Difference in $B^+$ and $B^0$ Direct CP Asymmetry as Effect of a Fourth Generation

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Direct CP violation in $B^0 \rightarrow K^+\pi^-$ decay has recently been observed \cite{1,2} at the B factories. The asymmetry in $B^+ \rightarrow K^+\pi^0$ decay is consistent with zero. This difference points towards possible New Physics in the electroweak penguin operator. We point out that a sequential fourth generation, with sizable $V_{t'q}, V_{t'b}$ and near maximal phase, could be a natural cause. We use the perturbative QCD factorization approach for $B \rightarrow K\pi$ amplitudes. While the $B^0 \rightarrow K^+\pi^-$ mode is insensitive to $t'$, we critically compare $t'$ effects on direct CP violation in $B^+ \rightarrow K^+\pi^0$ with $b \rightarrow s\ell^+\ell^-$ and $B_s$ mixing. If the $K^+\pi^0$-$K^+\pi^-$ asymmetry difference persists, we predict $\sin 2\Phi_{B_s}$ to be negative.

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Direct CP violation (DCPV) in $B^0 \rightarrow K^+\pi^-$ decay has recently been observed \cite{1,2} at the B factories. The combined asymmetry is $A_{K\pi} = -0.114 \pm 0.020$. However, the asymmetry in $B^+ \rightarrow K^+\pi^0$ decay is found to be $2\%^{+3\%}_{-0.4\%}$, which differs from $A_{K\pi}$ by

$$A_{K\pi^0} - A_{K\pi} = +0.163 \pm 0.045,$$  \hfill (1)

with 3.6$\sigma$ significance. All existing models have predicted $A_{K\pi} \sim A_{K\pi^0}$, as this basically follows from isospin symmetry. The large difference of Eq. (1) is not consistent, if it persists, could indicate isospin breaking New Physics (NP), likely $\lambda$ and $\lambda'$ through the electroweak penguin (EWP) operator.

In this paper we point out a natural source for such EWP effects: the existence of a 4th generation. The $t'$ quark can modify the DCPV coefficients, but leave the strong and electromagnetic penguin coefficients largely intact. Eq. (1) can be accounted for, provided that $m_{t'} \sim 300$ GeV, and the quark mixing elements $V_{t'q}, V_{t'b}$ is not much smaller than $V_{tb}$ and has near maximal CP phase. Independently, $b \rightarrow s\ell^+\ell^-$ and $B_s$ mixing constraints can allow large $t'$ effects only if $\lambda_{t'}$ associated CP phase is near maximal.

Precision electroweak data imply that $|m_{t'} - m_{t}|$ cannot be too large \cite{11}. Unitarity of quark mixing requires $|V_{tb}| < 0.08 \%^{+5}\%_{-3}\%$, while constraining $V_{t'q}, V_{t'b}$ appear Standard Model (SM) like, we set $V_{t'b} \sim 0$. We thus decouple from $s \rightarrow d$ constraints such as $\epsilon_K$ and $K \rightarrow \pi\nu\nu$ as well \cite{12}.

Adding a fourth generation modifies short distance coefficients. Defining $\lambda_{t'} = V_{t'q}, V_{t'b}$, the effective Hamiltonian relevant for $B \rightarrow K\pi$ can be written as

$$H_{\text{eff}} \propto \lambda_{t'} (C_1O_1 + C_2O_2) + \sum_{i=3}^{10} (\lambda_{c}C_i' - \lambda_{t'} \Delta C_i)O_i,$$  \hfill (2)

where $O_{1,2}$ are the tree operators, $\lambda_{c}C_i'$ are the usual SM penguin terms, and $-\lambda_{t'} \Delta C_i$ with $\Delta C_i \equiv C_{i'} - C_i$ is the 4th generation effect. We have used $\lambda_{u} + \lambda_{c} + \lambda_{s} + \lambda_{t'} = 0$, simplified by ignoring $|\lambda_{u}| \lesssim 10^{-3}$, such that $\lambda_{t'} \equiv -\lambda_{c} - \lambda_{t'}$. The penguin coefficients $\lambda_{c}C_{i'} + \lambda_{t'}C_i'$ at scale $\mu$ are then put \cite{10} in the form of Eq. (2), which respect the SM limit for $\lambda_{t'} \rightarrow 0$ or $m_{t'} \rightarrow m_{t}$. Explicit forms for $C_i$ and $O_i$ can be found, for example, in Ref. \cite{15}.

