PENGUINS IN $B$ DECAYS

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Abstract

We report on recent progress in studying two aspects of $B$ physics, in which penguin amplitudes play an important role:

1. Bounds on penguin pollution in $B^0(t) \to \pi^+\pi^-$ constraining the CKM parameters $\rho$ and $\eta$, and a lower bound on $B^0 \to \pi^0\pi^0$ improving precision in $\sin 2\alpha$.

2. A suggestion for measuring the photon polarization in electroweak penguin decay, $B \to K_{1}(1400)\gamma$, providing a test of the Standard Model and a probe for new physics.

1 Introduction

When being asked to choose a topic for my talk at this conference, I responded without hesitation by making the above choice. The topic of penguins in $B$ decays is quite broad and covers a large variety of aspects, some of which are discussed by other speakers at this conference. The two particular aspects to which I will address my talk are almost as old as the entire field of $B$ physics. Let me remind you how penguins entered heavy flavor physics. Gluonic penguin diagrams were introduced twenty five years ago\footnote{Invited talk at the Ninth International Symposium on Heavy Flavor Physics, Caltech, Pasadena, CA, Sept. 10–13, 2001.} when analyzing QCD effects in hadronic $K$ meson decays. Shortly afterwards penguin amplitudes were shown to play an important role in direct CP violation, first studied in $K$ decays\footnote{Inspired by the observation that intermediate heavy quarkonia imply sizable electroweak penguin amplitudes governing radiative $K$ and $B$ decays.} and soon afterwards in $B$ decays\footnote{This poses a difficulty in interpreting a measurement of the time-dependent CP}. A couple of years later it was realized that intermediate heavy fermions, such as a heavy top quark, imply sizable electroweak penguin amplitudes governing radiative $K$ and $B$ decays. These historical remarks lead naturally to my two topics.

1.1 Penguin pollution in $B^0(t) \to \pi^+\pi^-$

Calculations of direct CP violation in $B$ decays, due to interference between tree and penguin amplitudes, involve theoretical uncertainties in nonperturbative hadronic matrix elements of weak operators and uncertainties in final state interaction phases\footnote{This poses a difficulty in interpreting a measurement of the time-dependent CP}. This poses a difficulty in interpreting a measurement of the time-dependent CP
asymmetry in $B^0(t) \to \pi^+\pi^-$ in terms of a fundamental CKM phase $\beta, \gamma$. This problem, known as the problem of penguin pollution, is dealt with in Section 2. I will show first that a crude asymmetry measurement and an approximate knowledge of the ratio of penguin to tree amplitudes improve significantly our present knowledge of CKM parameters.

I will then discuss the cleanest way of resolving the penguin pollution $\beta$, which is based on applying isospin symmetry to the system of all three decays $B^0 \to \pi^+\pi^-, B^+ \to \pi^+\pi^0$ and $B^0 \to \pi^0\pi^0$. The most challenging experimental task in this method is measuring decay rates into two neutral pions while distinguishing between $B^0$ and $\bar{B}^0$ decays. I will report on recent theoretical progress made in order to overcome this difficulty.

1.2 Photon polarization in radiative $B$ decays

In the Standard Model radiative $B$ decays have one unambiguous signature which has not yet been tested. Namely, in decays of $B^-$ and $\bar{B}^0$ (containing a $b$ quark) the emitted photon is left-handed polarized, while in $B^+$ and $B^0$ it is right-handed. This prediction of maximal parity violation, holds to within a percent and, in principle, can serve as a precision test of the Standard Model. Deviations from this prediction are sensitive probes of new physics. In Section 3 I will survey several suggestions for studying photon helicity effects in radiative $B$ and $\Lambda_b$ decays, focusing on a particular method. A measurement of the photon polarization in $B \to K\pi\pi\gamma$, $m(K\pi\pi) = 1400$ MeV, through decay particle angular distributions, will be shown to be feasible at currently operating $B$ factories.

