Looking for a New Angle on CP Violation

The Future of Particle Physics
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The SM circa 1500

- until ~1500: Earth is at the center of the fixed, perfect celestial spheres (Ptolemy, 85–165 AD)
The First Golden Age

- **Astronomy:**
  - Copernicus (1473-1543): Heliocentric model of the Universe;

- **Physics:**
  - Galileo (1564-1642): Law of falling bodies, concept of inertia

- **Precision data:**
  - Planetary observations by Brahe, Kepler, Galileo (first telescopic observations)

- **Synthesis:**
  - Newton’s Laws unifying celestial & terrestrial motion
From Copernicus' notebook

Gronau-London bound on $2\alpha - 2\alpha_{\text{eff}}$

$\sin 2\beta \sim 0.7$

Gronau-Willer prescription for $\gamma$ in $B \to D K$
The Second Golden Age

- **Astronomy**
  - 1929: The galaxies are moving apart (Hubble)

- **Physics**
  - 1900 - 1920’s Quantum mechanics, relativity
  - 1928-32: Prediction of antimatter (Dirac)

- **Precision data**
  - accelerators, telescopes, balloons, satellites, underground detectors, etc

- **Synthesis**
  - Standard Model of particle physics
  - Standard Model of cosmology
Energy budget of Universe

Composition of the Cosmos

- Dark Energy: ~70%
- Dark Matter: ~25%
- Antimatter: 0%

- Heavy elements: 0.03%
- Neutrinos: 0.3%
- Stars: 0.5%
- Free hydrogen and helium: 4%
- Dark matter: ~25%
- Dark energy: ~70%
Why worry about what isn’t there?

- We know a lot about a little
- We have recently learned a great deal more about another 1% or so
- We know almost nothing about almost everything else

- Standard Models of particle physics & cosmology are incomplete
- New physics must involve new sources of CP violation to explain the absence of antimatter
- CP violation is a clue and constraint that can distinguish among theories beyond the SMs of both particles and cosmology
Is it possible we are living in a B=0 Universe?

- Absence of e+e- annihilation radiation => no antimatter within our galactic cluster (20 Mpc)
- Can Universe be a quilt of matter & antimatter domains?
  - Nuclear annihilation produces $\pi^0, \pi^\pm$; $\pi^0 \rightarrow \gamma\gamma$ from early universe are redshifted into $\gamma$ rays today
  - Gamma ray spectra empirically rule out domains smaller than 1000 Mpc

Sakharov’s Conditions

- Baryon number violation
- C and CP violation
- Thermal non-equilibrium

1 in $10^8$ baryons must survive annihilation to generate the BAU observed today:

$$\eta = \frac{n_B}{n_\gamma} = (6.1^{+0.3}_{-0.2}) \times 10^{-10}$$ (from WMAP)
Types of Baryogenesis

- Electroweak baryogenesis (SM, MSSM)
- GUT baryogenesis
- Leptogenesis
- Affleck-Dine mechanism
- Quintessential baryogenesis
- etc
Occam’s Razor
“Pluralitas non est ponenda sine neccesitate”

- Entities should not be multiplied unnecessarily (William of Ockham, 1280 - 1347)
- Einstein “Everything should be made as simple as possible, but not simpler.”
- SM model has all 3 of Sakharov’s ingredients for a matter dominated universe...
SM Electroweak Baryogenesis

- **Baryon number violation**
  - SM anomaly (‘t Hooft 1976) violates B+L, conserves B-L
  - occurs freely in early universe before EW phase transition; strongly suppressed today ($\tau_p > 10^{33}$ yr)
  - EW anomaly couples to left-handed quarks & leptons; can convert L $\longleftrightarrow$ B

- **Thermal non-equilibrium**
  - first order electroweak phase transition as Higgs field acquires non-zero vacuum expectation value

- **C & CP violation**
  - C and P are maximally violated in weak interactions
  - CP violation is tiny, discovered in $K^0$ decays (1964)
Only two small problems...

- CP violation in SM is much too small to produce observed BAU.... by 10 orders of magnitude!
- SM Higgs is heavy (LEP limit > 114 GeV), so EW phase transition is second order
  - thus there is no departure from thermal equilibrium

1st order transition:
both phases present, latent heat, change in volume

2nd order transition:
none of the above
What is Nature Telling Us?

