Observing directly the “weak arrow of time”

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SLAC Seminar
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Outline

- Introduction
  - Time reversal symmetries in the laws of Physics
  - Scenarios for T violation
  - T violation in unstable systems
- T violation and entanglement: strategy at a B factory
- Data sample and fitting strategy
  - The BaBar data set
  - Signal and backgrounds
  - Fitting strategy
- Results and interpretation
  - Results
  - Cross checks and systematic uncertainties
  - Significance of T violation
  - The raw T asymmetries
- Summary
Introduction
The dynamical laws of Physics have an intrinsic $t \rightarrow -t$ symmetry

**Microscopic $t$ symmetry, or $T$ symmetry**

- $CP$ violation exists in the Standard Model or any extension of it
- All field theories with local Lorentz invariance have $CPT$ symmetry
  - Straightforward connection between $CP$ violation and $T$ violation

- **Observed weak $CP$ violation in $K$ and $B$ mesons**

**$T$ should be violated as well in weak interactions**

**Can $T$ violation be directly observed, independently of $CP$ violation?**
Universe and Macroscopic $t$ asymmetries

- Effects in Physics $t \rightarrow -t$ asymmetric are not necessarily $T$ violating

**Universe $t$ asymmetry**

- The Universe is expanding, even accelerating
- Compatible with the $t$ symmetry in the underlying laws of Physics (Lorentz symmetry of general relativity)
- Due to the initial conditions of our Universe (Inflation?)
- Consistent with uniform average (same temperature) and its fluctuations in the cosmic background radiation map

**Macroscopic $t$ asymmetry, or “arrow of time”**

- Time is asymmetric with respect to the amount of order in an isolated system (Nature of Thermodynamics, Eddington)

3000 BC to 2000 BC

- Probably connected with the Universe $t$ asymmetry: the initial condition was improbable (more ordered)
- In particle physics, particle decays are an example of time asymmetric process:

  Mismatch between $P \rightarrow 1+\ldots+n$ and $1+\ldots+n \rightarrow P$
Non-zero expected value of a T-odd observable for stationary, non-degenerate states, like the permanent electric dipole moment (EDM) of a particle (with spin)

- Also violates parity, P
- EDM of the neutron or electron: PDGLive.org

\[ d_n < 2.9 \times 10^{-26} \text{ e-cm}; \quad d_e = (0.7 \pm 0.7) \times 10^{-26} \text{ e-cm} \]

For a reaction \( a \rightarrow b \), \( P(a \rightarrow b) \neq P(b \rightarrow a) \), once the initial conditions, namely \( a \) in one case and \( b \) in the other, have been precisely realized!

- Detailed balance when there are no spins
- With stable particles: \( \nu_e \rightarrow \nu_\mu \) vs. \( \nu_\mu \rightarrow \nu_e \) but needs future facility with a long baseline
- With unstable particles: \( a \rightarrow \) decay products vs. decay products \( \rightarrow a \), very difficult or impossible
T violation in unstable systems

➢ Compare \( a \rightarrow b \) vs. \( b \rightarrow a \) in **decay processes**

✓ BaBar and Belle have observed large direct CP violation in \( B \rightarrow K\pi \)

✓ Can we observe \( K\pi \rightarrow B \)?

\[
\begin{align*}
\text{CP} & \quad B^0 \rightarrow K^+\pi^-, \ R_1 \\
\text{CPT} & \quad \bar{B}^0 \rightarrow K^-\pi^+, \ R_2
\end{align*}
\]

Preparation of the initial state difficult (unfeasible).

The strong process will swamp the feeble weak process, \( \sigma(K\pi\rightarrow\text{hadrons}) >> \sigma(K\pi\rightarrow B) \)

⇒ Impossible rather than “merely” unfeasible.
Compare $a \rightarrow b$ vs. $b \rightarrow a$ in mixing processes

- Mixing has been observed in K, B, and more recently in D neutral systems

\[ K^0 \rightarrow \bar{K}^0 \]
\[ B^0 \rightarrow \bar{B}^0 \]
\[ \bar{K}^0 \rightarrow K^0 \]
\[ \bar{B}^0 \rightarrow B^0 \]

- Various criticisms in the interpretation of this observable

Kabir, PRD2, 540 (1970)

CPLEAR, PLB444, 43 (1998)


But, T and CP transformations lead to the same observation

- Can not distinguish T and CP

- Not a direct observation of T violation

The flavor mixing asymmetry is independent of time and requires $\Delta \Gamma \neq 0$