Finally, Section 4 contains several concluding remarks.

2 Bounds on penguin pollution in $B^0 \to \pi^+\pi^-$

2.1 CP asymmetry in $B^0(t) \to \pi^+\pi^-$

The weak phase $\alpha \equiv \arg(-V_{tb}^*V_{td}/V_{ub}^*V_{ud}) = \pi - \beta - \gamma$ occurs in the time-dependent rate of $B^0(t) \to \pi^+\pi^-$ and would dominate its asymmetry if only a tree amplitude $T$ contributed. In reality this process involves a second amplitude $P$ due to penguin operators which carries a different weak phase than the dominant tree amplitude, $A(B^0 \to \pi^+\pi^-) = |T|e^{i\delta_T}e^{i\gamma} + |P|e^{i\delta_P}$. \(1\)

The two terms contain CKM factors $V_{ub}^*V_{ud}$, $V_{cb}^*V_{cd}$ and weak phases $\gamma$ and 0, respectively. This leads to a generalized form of the time-dependent asymmetry, which includes in addition to the sin($\Delta mt$) term a cos($\Delta mt$) term due to direct CP violation $\beta$:

\[ A(t) = C_{\pi\pi} \cos(\Delta mt) + S_{\pi\pi} \sin(\Delta mt) \] \(2\)

\[ C_{\pi\pi} \equiv a_{dir} = \frac{1 - |\lambda_{\pi\pi}|^2}{1 + |\lambda_{\pi\pi}|^2}, \quad S_{\pi\pi} \equiv \sqrt{1 - a_{dir}^2} \sin 2(\alpha + \Delta \alpha) = \frac{2\text{Im}(\lambda_{\pi\pi})}{1 + |\lambda_{\pi\pi}|^2}. \] \(3\)
Figure 1: Constraints on parameters of the CKM matrix. Solid circles denote limits on $|V_{ub}/V_{cb}| = 0.090 \pm 0.025$ from charmless $b$ decays. Dashed arcs denote limits from $B^0$-$\bar{B}^0$ mixing. Dot-dashed arc denotes limit from $B_s$-$\bar{B}_s$ mixing. Dotted hyperbolae are associated with limits on CP-violating $K^0$-$\bar{K}^0$ mixing. Limits of $\pm 1\sigma$ from CP asymmetries in $B^0 \to J/\psi K_S$, $\sin(2\beta) = 0.79 \pm 0.10$, are shown by the solid rays. The small dashed lines represent constraints due to $1\sigma$ bounds $-0.53 \leq S_{\pi\pi} \leq 0.59$, with $0.21 \leq |P/T| \leq 0.34$. The plotted point lies in the middle of the allowed region.

where

$$\lambda_{\pi\pi} \equiv e^{-2i\beta} \frac{A(B^0 \to \pi^+\pi^-)}{A(B^0 \to \pi^+\pi^-)}.$$  \hspace{1cm} (4)

In the absence of the penguin amplitude one would have $C_{\pi\pi} = \Delta\alpha = 0$, $S_{\pi\pi} = \sin 2\alpha$. The time-dependent asymmetry measurement provides two equations for $C_{\pi\pi}$ and $S_{\pi\pi}$ in terms of $|P/T|$, $\delta \equiv \delta_P - \delta_T$ and $\alpha$. This is insufficient for a determination of $\alpha$. Knowledge of $|P/T|$ would, in principle, enable this determination up to discrete ambiguities. A crude estimate [10], $|P/T| = 0.3 \pm 0.1$, was obtained several years ago by applying flavor SU(3) to the ratio of $B \to \pi \pi$ and $B \to K\pi$ branching ratios first measured by CLEO [11]. A more precise evaluation including SU(3) breaking, from averaging recent CLEO, Belle and BaBar branching ratios [12], yields [13] $|P/T| = 0.276 \pm 0.064$. In a QCD factorization approach, where absolute hadronic weak amplitudes including strong phases are calculated, one finds [14] $|P/T| = 0.285 \pm 0.076$.

