Source of CP Violation for the Baryon Asymmetry of the Universe

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How to account for the matter predominance of our Universe is a fundamental issue at the core of our existence. One condition is CP violation, but the Standard Model falls short by more than $10^{-10}$. Taking cue from a recent result from the B factories, we find that a fourth quark generation can provide enhancement by a factor of $10^{13}$ or more. This could be the source of CP violation for the baryon asymmetry of the Universe. The main source of enhancement is the large Yukawa couplings of the heavy $t'$ and $b'$ quarks. With indications for a new, large CP violating phase $\sin 2\Phi_{B_s}$ emerging at the Tevatron, our suggestion can be verified or refuted at the LHC in the next few years.

1. THE LORE THAT DESPAIRS THE EXPERIMENTER

Having crossed the boundaries between theory and experiment, I attest that the experimenter feels like a hapless ant crawling on a desk, as far as searching for New Physics (NP) CP violation (CPV) is concerned.

Take, for example, the Belle Nature paper\textsuperscript{[1]} on the difference in direct CPV between $B^+$ and $B^0$ ($\Delta A_{K\pi}$). In reporting a large deviation, Belle cited the Baryon Asymmetry of the Universe (BAU) as the reason to pursue CPV studies, but immediately admitted that all data support the unique Kobayashi–Maskawa (KM,\textsuperscript{[2]}) source of CPV in the Standard Model (SM), which is “known to be too small” (by $10^{-10}$\textsuperscript{[2]} at least) for BAU. Because the gap (which the general experimenter knows only vaguely) between SM and the heavenly BAU is so large, it appears insurmountable, no matter what is found in the laboratory.

It is truly remarkable that the SM has\textsuperscript{[3]} an all the necessary ingredients for baryogenesis, i.e. the Sakharov conditions of baryon number violation, CPV, and deviation from equilibrium (in the very hot early Universe). The agony is the insufficiency in the latter two: CPV is way too small, while the electroweak phase transition (EWPhT) seems only a crossover. We see no antibaryons in our Universe, i.e. $n_\bar{B}/n_\gamma = 0$, while $n_B/n_\gamma = (6.1 \pm 0.2) \times 10^{-10}$ (WMAP); BAU is 100%. But the folklore is that SM falls short by $10^{-10}$. The source of this is the Jarlskog invariant\textsuperscript{[3]},

\begin{equation}
J = (m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_d^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2) A,
\end{equation}

which incorporates all requirements for CPV to be nonvanishing, where $A$ is twice the area of any unitarity triangle. Note that $J$ has dimensions $M^{12}$. To compare with $n_B/n_\gamma$, one typically normalizes by the EWPhT temperature $T \sim 100$ GeV (or roughly the v.e.v. scale). Putting in quark masses, and our knowledge that $A \simeq 3 \times 10^{-5}$, one immediately finds $J/T^{12} \sim 10^{-20}$, which falls short by $10^{-10}$. The main source of suppression is the smallness of light quark masses. The situation is in general much worse, since there are coupling constant factors as well.

--- We observe that, by extending from 3 to 4 quark generations, one can enhance Eq.\textsuperscript{[1]} by over $10^{13}$ ---

The thread that lead to this observation appeared concurrent with the 2004 observation of direct CPV in $B^0 \rightarrow K^+\pi^-$ mode, i.e. the first hint of $\Delta A_{K\pi} \equiv A_{K+\pi^0} - A_{K+\pi^-} \neq 0$. Written into the Belle paper\textsuperscript{[4]} at that time, it was noted that if the electroweak penguin $P_{EW}$ (Z penguin really) is the source of this apparent difference, then NP CPV is implied. However, as is well known, the so-called color-suppressed tree diagram $C$ could also generate $\Delta A_{K\pi} \neq 0$. Although Peskin\textsuperscript{[3]} stressed the equal possibility of $C$ vs $P_{EW}$ origins in his companion Nature paper, privately he is “very skeptical that the new Belle result is new physics”.

So, with the gap of $10^{-10}$ in mind, the hapless ant crawls on.
2. GOING UP A HILL, ... WHICH MAY BECOME A MOUNTAIN

2.1. Crawling Up a Hill

Noticing that the $P_{\text{F}}$ (or the $Z$ penguin), where the $Z$ is radiated off a virtual top or $W$ in a $b \rightarrow s$ loop and turns into a $\pi^0$ (but not a $\pi^-$), I recalled my first B paper on $b \rightarrow s \ell^+ \ell^-$ \footnote{recently pointed out that the 4th generation is not in such great conflict with EWPrt}. Naive counting would lead one to conclude that the photonic penguin diagram, at $\mathcal{O}(\alpha_{\text{em}})$, would dominate over the $Z$ penguin, at $\mathcal{O}(G^2_F)$. Even if one notes that the two differ by $m^2$ in dimensions, one would still have $G^2_F m^2_b \ll \alpha_{\text{em}}$. But it turns out, by direct computation, or by argument of conserved vector current vs spontaneous electroweak symmetry breaking (EWSB), that the $Z$ penguin behaves as $G^2_F m^2_b$ and actually dominates. This is called nondecoupling of heavy chiral quark masses in SM. I therefore embarked on crawling up the little hill of adding a 4th generation.