- The CKM mechanism is not the sole source for the observed CP violation?
CERN Courier, 1966: “We finally understand weak interactions”
CP Violation in the CKM Matrix (1973)

\[ V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \]

\[ \approx \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & -A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4) \]

\[ \lambda = \sin(\theta_{\text{Cabibbo}}) \approx 0.22 \]
\[ A \approx 0.85 \]

\[ \frac{V_{ub}^*V_{ud}}{V_{cb}^*V_{cd}} \]
\[ \frac{V_{tb}^*V_{td}}{V_{cb}^*V_{cd}} \]

\[ (\rho, \eta) \]

\[ \alpha \]
\[ \gamma \]
\[ (0,0) \]

\[ \beta \]
\[ (1,0) \]

Wolfenstein parameterization
Complex phase
The world average for \( \sin^2 \beta \) in 2001 is given by

\[
\sin^2 \beta = 0.48 \pm 0.16
\]

New B-factory measurements are in good agreement.

The world average in 2003 is

\[
\sin^2 \beta = 0.744 \pm 0.055
\]
Further constraints on the U.T. from B factories:

- $\sin 2\beta$ in additional modes
- Measure $\alpha, \gamma$ - is it a triangle?
- Improved precision on sides ($V_{ub}, V_{cb}, V_{td}$) - is it the same triangle as determined from the angles?
- Rare decays & direct CP violation - signal for new physics?
sin 2\(\beta\) in a different mode

- BaBar, Belle have measured \(\sin 2\beta\) in \(b \rightarrow c \bar{c} s\) modes
- \(b \rightarrow s \bar{s} s\) penguin modes also measure \(\sin 2\beta\) – should agree within a few percent
- NB: New physics could enter in loops!

Weak phase: 0

\[
\begin{align*}
\bar{b} & \rightarrow W^{+} \bar{s} \eta' \phi \\
B^0 & \rightarrow \bar{d} \bar{t} g \bar{s} \eta' \\
K^0 & \rightarrow d \bar{d}
\end{align*}
\]

Weak phase: \(\gamma\)

\[
\begin{align*}
\bar{b} & \rightarrow W^{+} \bar{u} \eta' \\
B^0 & \rightarrow \bar{d} \bar{t} g \bar{u} \eta' \\
K^0 & \rightarrow d \bar{d}
\end{align*}
\]

Suppressed by \(x0.04\)
Experimental Challenges for \(b \rightarrow s\) penguin modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>(\text{BF}(B \rightarrow f) \ (10^{-6}))</th>
<th>(\Pi_i \text{BF}_i \ (10^{-6}))</th>
<th>Reco. Efficiency</th>
<th>Purity</th>
<th>Tagged signal events</th>
</tr>
</thead>
<tbody>
<tr>
<td>(J/\psi K_s)</td>
<td>440</td>
<td>36.0</td>
<td>44%</td>
<td>97%</td>
<td>940</td>
</tr>
<tr>
<td>(\eta' K_s)</td>
<td>29</td>
<td>8.7</td>
<td>23%</td>
<td>~75%</td>
<td>110</td>
</tr>
<tr>
<td>(\phi K_s)</td>
<td>4</td>
<td>1.4</td>
<td>42%</td>
<td>~80%</td>
<td>34</td>
</tr>
</tbody>
</table>

80 fb\(^{-1}\) of BaBar Data
“sin 2β” from $b \rightarrow s$ penguin

\[ \sin 2\beta = 0.744 \pm 0.055 \]

\[ \eta'K_s \]
- Preliminary!
- **BaBar**: $0.02 \pm 0.34 \pm 0.03$
- **Belle**: $0.71 \pm 0.37 \pm 0.05$
- **Ave**: $0.34 \pm 0.25$

\[ \phi K_s \]
- **BaBar**: $-0.19 \pm 0.52 \pm 0.09$
- **Belle**: $-0.73 \pm 0.64 \pm 0.22$
- **Ave**: $-0.39 \pm 0.41$

\[ K^+K^-K_s \text{ non-resonant} \]
- **Belle**: $0.49 \pm 0.43 \pm 0.11 \pm 0.33$

Is this a hint of new physics beyond the CKM model?
Testing the CKM Model - Beyond J/Ψ K_s

- Further constraints on the U.T. from B factories:
  - \( \sin 2\beta \) in additional modes for consistency check
  - Measure \( \alpha, \gamma \) - is it a triangle?
  - Improved precision on sides \( (V_{ub}, V_{cb}, V_{td}) \) - is it the same triangle as determined from the angles?
  - Rare decays & direct CP violation - signal for new physics?

- Measurements in \( B_s \) decays
  - Tev RunII: \( B_s \) mixing, CP violation
  - BTeV, LHCb - next generation of precision CP measurements

- Measure \( \rho, \eta \) in \( K \rightarrow \pi\nu\nu \) decays
  - CKM, KOPIO for charged & neutral modes
What is Nature Telling Us?

The CKM mechanism is not the sole source for the observed CP violation?