The BaBar Collaboration reported recently the first measurements of $C_{\pi\pi}$ and $S_{\pi\pi}$ [15]

$$C_{\pi\pi} = -0.25^{+0.45}_{-0.47} \pm 0.14 \hspace{1cm} S_{\pi\pi} = 0.03^{+0.53}_{-0.56} \pm 0.11.$$  \hspace{1cm} (5)

This asymmetry measurement is still very crude. Nonetheless, to anticipate the significance of future improvements, we have studied recently [13] the implication of
present 1σ bounds, $-0.53 \leq S_{\pi\pi} \leq 0.59$, on CKM parameters. Assuming that $\delta$ is small [6, 14], one has

$$S_{\pi\pi} \simeq \sin[2(\alpha + \Delta\alpha)] \; , \; \tan\alpha = \frac{\eta}{\eta^2 - \rho(1 - \rho)} \; , \; \tan\Delta\alpha = \frac{\eta|P/T|}{\sqrt{\rho^2 + \eta^2 + \rho|P/T|}} .$$

Using $0.21 \leq |P/T| \leq 0.34$ we found in [13] that the above 1σ bounds exclude more than half of the $(\rho, \eta)$ parameter space [16] allowed by all other constraints on CKM parameters. Results are shown in Fig. 1. The exclusion plot due to $S_{\pi\pi}$ is rather striking in view of the large uncertainties assumed here for $S_{\pi\pi}$ and $|P/T|$ which imply an uncertainty $\Delta\alpha$ in $\alpha$ as large as about $\pm 20^\circ$. The assumption of a small $\delta$ can be tested by improving limits on $C_{\pi\pi}$.

2.2 Combining $B^0 \rightarrow \pi^+\pi^-$ with $B^+ \rightarrow \pi^+\pi^0$, $B^0 \rightarrow \pi^0\pi^0$

The isospin method [9] requires measuring also the time-integrated rates of $B^+ \rightarrow \pi^+\pi^0$, $B^0 \rightarrow \pi^0\pi^0$ and their charge-conjugates. The three $B \rightarrow \pi\pi$ amplitudes obey an isospin triangle relation,

$$A(B^0 \rightarrow \pi^+\pi^-)/\sqrt{2} + A(B^0 \rightarrow \pi^0\pi^0) = A(B^+ \rightarrow \pi^+\pi^0) ,$$

while a similar relation holds for the charge-conjugate processes. One uses the different isospin properties of the penguin ($\Delta I = 1/2$) and tree ($\Delta I = 1/2, 3/2$) contributions and the well-defined weak phase ($\gamma$) of the tree amplitude. The electroweak penguin amplitude is very small [17], and can be dealt with as function as $V_{td}/V_{ub}$ in the isospin symmetry limit [18]. Laying the two isospin triangles such that they have a common side, $A(B^+ \rightarrow \pi^+\pi^0) = A(B^- \rightarrow \pi^-\pi^0)$, the angle between $A(B^0 \rightarrow \pi^+\pi^-)$ and $A(B^0 \rightarrow \pi^+\pi^-)$ is $2\Delta\alpha$ which then determines $\alpha$ from the asymmetry (2).

While this method is the cleanest theoretically, it suffers from the experimental difficulty associated with the two neutral pion mode. In fact, this introduces three kinds of practical complications:

1. $B^0 \rightarrow \pi^0\pi^0$ is argued to be color-suppressed and, although there exists no reliable calculation for this branching ratio, it is customarily assumed to be much smaller than the other two branching ratios.

2. One requires neutral $B$ flavor tagging in order to distinguish between $B^0 \rightarrow \pi^0\pi^0$ and $\bar{B}^0 \rightarrow \pi^0\pi^0$.