The $K\pi$ amplitudes are dominated by $C_4$. To illustrate $t'$ sensitivity, in Fig. 1 we plot $-\Delta C_i/C_{10}$ at $m_{t'}$ scale vs $m_{t'}$. The effect is clearly most prominent for the EWP C9 coefficient, with linear $\lambda_{t'} \propto m_{t'}/M_{W}^2$ dependence arising from $Z$ and box diagrams \cite{13}. $\Delta C_7$ has similar dependence but has weaker strength. For the strong penguin $\Delta C_{4,6}$, the $t'$ effect in the QCD penguin loop is weaker than logarithmic \cite{15} and is very mild. As we shall see, the $B^0 \rightarrow K^+\pi^-$ amplitude does not involve the EWP. In contrast, the $B^+ \rightarrow K^+\pi^0$ amplitude is sensitive to the EWP via $\Delta C_9 - \Delta C_7$ (virtual $Z$ materializing as $\pi^0$).

We see that it is natural for the 4th generation to show itself through the EWP. The effect depends also on the quark mixing matrix product, parameterized as \cite{10}

$$\lambda_{t'} = V_{t'q}^* V_{tb} = r_s e^{i\phi_s}. \hfill (3)$$

The phase $\phi_s$ is needed to affect the CPV observables, Eq. (4). Most works on the 4th generation have ignored the phase in $V_{t'q}^* V_{tb}$, making the 4th generation effect far less flexible nor interesting.

Let us first see how $A_{K\pi} < 0$ can be generated. In the usual QCD factorization (QCDF) approach \cite{10}, strong phases are power suppressed, while strong penguin $C_4$ and $C_6$ coefficients pick up perturbative absorptive parts. Thus, the predicted $A_{K\pi}$ is small, and turns out to be positive. For the perturbative QCD factorization (PQCDF) \cite{17} approach, one has an additional absorptive part coming from the annihilation diagram, which
arises from a cut on the two quark lines in $B \to s\bar{q} \to K\pi$ decay. In this way, the PQCDF approach predicted the sign and order of magnitude of $A_{K\pi}$. By incorporating annihilation contributions as in PQCDF, however, QCDF can also give negative $A_{K\pi}$.

We adopt PQCDF as a definite calculational framework. The $B^0 \to K^-\pi^+$ amplitude for the 3 generation SM is roughly given by

$$M_{K^-\pi^+} \propto \lambda_u f_K F_e + \lambda_c (f_K F_e^c + f_B F_a^c),$$

where $F_e^c$ is the color-allowed tree (strong penguin) contribution and is real, and $F_a^c$ is the strong penguin annihilation term that has a large imaginary part. We have dropped subdominant non-factorizable effects for sake of presentation. Details cannot be given here, but these factorizable contributions can be computed by following Ref. [17], convoluting the hard part (related to short distance coefficients $C_i$) and the soft, nonperturbative meson wave functions. Basically, all the $F_j^{(P)}$s are integrals over Bessel functions, and in particular, a Hankel function for $F_0^a$ [17]. We give the SM numbers for $F_e$, $F_e^c$ and $F_a^c$ in Table I, which leads to $A_{K\pi} = -0.16$ for $\phi_3 \equiv \arg \lambda_u^* = 60^\circ$ (value used throughout [18]), compared to the experimental value of $-0.114 \pm 0.020$.

For $B^+ \to K^-\pi^0$, the difference with $K^-\pi^0$ is

$$\sqrt{2} M_{K^-\pi^0} - M_{K^-\pi^+} \propto \lambda_u f_K F_e + \lambda_c f_K F_e^c,$$

where $F_{ek}$ is the color suppressed tree term, while $F_e^c$ is the color allowed EWP, and both are real. A negligible tree annihilation term $\lambda_u f_B F_a$ has been dropped. Since both the $F_{ek}$ and $F_{ek}^c$ terms are subdominant compared to $F_e^c$ in the 3 generation SM, $A_{K^-\pi^0}$ and $A_{K\pi}$ cannot be far apart. From the values of $F_{ek}$ and $F_{ek}^c$ given in Table I, we get $A_{K^-\pi^0} = -0.10$, which is less negative than $A_{K\pi}$, but at some variance with Eq. (1).