EW baryogenesis involves new particles with additional CPV phases and dynamics?
Electroweak Baryogenesis in the Minimal Supersymmetric SM

Chiral chargino current => asymmetry in left and right-handed top quarks

\[ t_L < \tilde{t}_L \quad t_R > \tilde{t}_R \]

EW anomaly partially converts \( t_L \) asymmetry into \( L \) asymmetry but \( t_R \) is unaffected => net \( B \) asymmetry

\[ t_L + \tilde{t}_R > \tilde{t}_L + \tilde{t}_R \]
Can we test MSSM EWB?

- MSSM EWB requires light right-handed scalar top (< m_t) and light chargino
  - opportunity for TeV RunII and for LHC

- No new CP violation in B’s, but mixing may be enhanced
  - lattice calculations needed to reduce theoretical uncertainty
  - Bs mixing would also show an effect

- SUSY also may affect b → s\gamma

- EW baryogenesis in MSSM is testable - the lamp post under which we can look.
Status of $b \rightarrow s \gamma$

- **BaBar inc.**
  \[ B \pm \text{stat} \pm \text{syst} \pm \text{theo} / 10^{-4} \]
  \[ 3.88 \pm 0.36 \pm 0.37^{+0.43}_{-0.28} \]

- **BaBar semi.**
  \[ 4.3 \pm 0.5 \pm 0.8 \pm 1.3 \]

- **CLEO**
  \[ 3.21 \pm 0.43 \pm 0.27^{+0.18}_{-0.10} \]

- **BELLE**
  \[ 3.36 \pm 0.53 \pm 0.42 \pm 0.52 \]

- **ALEPH**
  \[ 3.11 \pm 0.80 \pm 0.72 \]
What is Nature Telling Us?

The CKM mechanism is not the sole source for the observed CP violation?

EW baryogenesis involves new particles with additional CPV phases and dynamics?

EW baryogenesis is not the source of the BAU; try something else?
Today $T = 2.73$ K

“Surface of last scattering” - CMB
$T = 3000$ K ($\sim 1$ eV)

EW Phase transition
EM & weak forces decouple; $T \sim 300$ GeV

Inflation, GUT era
$T = 10^{15}$ GeV

Today: 14 billion years

0.4 Myr

$10^{-35}$ s

$10^{-11}$ s

The Planck epoch
The quantum gravity barrier

The Particle Desert
Axions, supersymmetry?

Grand unification transition
$G \to SU(3) \times SU(2) \times U(1)$
Inflation, baryogenesis, monopoles, cosmic strings, etc.

Electroweak phase transition
Electromagnetic & weak nuclear forces become differentiated:
$SU(3) \times SU(2) \times U(1) \to SU(3) \times U(1)$

Quark-hadron transition
Hadrons form, protons & neutrons

Nucleosynthesis
Light elements created: $\text{D, He, Li}$

Recombination
Relic radiation decouples (CMB)

Galaxy formation
Epoch of gravitational collapse

Matter domination
Onset of gravitational instability

Today $t_0$
Life on earth
Solar system
Quasars
GUT Baryogenesis

Thermal non-equilibrium
heavy particles ($10^{10}$ - $10^{15}$ GeV) produced in thermal equilibrium in hot dense early universe
decay more slowly than Universe expands, resulting in out-of-equilibrium abundance at later times

Baryon number violation
occurs naturally in models which seek to unify quarks, leptons; heavy GUT particles violate B in their decays

C and CP violation
from interference between tree and one-loop diagrams for B violating decays of heavy particles

Elegant, economical and completely untestable...
Leptogenesis

Thermal non-equilibrium
heavy particles (N) produced in thermal equilibrium at early times are right-handed Majorana ν’s
see-saw mechanism explains light ν mass: $m_\nu \propto 1/m_N$

Baryon number violation
N violates L in its decay; excess L is converted to excess B via SM EW anomaly (violates B+L but conserves B-L)

C and CP violation
from interference between tree and one-loop diagrams for decay of N
Can Leptogenesis be Tested?

- Violation of lepton flavor => established in \( \nu \) oscillations!

- Light but non-zero \( \nu \) masses are consistent with see-saw mechanism and heavy \( N \)

- Sum of all light \( \nu \) masses in range 0.001 - 0.1 eV is required to obtain correct \( \eta \) (Buchmuller et al hep-ph 0302092)

- CP violation in light \( \nu \) sector? Different phase from that in \( N \) decay => circumstantial evidence

- Confirmed detection of \( 0\nu2\beta \) decay, establishing the Majorana nature of \( \nu \)'s would provide even more compelling circumstantial evidence...
2003: “We finally understand CP Violation”
Conclusion

- CP violation is a necessary ingredient in a baryon-dominated Universe and required in new physics.
- Precision data in the quark and neutrino sector are sensitive probes of new physics, and may ultimately shed light on the mystery of baryogenesis.
- The particle physics discoveries of the next decade will have profound impact on our understanding of the Universe as we go beyond the SM - both of them!