3. Neutral pions have a somewhat lower detection efficiency than charged pions.

In the subsequent discussion we will show how to overcome the first two obstacles, which lead one to ask the following question: Assuming that one has only an upper bound on the sum of $B^0$ and $\bar{B}^0$ decay branching ratios to $\pi^0\pi^0$, can one put an upper limit on $|\Delta\alpha|$? This question was addressed a few years ago, and a partial answer was given under the assumption that the sum of rates of $B^+ \rightarrow \pi^+\pi^0$ and its charge conjugate is known. An upper bound, based on right angle isospin triangles,
was given in terms of the ratio of charged-to-neutral $B$ lifetimes \cite{19} and the ratio of charge-averaged branching ratios $\mathcal{B}(B \to \pi^0\pi^0)/\mathcal{B}(B^\pm \to \pi^\pm\pi^0)$ \cite{20}:

$$|\sin(\Delta \alpha)| \leq \sqrt{\frac{r_B \mathcal{B}(B \to \pi^0\pi^0)}{\mathcal{B}(B^\pm \to \pi^\pm\pi^0)}}, \quad r_B = \frac{\tau_{B^+}}{\tau_{B^0}} = 1.068 \pm 0.016.$$  \hspace{1cm} (8)

A slight improvement, involving the direct CP asymmetry in $B^0 \to \pi^+\pi^-$, $a_{\text{dir}}$, as well as an independent bound assuming the knowledge of $\mathcal{B}(B \to \pi^+\pi^-)$ instead of $\mathcal{B}(B^\pm \to \pi^\pm\pi^0)$, were suggested in \cite{21}.

Although these two bounds are somehow related to the isospin triangles, neither of them involves all three $B \to \pi\pi$ processes, implying that the saturation of these bounds may be inconsistent with the closure of the triangles. Thus, the real question is what is the maximum value of $|\Delta \alpha|$, consistent with the closure, for given $\mathcal{B}(B \to \pi^+\pi^-)$ and $\mathcal{B}(B^\pm \to \pi^\pm\pi^0)$ and for an upper bound on $\mathcal{B}(B \to \pi^0\pi^0)$. The correct answer to this question was found recently \cite{22},

$$\cos(2\Delta \alpha) \geq \frac{(B^{+\mp}/2 - B^{00} + B^{+0}/r_\tau)^2 - B^{+\mp}B^{+0}/r_\tau}{\sqrt{1 - a^2_{\text{dir}}B^{+\mp}B^{+0}/r_\tau}}.$$  \hspace{1cm} (9)

where $B^{ij}$ are corresponding charge-averaged branching ratios. This bound is stronger than Eq. (8) and the bound \cite{21}, as demonstrated in \cite{22}. A crucial difference between Eq. (9) and the earlier bounds is that (9) includes also a lower bound on $B^{00}$, following from the triangle construction:

$$B^{00} \geq B^{+0}/r_\tau + B^{+\mp}/2 - \sqrt{(1 + \sqrt{1 - a^2_{\text{dir}}})B^{+\mp}B^{+0}/r_\tau} \geq \left(\sqrt{B^{+0}/r_\tau} - \sqrt{B^{+\mp}/2}\right)^2.$$  \hspace{1cm} (10)

The advantage of the two bounds Eqs. (9) and (11) over (8) and \cite{21} was demonstrated in \cite{22} when using the present world averaged branching ratios in units of $10^{-6}$ \cite{12}.

$$B^{+\mp} = 4.4 \pm 0.9, \quad B^{+0} = 5.6 \pm 1.5, \quad B^{00} < 5.7 \text{ (90\% C.L.)}.$$  \hspace{1cm} (11)

In order to illustrate the future potential power of these bounds in reducing the error in $\alpha$ due to penguin pollution, we list below values of the three branching ratios with corresponding errors, which were measured and which can be measured at $B$ factories with higher integrated luminosities. Errors in $B^{ij}$ scale down as $1/\sqrt{\text{luminosity}}$. For illustration purpose, we will take the future central value of $B^{+0}$ to be less than $1\sigma$ above its present central value.