Adding the $t'$ quark, one finds $M_{K^-\pi^+} \equiv M_{K^-\pi^0}$. The difference is proportional to $\lambda_u (f_K \Delta F_{e,a} + f_B \Delta F_{a}^c)$, which is small unless $\lambda_u$ is very large. This is because $F_{a,\pi}$ are strong penguins, hence $\Delta F_{e,a}$ depends very weakly on $m_{t'}$, as can be seen from Table I (for $m_{t'} = 300$ GeV) and Fig. 1. Thus, $A_{K\pi}$ is insensitive to the 4th generation. For $K^-\pi^0$, one finds

$$\sqrt{2} M_{K^-\pi^0} - \sqrt{2} M_{K^-\pi^+} \propto -\lambda_u f_{\pi} \Delta F_{ek},$$

where again $\Delta F_{e,a}$ terms have been dropped, and $\Delta F_{ek}$ is the $t'$ correction to the EWP, which is generated by $\Delta C_9 - \Delta C_7$ at short distance.

Let us put the $K^-\pi^+$ and $K^-\pi^0$ amplitudes in more heuristic form. Eq. (1) can be put in the form

$$M_{K^-\pi^+} \approx M_{K^-\pi^0} \propto re^{-i\phi_3} + e^{i\delta},$$

and the 4th generation effect is minor. The ratio $r = |\lambda_u| f_K F_e/|\lambda_c| f_K F_e^c + f_B F_a^c|$ parameterizes the relative strength of tree $(T)$ vs. strong penguins $(P)$, and $\delta$ is the strong phase of $f_K F_e^c + f_B F_a^c$, arising from $F_a^c = |F_a^c| e^{i\delta_a}$. Analogously, for $K^-\pi^0$ one roughly has

$$M_{K^-\pi^0} \propto r \left(1 + \frac{f_{\pi} F_{ek}}{f_K F_e^c + f_B F_a^c} \right) e^{-i\phi_3} + \frac{f_{\pi} F_{ek}}{f_K F_e^c + f_B F_a^c} e^{i\phi_3} + e^{i\delta} - \frac{f_{\pi} \Delta F_{ek}}{f_K F_e^c + f_B F_a^c} \frac{V_{ub}^* V_{tb}}{V_{cb}^* V_{tb}} e^{i\phi_3},$$

where $F_{ek}$ and $F_{ek}^c$ terms come from SM (see Eq. (3)), and the $\Delta F_{ek}$ term comes from the $t'$ effect of Eq. (4). Since $r \sim 1/5$, we see from Table I that, for $m_{t'} \sim 300$ GeV and $|V_{ub} V_{tb}| \equiv r_5$ not much smaller than $|V_{cb}^* V_{tb}| \sim 0.04$, the impact of $t'$ on $A_{K^-\pi^0}$ could be significant.

We have presented in the above the major contributions in PQCDF framework. Performing a detailed calculation following Ref. [17], we plot $A_{K\pi}$ and $A_{K\pi^0}$ vs. $\Phi$ in Fig. 2(a) for $m_{t'} = 300, 350$ GeV and $r_5 = 0.01$ and 0.03. We see that, indeed, $A_{K\pi}$ is almost independent of $t'$, while it is clear that the largest impact on $A_{K\pi^0}$ is for $\phi_3 \sim \pm \pi/2$ and large $m_{t'}$ and $r_5$. To maximize $A_{K\pi^0} - A_{K\pi} > 0$, $\phi_3 \sim +\pi/2$ is selected, and Eq. (1) can in principle be accounted for.