But this usually appears as running against a wall in a quixotic way; the 4th generation has long been viewed by many as ruled out already, by neutrino counting and electroweak precision tests (EWPrT). However, we now know that neutrinos have mass, which calls for New Physics, while Kribs et al. \footnote{recently pointed out} recently pointed out that the 4th generation is not in such great conflict with EWPrT. In any case, we demonstrated, both at LO \footnote{ICHEP 2006} and NLO \footnote{ICHEP 2006} in QCDF factorization approach (the only one that predicted the size and sign of $A_{K^+ \rightarrow s}$), that the 4th generation can generate the observed $\Delta A_{K^+}$.

In Ref. \footnote{ICHEP 2006} we showed that $\Delta S_{K^0 \rightarrow s}$ and $\Delta S_{K^0 \rightarrow d}$ moved downwards by $\sim -0.1$, which is the right direction and consistent with current data. Both the sign and strength are nontrivial.

2.2. Becoming a Mountain?

$\Delta A_{K^+} \sim 15\% > -A_{K^+} \sim 10\%$ is rather large for a NP effect. Given that the $b \bar{s} \leftrightarrow \bar{b}s$ box diagram has similar $m^{(i)}$ dependence as in the $b \rightarrow s$ $Z$ penguin, with the CDF measurement of $B_s$ mixing, a very sizable, and negative, mixing-dependent CPVs predicted \footnote{ICHEP 2006} for $B_s \rightarrow J/\psi \phi$, i.e.

$$\sin 2\Phi_{B_s} = -\sin 2\beta_s \sim -0.5 \rightarrow -0.7,$$

(2)

compared with $\sin 2\Phi_{B_s}^{\text{SM}} \sim -0.04$. The range of $-0.4$ to $-0.7$ was already predicted in Ref. \footnote{ICHEP 2006} and reported \footnote{ICHEP 2006} at ICHEP 2006 in Moscow. The improvement of Eq. (2) came with the more precisely determined $B_s$ mixing, while the sign is determined by the sign of $\Delta A_{K^+}$. So at ICHEP 2006, I already asked “Can large CPV in $B_s$ mixing be measured at Tevatron?”

Interestingly, by end of 2007, CDF reported \footnote{ICHEP 2006} indications for $\sin 2\beta_s$ that is consistent with Eq. (2) but less consistent with the SM expectation. By this conference, the $D^0$ measurement \footnote{ICHEP 2006} and a CDF update \footnote{ICHEP 2006} both confirm this trend, and the combined deviation from SM is now \footnote{ICHEP 2006} more than $2\sigma$, with central value of $\sim -0.6$!

This incredible development makes 2009–2010 very interesting, whether LHCb arrives on the scene or not.

3. SOARING TO THE STARRY HEAVENS

Heavy SM chiral quark effects are nondecoupled in the box and $Z$ penguin diagrams. The source is both because of the subtleties of spontaneous EWSB, and that heavy quark masses are due to large Yukawa couplings to the v.e.v. This I knew since twenty some years. Stimulated by large $\Delta A_{K^+}$, in the past 4 years I could not stop from pushing the work on the 4th generation, utilizing large $t'$ Yukawa couplings, and CPV phase in $V_{ts} V_{tb}^*$. I cannot remember when and how, but one day the “YuReKaw(a)’’ moment came: large Yukawa couplings can modify Eq. (1) \footnote{recently pointed out}. If one shifts by one generation with 4th generation SM (SM4), then Eq. (1) becomes \footnote{recently pointed out}

$$J^b_{(2,3,4)} \approx (m_t^2 - m_c^2) (m_b^2 - m_d^2) (m_s^2 - m_u^2) (m_b^2 - m_d^2)(m_b^2 - m_s^2) (m_b^2 - m_s^2) A_{234}^b.$$  

(3)

The notation will be clarified soon, but it is clear that the difference of light quark mass pairs, $(m_t^2 - m_c^2)(m_b^2 - m_d^2)(m_s^2 - m_u^2)$ now all drop out, and one gains in the mass factors (assuming $m_{t',b'} \sim 300$ GeV) by $10^{13}$! For the change in CPV “area” $A$, if the hints from $\Delta A_{K^+}$ and $\sin 2\Phi_{B_s}$ hold up, one could gain a further factor of 30.
To illustrate this last point, we show in Figure 1 the \( b \to s \) quadrangle corresponding to the SM4 unitarity relation \( V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0 \), together with the SM3 \( b \to d \) triangle \( V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \). The latter is from the current 3 generation fit to all data, the success of which led to KM receiving the 2008 Nobel Prize. For the former, it comes from the program that started with \( \Delta A_{K\pi} \) that started with \( \Delta A_{K\pi} \) (fixes \( V_{t's}V_{t'b}^* \) for given \( m_t' \)), but incorporating the \( Z \to b\bar{b} \) and rare kaon constraints on \( V_{t'b}V_{t'b}^* \) and \( V_{t'd}V_{t'd}^* \), using unitarity of \( 4 \times 4 \) CKM matrix.