| luminosity: | 30 fb$^{-1}$ | 120 fb$^{-1}$ | 500 fb$^{-1}$ |
|------------|-------------|-------------|-------------|
| $B^{+\mp}$ | 4.4 ± 0.9   | 4.4 ± 0.4   | 4.4 ± 0.2   |
| $B^{+0}$   | 5.6 ± 1.5   | 7.0 ± 0.8   | 7.0 ± 0.4   |
| $B^{00}$   | < 5.7       | < 1.4       | < 0.4 or seen |
| $B^{00}$   | ≥ 0.78 ± 0.62 | ≥ 1.35 ± 0.38 | ≥ 1.35 ± 0.19 |
The last line in the table gives the lower bounds on \( B^{00} \) obtained from Eq. (10) for the corresponding values of \( B^{+−} \) and \( B^{+0} \).

Thus, while an upper bound on \( B^{00} \) can be obtained from a direct measurement, useful lower bounds follow from measuring the other two branching ratios. If \( B^{00} \) is not very small, which does not seem unlikely in view of the present values of \( B^{+−} \) and \( B^{+0} \), one may be able to restrict its values from above and below to a narrow range. Consequently, the uncertainty in measuring \( \alpha \) becomes small. Assuming, for instance, that one finds \( 1.2 \leq B^{00} \leq 1.3 \), permitted by the lower bound derived for 500 fb\(^{-1} \), one obtains from Eq. (9) \( |\Delta \alpha| < 9° \). In comparison, the bound (8) implies only \( |\Delta \alpha| < 26° \). We stress that this demonstration of a rather precise determination of \( \alpha \) (where the uncertainty follows only from penguin pollution) assumes no separation between \( B^0 \) and \( \bar{B}^0 \) decays to \( \pi^0 \pi^0 \). Neutral \( B \) flavor tagging will reduce the uncertainty further.

### 3 The photon polarization in \( b \to s\gamma \)

The present agreement between experiment and the Standard Model (SM) prediction for the rate of inclusive \( B \to X_s\gamma \) is reasonable, at a level of 20% [23]. However, one basic feature, the left-handedness of the emitted photon in \( b \to s\gamma \), has never been tested. The photon is predominantly left-handed, since the recoil \( s \) quark which couples to a \( W \) is left-chiral. In several extensions of the SM, including left-right symmetric [24] and supersymmetric models [25], in which decay amplitudes involve \( W_L - W_R \) mixing and scalar exchange, the photon can acquire a large right-handed component without affecting substantially the inclusive rate.

Formally, the effective weak Hamiltonian for radiative \( b \) decays contains two Wilson coefficients, \( C_7L \) and \( C_7R \), multiplying operators, \( \mathcal{O}_{7L} \) and \( \mathcal{O}_{7R} \), describing left and right handed emitted photons,

\[
\mathcal{H}_{\text{rad}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* (C_{7L} \mathcal{O}_{7L} + C_{7R} \mathcal{O}_{7R}) , \quad \mathcal{O}_{7L,R} \equiv \frac{e}{16\pi^2 m_b s} \sigma_{\mu\nu} \frac{1}{2} \gamma_5 b F^{\mu\nu} . \quad (12)
\]

The photon polarization in inclusive \( b \to s\gamma \) is

\[
\lambda_\gamma \equiv \frac{|C_R|^2 - |C_L|^2}{|C_R|^2 + |C_L|^2} . \quad (13)
\]

In the SM, where \( C_{7R}/C_{7L} = m_s/m_b \), the polarization in exclusive decays is \( \lambda_\gamma = -1 \) within a percent, also when modified by long distance hadronic effects [26]. This prediction can provide precision tests of the SM and sensitive probes for new physics.