The $A_{K\pi} \sim -0.16$ value is at some variance with the experimental value of $-0.114 \pm 0.020$. This number depends crucially on the strong penguin phase. Rather

| $F_{ek}$ | 0.841 [0.843] | -0.074 [0.075] | -0.076 [0.078] |
| $F_{ek}^c$ | N.A. [0.001 + 0.026 i] | 0.003 + 0.026 i [0.003 + 0.026 i] | 0.003 + 0.026 i [0.003 + 0.026 i] |
| $F_{ek}$ | N.A. [-0.105] | N.A. [-0.014] | N.A. [-0.029] |

TABLE I: Factorizable contributions for $B^{0(\ast)} \to K^+\pi^-[0]$ in Standard Model, and for $m_{t'} = 300$ GeV. The difference between the $t'$ and $t$ penguin contributions gives $\Delta F_{ek}^{t'}$. "N.A." stands for "not applicable."
than varying detailed model parameters, we vary $\delta \equiv \arg (f_K F^F + f_B F^B)$. The sign difference between tree and strong penguin constitutes a phase of $\pi$ and $\pi - \delta \sim 24^\circ$ is perturbative. We plot $A_{K\pi}$ and $A_{K\pi^0}$ vs. $\phi_\pi$ in Fig. 2(b) for $m_{\ell\ell} = 300$ GeV and $r_s = 0.03$, for $\delta = 155^\circ$, 156$^\circ$ (nominal) and 160$^\circ$. We see that a slightly smaller $\pi - \delta$ lowers $|A_{K\pi}|$ and is preferred. Note that $A_{K\pi^0} \sim 0$ around $\phi_\pi \sim 90^\circ$ is due to a near cancellation between the $\phi_\pi$ (tree) and $\phi_\pi$ (EWP) contributions. Thus, we think PQCDP can account for $A_{K\pi} = -0.114 \pm 0.020$ without affecting $A_{K\pi^0}$, but the NP phase $\phi_\pi$ should be rather close to 90$^\circ$.

To entertain a large EWP effect in CPV in $b \to s$ decay, one needs to be mindful of the closely related $b \to s\ell^+\ell^-$ and $B_s$ mixing constraints, as well as the usually stringent $b \to s\gamma$ constraint. We have checked that the $b \to s\gamma$ rate constraint is well satisfied for the range of parameters under discussion. This is because on-shell photon radiation is generated by the $b \to s$ transition operator $O_{\gamma s}$, and the associated coefficient $\Delta C_{\gamma}$ has weaker $m_{\ell\ell}$ dependence than $\Delta C_{\gamma}$ shown in Fig. 1. However, $b \to s\ell^+\ell^-$ is generated by EWP operators very similar to $O_{\gamma s}$ in Eq. 2 for $b \to s\ell\ell$. The difference is basically just in the Z charge of $q$ vs. $\ell$, hence with same $m_{\ell\ell}$ dependence. The box diagram for $B_s$ mixing also has similar $m_{\ell\ell}$ dependence. Taking the formulas from Ref. 10, we plot $b \to s\ell^+\ell^-$ rate ($m_{\ell\ell} > 0.2$ GeV) and $\Delta m_{B_s}$ vs. $\phi_\pi$ in Figs. 3(a) and (b), for $m_{\ell\ell} = 300$, 350 GeV and $r_s = 0.01$ and 0.03.

We can understand the finding of Ref. 10 that $\phi_\pi \sim 90^\circ$ is best tolerated by the $b \to s\ell^+\ell^-$ and $\Delta m_{B_s}$ constraints. For $\cos \phi_\pi < 0$, the $b \to s\ell^+\ell^-$ rate gets greatly enhanced 12, and would run against recent measurements. One is therefore forced to the $\cos \phi_\pi > 0$ region, where $t'$ effect is destructive against SM $t$ effect. For $\Delta m_{B_s}$, the effect gets destructive for $\cos \phi_\pi > 0$ when $r_s$ is sizable. Since one just has a lower bound $|11|$ of 14.4 ps$^{-1}$, $\Delta m_{B_s}$ tends to push one away from the cos $\phi_\pi > 0$ region. The combined effect is to settle around $\phi_\pi \sim \pm \pi/2$, i.e. imaginary $10$. This result is independent of the discrepancy of Eq. $11$.