- Various criticisms in the interpretation of this observable
e electric dipole moment
μ electric dipole moment
μ decay parameters
- transverse $e^\pm$ polarization normal to plane of $\mu$ spin, $e^\pm$ momentum
  $\alpha'/A$
  $\beta'/A$
$\text{Re}(d_\tau) = \tau$ electric dipole moment
$P_T$ in $K^+ \rightarrow \pi^0 \mu^+ \nu_\mu$
$P_T$ in $K^+ \rightarrow \mu^+ \nu_\mu \gamma$
$\text{Im}(\xi)$ in $K^+ \rightarrow \pi^0 \mu^+ \nu_\mu$ decay (from transverse $\mu$ pol.)
  asymmetry $A_T$ in $K^0$-$\bar{K}^0$ mixing
  $\text{Im}(\xi)$ in $K^0_{\mu3}$ decay (from transverse $\mu$ pol.)
$A_T(D^0 \rightarrow K_S^0 K^{\pm} \pi^\mp)$
$A_T(D^0 \rightarrow K^+ K^{-} \pi^0)$
$A_T(D^0_{s \rightarrow K_S^0 K^{\pm} \pi^\mp})$
$p$ electric dipole moment
$n$ electric dipole moment
$n \rightarrow p e^- \bar{\nu}_e$ decay parameters
  $\phi_{AV}$, phase of $g_A$ relative to $g_V$
  triple correlation coefficient $D$
  triple correlation coefficient $R$
Λ electric dipole moment
triple correlation coefficient $D$ for $\Sigma^- \rightarrow n e^- \bar{\nu}_e$

<10.5 \times 10^{-28}$ e cm, CL = 90%
(-0.1 \pm 0.9) \times 10^{-19}$ e cm

(-2 \pm 8) \times 10^{-3}
(-10 \pm 20) \times 10^{-3}
(2 \pm 7) \times 10^{-3}

-0.220 to 0.45 \times 10^{-16}$ e cm, CL = 95%
(1.7 \pm 2.5) \times 10^{-3}
(-0.6 \pm 1.9) \times 10^{-2}
-0.006 \pm 0.008

(5.6 \pm 1.6) \times 10^{-3}
-0.007 \pm 0.026

<0.54 \times 10^{-23}$ e cm
<0.29 \times 10^{-25}$ e cm, CL = 90%

[c] (180.018 \pm 0.026)^{\circ}
[d] (-1.2 \pm 2.0) \times 10^{-4}
[d] 0.009 \pm 0.016
<15 \times 10^{-16}$ e cm, CL = 95%
0.11 \pm 0.10

**CPLEAR: PLB 444, 43 (1998)**
Comparing $K^0 \rightarrow \bar{K}^0$ and $\bar{K}^0 \rightarrow K^0$
- Mixing rate.
- Related by $T$ and CP.
- Not time-dependent.
- Various criticisms.

**BABAR:**
- PRD(RC)81, 111103 (2010)
- PRD(RC) 84, 031103 (2011)
- Triple products
CP violation in mixing-decay interference

- Large CP violation observed in the interference between mixing and decay in B mesons, measured precisely with golden channels.

\[ B^0 \rightarrow J/\psi K_S \quad CP = -1 \]
\[ B^0 \rightarrow J/\psi K_L \quad CP = +1 \]

Cannot be interpreted as T violation:
Assume CPT invariance and \( \Delta \Gamma = 0 \)
No exchanges \( t \leftrightarrow -t \) and in \( \leftrightarrow \) out states

How could we directly observe T violation in this privileged system of Nature?
T violation and entanglement: strategy at a B factory
Quantum (EPR) entanglement at B factories

Γ(4S) decay yields an entangled state of B mesons

\[ |i\rangle = \frac{1}{\sqrt{2}} \left[ B^0(t_1)\overline{B}^0(t_2) - \overline{B}^0(t_1)B^0(t_2) \right] \]

Antisymmetric wave function (P-wave particle system)

States 1 and 2 are defined by the time of their decay with \( t_1 < t_2 \)

Can be expressed in terms of any linear combination of flavor eigenstates

Time evolution (including mixing) preserves only \( B^0\overline{B}^0 \), or \( B_+B_- \) terms

Flavor tag: e.g. B semileptonic decay to \( l^+X \) (\( l^-X \)) projects \( B^0 (\overline{B}^0) \)

\( \Rightarrow \overline{B}^0 (B^0) \) tag

CP tag: B decay to \( J/\psi K_L \) projects \( B_+ \approx \frac{1}{\sqrt{2}} \left[ B^0 + \overline{B}^0 \right] \)

\( \Rightarrow B_- \) tag ("CP-odd")

B decay to \( J/\psi K_S \) projects \( B_- \approx \frac{1}{\sqrt{2}} \left[ B^0 - \overline{B}^0 \right] \)

\( \Rightarrow B_+ \) tag ("CP-even")

Conclusion: ability to prepare a quantum state without destroying it ("tag") , and then study its time evolution
T violation: strategy at a B factory

Entangled

\( \beta \gamma \sim 0.56 \)

\( \Upsilon(4S) \)

\( B^0 \rightarrow \bar{B}^0 \)

projects

Inclusive B meson flavor Identification

Entangled

\( \Upsilon(4S) \)