Several ways of carrying out such measurements were proposed in the past. They require very high luminosity \( B \) factories or new experimental facilities. We will describe very briefly these early suggestions, and will focus our attention on a recent proposal which is feasible at currently operating \( B \) factories.

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6
3.1 CP asymmetry in $B^0(t) \to X^{CP}_{s(d)} \gamma$

Consider the time-dependent rate of \[ B^0(t) \to X^{CP}_{s(d)} \gamma, \] where $X^{CP}_{s} = K^o \to K_S \pi^0$ or $X^{CP}_{d} = \rho^0 \to \pi^+ \pi^-$. The time-dependent CP asymmetry follows from interference between $B^0$ and $\bar{B}^0$ decay amplitudes into a common state of definite photon polarization, and is proportional to $C^7_R/C^7_L$. For instance, in the SM the asymmetry in $B^0(t) \to f, f = K^o \gamma \to (K_S \pi^0) \gamma$, is given by

\[
A(t) \equiv \frac{\Gamma(B^0(t) \to f) - \Gamma(\bar{B}^0(t) \to f)}{\Gamma(B^0(t) \to f) + \Gamma(\bar{B}^0(t) \to f)} = \frac{2A_LA_R}{A_L^2 + A_R^2} \sin 2\beta \sin(\Delta m t),
\]  

where $A_{L(R)}$ is the amplitude for a left (right) handed photon in $\bar{B} \to \bar{K}^* \gamma$. In the SM one expects $A_R/A_L \leq 0.05$ in the presence of long distance effects, whereas in extensions of the SM this ratio may be much larger [27].

3.2 Angular distribution in $\bar{B} \to \bar{K}^* \gamma \to \bar{K} \pi e^+ e^-$

Consider the decay distribution in this process as function of the angle $\phi$ between the $\bar{K} \pi$ and $e^+ e^-$ planes, where the photon can be virtual [28] or real, converting in the beam pipe to an electron-positron pair [29]. The $e^+ e^-$ plane acts as a polarizer, the distribution in $\phi$ is isotropic for purely circular polarization, and the angular distribution is sensitive to interference between left and right polarization. One finds

\[
\frac{d\sigma}{d\phi} \propto 1 + \xi A_L A_R \cos(2\phi + \delta),
\]  

where the parameters $\xi$ and $\delta$ are calculable and involve hadronic physics.

3.3 Forward-backward asymmetry in $\Lambda_b \to \Lambda \gamma \to p \pi \gamma$

The forward-backward asymmetry of the proton with respect to the $\Lambda_b$ in the $\Lambda$ rest-frame is proportional to the photon polarization $\lambda_\gamma$ [30]. Using polarized $\Lambda_b$’s from extremely high luminosity $e^+ e^-$ $Z$ factories, one can also measure the forward-backward asymmetry of the $\Lambda$ momentum with respect to the $\Lambda_b$ boost axis [31]. This asymmetry is proportional to the product of the $\Lambda_b$ and photon polarizations.

3.4 Angular distribution in $B \to K_1(1400) \gamma \to K \pi \pi \gamma$

In order to measure the photon polarization $\lambda_\gamma$ in radiative $B$ decays through the recoil hadron distribution, one requires that the hadrons consist of at least three particles. A hadronic quantity which is proportional to $\lambda_\gamma$ must be parity odd. The pseudoscalar quantity, which contains the smallest number of hadron momenta, is a triple product. The idea is then to measure an expectation value $\langle \vec{p}_\gamma \cdot (\vec{p}_1 \times \vec{p}_2) \rangle$, where $\vec{p}_1$ and $\vec{p}_2$ are momenta of two of the hadrons. Since the triple product is also time-reversal odd, a nonzero expectation value requires a phase due to final state
interactions. While in general such a phase would be incalculable, there are special cases where the decay occurs through two isospin-related intermediate resonance states, and the phase can be calculated simply in terms of Breit-Wigner forms [32].