For sake of discussion we have plotted, as horizontal solid straight lines in Fig. 3(a), the $1\sigma$ range of $B(B \to X_s \ell^+\ell^-) = (6.1 \pm 2.0) \times 10^{-6}$ 11 for $m_{\ell\ell} > 0.2$ GeV. This is the Particle Data Group (PDG) 2004 average over Belle and BaBar results 20, 21, with a combined total of 154M $BB$ pairs. Belle has recently measured 22 with 152M $BB$ pairs the value $B(B \to X_s \ell^+\ell^-) = (4.11 \pm 0.83^{+0.74}_{-0.70}) \times 10^{-6}$ for $m_{\ell\ell} > 0.2$ GeV, which would be more stringent. However, this lower result should be confirmed by BaBar, hence we use the more conservative 23 PDG 2004 range. For $\Delta m_{B_s}$, we plot the PDG bound of 14.4 ps$^{-1}$ $11$ as horizontal solid straight line in Fig. 3(b).

Comparing Figs. 2(a) and 3(a), 3(b), we set $A_{K\pi^0} > -0.05$ as a requirement for a solution, for otherwise it is hard to satisfy Eq. 11, and in any case the 4th generation would seem no longer needed. This requirement demands $r_s > 0.01$. For $m_{\ell\ell} = 350$ GeV and $r_s = 0.03$, which can best bring $A_{K\pi^0} \gtrsim 0$, Figs. 3(a) and 3(b) mutually exclude each other. For $m_{\ell\ell} = 300$ GeV and $r_s = 0.03$ (the case for $m_{\ell\ell} = 350$ GeV and $r_s = 0.02$ is very similar), one finds $\phi_\pi \approx 75^\circ$ gives $A_{K\pi^0} \sim 0$. However, $B(b \to s\ell\ell)$ must be close to the maximal value of $\sim 8 \times 10^{-6}$, and $\Delta m_{B_s}$ would be just above the bound. For lower $r_s$ values, the solution space is broader. For example, for $m_{\ell\ell} = 300$ GeV and $r_s = 0.02$, one has $A_{K\pi^0} \gtrsim -0.05$ for $\phi_\pi \sim 63^\circ -100^\circ$, $B(b \to s\ell\ell)$ can reach below $6 \times 10^{-6}$, but then $\Delta m_{B_s}$ would again approach the current bound.

We see that for a range of parameter space roughly around $m_{\ell\ell} \sim 300$ GeV and $0.01 < r_s \lesssim 0.03$, solutions to Eq. 11 can be found that do not upset $b \to s\ell\ell$ and $\Delta m_{B_s}$. Both large $t'$ mass and sizable $V_{ts}$ mixing are needed; no solutions are found for $m_{\ell\ell} = 250$ GeV.

As the CPV effect through the EWP is large, one may worry if similar effects may show up already in $b \to s\gamma$. We follow Ref. 24, extend to 4 generations, and plot $A_{CP}(b \to s\gamma)$ vs $\phi_\pi$ in Fig. 3(c). Like the $A_{K\pi^0}$ case, the $t'$ effect cancels against the SM phase. $|A_{CP}(b \to s\gamma)|$ is in general smaller than the SM value of $\sim 0.5\%$, and consistent with the current measurement of $0.004 \pm 0.036$ 25. In fact, it is below the sensitivity for the proposed high luminosity “Super B factory”.

As proposed, we find sin$2\Phi_{B_s} < 0$ for CPV in $B_s$ mixing, which is plotted vs $\phi_\pi$ in Fig. 3(d). We find sin$2\Phi_{B_s}$ in the range of $-0.2$ to $-0.7$ and correlating with $A_{K\pi^0} - A_{K\pi}$. Three generation SM predicts zero. Note that refined measurements of $B(b \to s\ell\ell)$ and future measurements of $\Delta m_{B_s}$ and sin$2\Phi_{B_s}$, together with theory improvements, can pinpoint $m_{\ell\ell}$, $r_s$ and $\phi_\pi$. We note further that $11$ $14.4$ ps$^{-1} < \Delta m_{B_s} < 21.8$ ps$^{-1}$ cannot yet be excluded because data is compatible with a signal in this region. We eagerly await $B_s$ mixing and

![FIG. 3: (a) $B(b \to s\ell^+\ell^-)$, (b) $\Delta m_{B_s}$, (c) $A_{CP}(b \to s\gamma)$ and (d) sin$2\Phi_{B_s}$ vs. $\phi_\pi = \arg V_{ts}^* V_{ts}$. Notation is same as Fig. 2(a), with effect strongest for larger $r_s$ and $m_{\ell\ell}$. Horizontal solid band in (a) corresponds to 1$\sigma$ experimental range, and solid line in (b) is the lower limit, both from Ref. 11. The experimental range for (c) is outside the plot.](image-url)
associated CPV measurement in the near future.

