$ involves $BW_\rho(s_{ij})$

$$\frac{d\Gamma}{d\cos\theta} = (|H_+|^2 - |H_-|^2)\cos\theta \,\mathrm{Im}[(\vec{J} \times \vec{J}^*) \cdot \hat{n}] + (|H_+|^2 + |H_-|^2)\frac{1}{2}(1+\cos^2\theta)|\vec{J}|^2 + |H_0|^2 \sin^2\theta |\vec{J}|^2$$

$\theta =$ angle between normal to a_1 decay plane and D^*

θ distribution determines $|H_0|^2,\ |H_\pm|^2$

Test for factorization and $V-A$

- Factorization and HQ symmetry for $B^0 \to D^{*-} a_1^+$:

$$|H_0|^2 = 0.75\ , \quad |H_+|^2 = 0.21\ , \quad |H_-|^2 = 0.04$$

Left-component of $D^* \ll$ Right-component.

- Up-down asymmetry:

$$\mathcal{A} = \frac{\int_0^{\pi/2} d\Gamma - \int_{\pi/2}^{\pi} d\Gamma}{\int_0^{\pi} d\Gamma} = -0.042$$

5000 events are needed, BABAR measured 18,000

- $\bar{c}\gamma_\mu(1+\gamma_5)b$ would imply $\mathcal{A} = +0.042$

Time-dependent measurement of $2\beta + \gamma$

- interference of $B^0 \to D^{*-} a_1^+ \ (\bar{b} \to \bar{c} u \bar{d}) \quad \equiv H_i$
  and $\bar{B}^0 \to D^{*-} a_1^+ \ (b \to u \bar{c} d) \quad \equiv h_i$
- 2β = phase of $B^0 - \bar{B}^0$ mixing; $\quad \gamma$ = phase of V_{ub}^*

$$A \equiv A(B^0 \to D^{*-}(3\pi)^+) = \sum_{i=0,\|,\perp} H_i A_i$$

$$\bar{A} \equiv A(\bar{B}^0 \to D^{*-}(3\pi)^+) = \sum_{i=0,\|,\perp} h_i A_i$$

$$H_i = |H_i| \exp(i\Delta_i), \quad h_i = |h_i| \exp(i\delta_i) \exp(-i\gamma)$$

A_i = calculable functions of θ, ψ (defining D^* decay plane)

warning: $|h_i/H_j| \sim |V_{ub}V_{cd}/V_{cb}V_{ud}| \approx 0.02$

Time and angular dependence

$$\Gamma(B^0(t) \to D^{*-}(3\pi)^+) \propto 2\mathrm{Im}\left(e^{2i\beta} A\bar{A}^*\right) \sin\Delta m t$$
$$+ \ (|A|^2 + |\bar{A}|^2) + (|A|^2 - |\bar{A}|^2) \cos\Delta m t$$

$|A|^2,\ |\bar{A}|^2,\ \mathrm{Im}\left(e^{2i\beta} A\bar{A}^*\right) =$ sums over bilinears in H_i and h_j multiplying calculable functions of θ, ψ

$\Rightarrow$ determines all $\mathrm{Re}(H_i H_j^*),\ \mathrm{Im}(H_i H_j^*)$, $\mathrm{Re}[e^{2i\beta}(H_i h_j^* - H_j h_i^*)],\ \ \mathrm{Im}[e^{2i\beta}(H_i h_j^* + H_j h_i^*)]$

$$H_i = |H_i| \exp(i\Delta_i), \quad h_i = |h_i| \exp(i\delta_i) \exp(-i\gamma)$$

This fixes $2\beta + \gamma$ without any ambiguity and without having to measure $|h_i|^2$

Comparison with $B^0(t) \to D^{*-}\rho^+$

$B \to D^*\rho \ \ (\pi^0)$ London & Sinha's	$B \to D^* a_1 \ \ (\pi^\pm)$ above
helicity amps $g_i(\rho \to 2\pi)$	decay amps $A_i(a_1 \to 3\pi)$
$g_0, \ g_\parallel =$ real, $g_\perp$ = imaginary	A_i are all complex
no P-odd term	depends on $\lvert H_+\rvert^2 - \lvert H_-\rvert^2$
no $\mathrm{Re}[e^{2i\beta}(H_i h_j^* - H_j h_i^*)]$ AND $\mathrm{Im}[e^{2i\beta}(H_i h_j^* + H_j h_i^*)]$	rate measures both terms
$\Downarrow$ 1. cannot distinguish $H_+, \ H_-$ 2. sign ambiguity in $\sin(2\beta+\gamma)$	$\Downarrow$ measures $\lvert H_+\rvert$ and $\lvert H_-\rvert$ no ambiguity

Feasibility

- $\mathcal{B}(B^0 \to D^{*-} a_1^+) = 1.2\%$
- CP asymmetry in $\sin \Delta m t \;=\; 2|V_{ub}V_{cd}/V_{cb}V_{ud}| \approx 0.04$
- ~ 200 events are needed for angular dependence (CLEO)
- allow an order of magnitude for efficiencies and background

$\Rightarrow$ one needs at least $\mathcal{O}(10^8)$ B's

BABAR and Belle have 10^8 B's

Other applications

$\sin 2\beta$ was measured in $B^0(t) \to J/\psi K_S,\ J/\psi K^{*0}$

two-fold ambiguity between β and $\pi/2 - \beta$ can be resolved by measuring the sign of $\cos 2\beta$

- $B \to J/\psi K_1(1400) \quad \Rightarrow \quad \mathrm{sign}(\cos 2\beta)$
- $B \to D^{*-} K_1^+(1400) \Rightarrow$ another unambiguous measurement of $2\beta + \gamma$

Conclusion

- chirality tests of $V - A$ at tree level and one-loop
- clean and unambiguous determination of weak phases β and γ
- prospects for deviations from Standard Model

In the Standard Model P and CP violation are introduced by-hand; they may have a common origin

If P violation and the quark mass hierarchy have a common origin $\Rightarrow$ enhanced right-handed b couplings