Consider thedecays $B^+ \rightarrow K_1^+(1400)\gamma$ and $B^0 \rightarrow K_1^0(1400)\gamma$, where $K_1^+$ and $K_1^0$ are observed through

$$K_1^+(1400) \rightarrow \left\{ \begin{array}{l} K^{*+}\pi^0 \\ K^0\pi^+ \end{array} \right\} \rightarrow K^0\pi^+\pi^0, \quad K_1^0(1400) \rightarrow \left\{ \begin{array}{l} K^{*+}\pi^- \\ K^0\pi^0 \end{array} \right\} \rightarrow K^+\pi^-\pi^0. \quad (16)$$

Two Breit-Wigner amplitudes interfere due to intermediate $K^{*+}$ and $K^0$, $B(K_1 \rightarrow K^*\pi) = 0.94 \pm 0.06$ [10]. Decay to $\rho K$ will be neglected at this point, $B(K_1 \rightarrow \rho K) = 0.03 \pm 0.03$. The two $K^*$ amplitudes are related by isospin; therefore phases other those related to the Breit-Wigner phase cancel. The decay $K_1 \rightarrow K^*\pi$ is dominated by an $S$ wave and involves a small $D$ waves, where the $D/S$ ratio of rates is $|A_D/A_S|^2 = 0.04 \pm 0.01$ [16]. Using Lorentz invariance, it is straightforward to write down the decay amplitude for $B \rightarrow (K\pi\pi)_{K_1}\gamma$, and to calculate the decay distribution [32],

$$\frac{d\Gamma}{ds_{13}ds_{23}d\cos \theta} \propto |\tilde{J}|^2(1 + \cos^2 \theta) + \lambda\gamma 2\text{Im}(\hat{n} \cdot (\tilde{J} \times \tilde{J}^*) \cos \theta), \quad (17)$$

where

$$\tilde{J} = \tilde{p}_1 \left[ \left(1 - m_K^2 - m_\pi^2 \right) \left(1 - \kappa (p_{K^*} \cdot p_1 - m_\pi^2) \right) - 2\kappa p_1 \cdot p_2 \right] B(s_{23}) - 2B(s_{13}) \right], \quad (18)$$

$$B(s) = \left(s - m_{K^*}^2 - i m_{K^*} \Gamma_{K^*} \right)^{-1}, \quad s_{ij} = (p_i + p_j)^2. \quad (19)$$

The parameter $\kappa = [0.38 + 8.66 A_D/A_S e^{i(\delta_D - \delta_S)}][1 + 0.71 A_D/A_S e^{i(\delta_D - \delta_S)}]^{-1}\text{GeV}^{-2}$, $\delta_D - \delta_S = (260 \pm 20)^\circ$, parametrizes the $D$ wave contribution [16]. $p_1$ and $p_2$ are the two pion momenta, $p_3$ is the $K$ momentum, and $\theta$ is the angle between the normal to the decay plane $\hat{n} \equiv (\tilde{p}_1 \times \tilde{p}_2)/|\tilde{p}_1 \times \tilde{p}_2|$ and $-\tilde{p}_{\gamma}$, all measured in the $K_1$ rest frame. A useful definition of the normal is in terms of the slow and fast pion momenta, $(\tilde{p}_{\text{slow}} \times \tilde{p}_{\text{fast}})/|\tilde{p}_{\text{slow}} \times \tilde{p}_{\text{fast}}|$. The angle between this normal and $-\tilde{p}_{\gamma}$ will be denoted by $\hat{\theta}$.