It is of interest to predict the asymmetries for the other two $B \rightarrow K\pi$ modes. $K^0\pi^-$ is analogous to $M_{K^0\pi^+}$ except tree contribution is absent. We find $M_{K^0\pi^-} \simeq M_{K^0\pi^+} \lambda_f (f_{K^0}\bar{F} + f_{B}\bar{F}_a)$, so $A_{K^0\pi^-} \simeq 0$ and insensitive to $t'$. For $B_0 \rightarrow K^0\pi^0$, we have $M_{K^0\pi^0} \propto \lambda_f f_{K^0}\bar{F} + \lambda_a f_{B}\bar{F}_a + \lambda_f (f_{K^0}\bar{F} + f_{B}\bar{F}_a) - \lambda_f f_{B}\Delta_{ek}$. Numerics can still be obtained from Table I, giving $A_{K^0\pi^0} - A_{K^0\pi^-} \sim 0.1$ if $A_{K^0\pi^-} = A_{K^0\pi}$ is of order suggested by Eq. 1. The impact on mixing-dependent CPV in $\phi K_S$ and $\eta'K_S$ modes are insignificant.

The measurement of $A_{K^0\pi}$ itself should not yet be viewed as settled, since the recent BaBar value of $+0.06\pm 0.07\pm 0.01$ changed sign from the previous $-0.09\pm 0.09\pm 0.01$. But if $A_{K^0\pi} \sim 0$ hence Eq. 1 stays, we would need a large effect in the EWP with a new CPV

ph. Note that, unlike most treatments of the EWP, our strong phase is not a fitted parameter, but calculated from PQCD.

We have also studied separately the final state rescattering (FSI) model as a different proposed source of strong phase. In this model, one allows $K^+\pi^-\leftrightarrow K^0\pi^0\leftrightarrow K^0\pi^+$ rescattering in the final state (power suppressed in QCDF and PQCD), and, to avoid double counting, one uses naive factorization amplitudes as source before rescattering. In this way, one can account for $A_{K^0\pi} < 0$, and also generate a sizable $\pi^0\pi^0$ via rescattering from $\pi^+\pi^-$. Neither QCDF nor PQCD can account for $B(B^0 \rightarrow \pi^0\pi^0) > 10^{-6}$. However, in contrast to Eq. 1, $A_{K^0\pi}$ is found to be more negative than $A_{K^0\pi}$ for $A_{K^0\pi} < 0$. We find no solution to Eq. 1, even when $t'$ is considered. Besides the problem that already exists in 3 generation SM, rescattering brings the electroweak penguin into the $K^-\pi^+$ amplitude from the $K^0\pi^+$ mode, so adding the $t'$ does not help.

We have shown that a fourth generation $t'$ quark can account for $A_{K^0\pi} \sim 0$. Using PQCD factorization calculations, one can account for $A_{K^0\pi} < 0$ (unbathed by $t'$) and generate the needed $A_{K^0\pi} - A_{K^0\pi}$ splitting, which repeats in $A_{K^0\pi} - A_{K^0\pi}$. The closely related $b\rightarrow sl^{+}l^{-}$ should have rate not less than $6 \times 10^{-6}$, and $B_s$ mixing should not be far above the current bound of $14.4$ ps$^{-1}$. In fact, between the $b\rightarrow sl^{+}l^{-}$ rate and the bound on $B_s$ mixing, $V_{tb}V_{tb}^*$ should be near imaginary if one wants a large $t'$ effect. We predict a quite measurable $CP$ violating phase sin$2\phi_{B_s}$ in the $-0.2$ to $-0.7$ range. Refined measurements of the last three measurable can determine $m_\nu$ and the strength and phase of $V_{tb}V_{tb}^*$.

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