We note that, if one draws the line linking \( S \) and \( O \) in Figure 1, the rather squashed and elongated triangle corresponds to \( V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0 \) for SM3, the 3 generation SM. This triangle has the same area \( A/2 \) as the \( b \to d \) triangle. It is the very tiny phase angle of the \( b \to s \) triangle in SM3 at the vertex \( S \) that gives rise to the very small value of \( \sin 2\Phi_{B_s}^{[\text{SM3}]} \). The sign, which is opposite to \( \sin 2\Phi_{B_d}^{[\text{SM3}]} \), is because the “orientation” is opposite that of the SM3 \( b \to d \) triangle. The large phase angle in SM4 at vertex \( S \) leads to the large area of the quadrangle, or \( A_{234}^{b-d} \sim 30 \), hence our prediction of Eq. 2.

Why do the \( b \to d \) processes give a triangle, rather than a quadrangle, if there are 4th generation effects lurking in \( b \to s \) transitions? This question was dealt with in Ref. [18]: with large \( V_{t's}V_{t'b}^* \) (including CPV phase), after taking into account the \( Z \to b\bar{b} \) and rare kaon constraints, the actual \( b \to d \) quadrangle mimics the SM3 triangle, or \( b \to d \) transitions are SM-like. This is a nontrivial test, and indeed another possible solution is rejected by this.

4. DISCUSSION AND CONCLUSION

4.1. Towards Solution of BAU

The original Jarlskog invariant of Eq. 1 was derived using \( \text{Im} \det [m_u^1 m_d^1, m_d m_u^1] \equiv \text{Im} \det [S, S'] \). Jarlskog generalized to \( n \) generations, and found the invariant CPV measure in terms of “3 cycles”, the trace of the cube of commutators of quark mass squares, or \( \text{Im} \text{tr} [S, S']^3 \), which looks considerably more complicated. To cut a long story short (and somehow never invoked by Jarlskog in actual detail), note that we are close to the \( d-s \) (and \( u-c \) as well) degeneracy limit on the v.e.v. scale. In this degeneracy limit, the 4 generation world actually becomes the effectively 3 generation world of 2-3-4 generation quarks! One sees now why Eq. 3 would turn out to be by far the dominant, and why \( J \) in Eq. 1 which could be written as \( J(1,2,3) \), is so tiny (the \( 10^{-19} \) gap!).

Out of the 3 independent phases in SM4, one is already measured in \( b \to d \) transitions, one could be emerging in a spectacular way in \( b \to s \) transitions. A third subdominant phase can be glimpsed from Figure 1. Since \( V_{us}V_{ub}^* \) is small, the resulting triangle by shrinking \( V_{us}V_{ub}^* \to 0 \) is not much different from the quadrangle. Thus, we have
been a little cavalier in the notation of $A_{234}^b$, but again there is no doubt that $J_{2,3,4}^b$ of Eq. 3 is the predominant CPV effect in SM4, and the relevant one for BAU. Judging from the combined $10^{15}$ enhancement from $J$ to $J_{2,3,4}^b$, it seems sufficient to overcome the large gap of $10^{-10}$, even taking into account the gauge factors that we have alluded to.

What about EWPHT? It is claimed that a first order transition is not possible for SM4 [20]. But perhaps strong Yukawa couplings, beyond the unitarity limit of heavy $t'$ and $b'$ masses (perturbativity is lost), opens a new possibility, as EWSB itself could be through the Nambu–Jona-Lasinio [21] mechanism with large Yukawa couplings.

4.2. Tevatron/LHC Verification

Given the developments at the Tevatron on $\sin 2\Phi_{B_s}$ in the past year [13, 14, 15, 16], 2009 appears extremely interesting, while LHCb may not deliver physics even by 2010. Judging from the recent performance of the Tevatron accelerator and experiments, if the current central value (consistent with Eq. 2) stays, we would have evidence in 2009, perhaps even observation in 2010, if Tevatron could continue running beyond 2009. Regardless, once LHCb has of order 0.5 fb$^{-1}$ data analyzed, whether one has NP CPV enhancement or not, the whole situation would precipitate.

But measurement of large $\sin 2\Phi_{B_s}$, while exciting, does not constitute proof for a 4th generation. The real litmus test, as always, would be direct search. Current CDF limit gives $m_{\nu'} > 311$ GeV at 90% C.L., using 2.8 fb$^{-1}$ data. Again, once LHC data becomes available, the full terrain can be covered in a straightforward way.

4.3. Conclusion

The gain of $10^{13}$ ($10^{15}$ if $m_{\nu',\nu} \sim 600$ GeV is used) in mass factors of Eq. 3 with 4 generations, over Eq. 1 with only 3 generations, seem to give enough CPV for generating BAU. Maybe there is a 4th Generation.

In several years we should know whether the KM mechanism — with 4th generations — could provide sufficient CPV for BAU. It would be amazing if what we find on Earth really has something to do with (baryo-)Genesis!

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