The decay distribution exhibits an up-down asymmetry of the photon momentum with respect to the $K_1$ decay plane. The up-down asymmetry is proportional to the photon polarization. When integrating over the entire Dalitz plot one finds

$$A_{\text{up-down}} \equiv \frac{\int_0^{\pi/2} \frac{d\Gamma}{d\cos \theta} d\cos \hat{\theta} - \int_0^{\pi/2} \frac{d\Gamma}{d\cos \theta} d\cos \hat{\theta}}{\int_0^{\pi} \frac{d\Gamma}{d\cos \theta} d\cos \hat{\theta}} = (0.34 \pm 0.05) \lambda\gamma. \quad (20)$$

The uncertainty follows from experimental errors in the $\rho K$ and in the $D$ wave amplitudes. In the SM, where $\lambda\gamma \approx -1$, the asymmetry is $34 \pm 5\%$ and the polarization signature is unambiguous: In $B^-$ and $B^0$ decays the photon prefers to be emitted in the hemisphere of $\tilde{p}_{\text{slow}} \times \tilde{p}_{\text{fast}}$, while in $B^+$ and $B^0$ it is more likely to be emitted in the opposite hemisphere.
Is this measurement feasible at currently operating $B$ factories? A 3σ measurement of a 34% up-down asymmetry requires about 80 reconstructed $B \rightarrow K_1(1400)\gamma \rightarrow K\pi\pi\gamma$ events, including charged and neutral $B$ and $\bar{B}$ decays. Assuming $\mathcal{B}(B \rightarrow K_1\gamma) = 0.7 \times 10^{-5}$ [33] and including $K_1$ and $K^*$ branching ratios to the relevant charge states, one finds that this number of reconstructed events can be obtained from a total of $2 \times 10^7 B\bar{B}$ pairs, including charged and neutrals. This number has already been produced at $e^+e^-$ colliders. Since we ignored experimental efficiencies, resolution and background, one may have to wait a year or so before obtaining the required number of events.

The region of $K\pi\pi$ invariant mass around 1400 MeV contains also two other resonances, a spin 2 positive-parity $K^*_2(1430)$ which has already been observed in radiative $B$ decays [34, 35], and a vector state $K^*_1(1410)$, both of which decay to $K^*\pi$. (A nonresonant contribution in a narrow bin around $m(K\pi\pi) = 1400$ MeV is expected to be very small.) The $K^*_2$ decays involve a smaller up-down asymmetry with the same sign as $K_1$ [32] (although the integrated asymmetry vanishes), while the decay of $K^*_1$ is up-down symmetric. Whereas the overall polarization signature is unchanged, the integrated up-down asymmetry would be diluted relative to the asymmetry from $K_1(1400)$ if all three resonance contributions would be added. It is therefore useful to isolate the $K_1$ from the other two resonances. This can be achieved by applying to the data an angular decay distribution characterizing an axial vector particle.

### 4 Concluding remarks

- While the study of CP asymmetry in $B^0 \rightarrow \pi^+\pi^-$ in terms of $\sin 2\alpha$ is complicated by a penguin amplitude, even crude limits on the asymmetry may exclude a large part of the presently allowed CKM parameter space.

- A lower bound on the charge-averaged branching ratio of $B \rightarrow \pi^0\pi^0$ from measured $B \rightarrow \pi^+\pi^-$ and $B^\pm \rightarrow \pi^\pm\pi^0$ may reduce the uncertainty of measuring $\sin 2\alpha$, without carrying out the complete isospin analysis.

- The photon polarization in $b \rightarrow s\gamma$, predicted to be left-handed in the Standard Model, can be measured through angular decay distributions in $B \rightarrow K\pi\pi\gamma$ around $m(K\pi\pi) = 1400$ MeV.

I expect that in a year these measurements will lead to interesting and useful results.

### 5 Acknowledgments

I am grateful to D. Atwood, Y. Grossman, D. London, D. Pirjol, J. L. Rosner, A. Ryd, N. Sinha, R. Sinha and A. Soni for enjoyable collaborations on work discussed in this talk. I wish to thank SLAC and the Aspen Center for Physics where this talk was prepared. This work was supported in part by the Fund for the Promotion
of Research at the Technion, by the Israel Science Foundation founded by the Israel Academy of Sciences and Humanities, and by the U. S. – Israel Binational Science Foundation through Grant No. 98-00237.

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