\( t_1 \)

\( \Delta \tau \)

\( l^- \)

\( B^0 \rightarrow \text{Tag} \)

\( J/\psi \)

\( K_L \)

projects

\( B_+ \)

It is NOT the exchange \( t_1 \leftrightarrow t_2 \)

Exclusive B-meson reconstruction

\( B^0 \rightarrow \Delta \tau \rightarrow B_+ \)

\( B_+ \rightarrow \Delta \tau \rightarrow B^0 \)

projects

\( B^- \)

\( B^- \rightarrow \text{Tag} \)

\( J/\psi \)

\( K_L \)

\( \Delta \tau \)

\( l^+ \)

Time reconstruction

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T violation analysis at a glance

Completely reconstructed B

\[ b \rightarrow c + b \quad \text{etc.} \]

Inclusive reconstructed B: flavor identification (extract features to determine $b$ or $\bar{b}$ quark content)

\[ |B^0\rangle = |\bar{b}d\rangle \quad |\bar{B}^0\rangle = |bd\rangle \]

\[ \ell^+ \quad K^+ \quad \text{etc.} \]

\[ \ell^- \quad K^- \quad \text{etc.} \]
In B factory CP violation canonical analysis, we define

\[ \Delta t = t_{CP} - t_{flav} \approx \Delta z / \beta \gamma c \]

Signed decay time difference

If \( \Delta t < 0 \), we can exchange the roles of the two B’s in above picture.

\[ \beta \gamma \approx 0.56 \text{ (BABAR)} \]

\[ \langle \Delta z \rangle \approx 250 \text{ \( \mu m \)} \]
$\hat{\gamma} \sim 0.56$

$\Upsilon(4S)$

Inclusive $B$ meson flavor Identification

It is NOT the exchange $t_1 \leftrightarrow t_2$

Exclusive $B$-meson reconstruction

$B^0 \xrightarrow{\Delta \tau} B_+$

$\Delta t > 0$

$B_+ \xrightarrow{\Delta \tau} B^0$

$\Delta t < 0$

$\Delta t = \pm \Delta \tau$

T violation: strategy at a B factory

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T-transformed processes

Define processes of interest and their T-transformed counterparts

<table>
<thead>
<tr>
<th>Reference (X,Y)</th>
<th>T-Transformed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow B_+$</td>
<td>$(\ell^-, J/\psi K^0_L)$</td>
</tr>
<tr>
<td>$B^0 \rightarrow B_-$</td>
<td>$(\ell^-, J/\psi K^0_S)$</td>
</tr>
<tr>
<td>$\bar{B}^0 \rightarrow B_+$</td>
<td>$(\ell^+, J/\psi K^0_L)$</td>
</tr>
<tr>
<td>$\bar{B}^0 \rightarrow B_-$</td>
<td>$(\ell^+, J/\psi K^0_S)$</td>
</tr>
</tbody>
</table>

$T$ implies comparison of:
1) Opposite $\Delta t$ sign
2) Different reco states ($\psi K_S$ v. $\psi K_L$)
3) Opposite flavor states ($B^0$ v. $\bar{B}^0$)

In total we can build:
• 4 independent $T$ comparisons
• 4 independent $CP$ comparisons
• 4 independent $CPT$ comparisons

...and similar for $CP$, $CPT$
Signal parameters $\Delta S^\pm$ and $\Delta C^\pm$

8 Signal PDFs: $g_{\alpha,\beta}^\pm(\Delta \tau) \propto e^{-\Gamma \Delta \tau} \{1 + S_{\alpha,\beta}^\pm \sin(\Delta m_d \Delta \tau) + C_{\alpha,\beta}^\pm \cos(\Delta m_d \Delta \tau)\}$

$\Delta t = t_{CP} - t_{flav} = \begin{cases} +\Delta \tau & \text{for } "flavor tag" \\ -\Delta \tau & \text{for } "CP tag" \end{cases}$

$\alpha \in \{B^0, \bar{B}^0\}; \quad \beta \in \{K^0_S, K^0_L\}$

Assumes $\Delta \Gamma = 0$

For $T$ violation
- In interference $\Delta S_{T}^+ \neq 0, \Delta S_{T}^- \neq 0$
- In decay $\Delta C_{T}^+ \neq 0, \Delta C_{T}^- \neq 0$

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Let’s call the state $B_-$ as the one defined by the B decay to $J/\psi\pi\pi$ ($J/\psi K_S, K_S \rightarrow \pi\pi$) [a pure CP-odd final state]

$	ilde{B}_+$ is the state orthogonal to $B_-$, $\langle \tilde{B}_+ | B_- \rangle = 0$, defined by entanglement, thus cannot decay to $J/\psi\pi\pi$, i.e., $\langle J/\psi\pi\pi \big| T \big| \tilde{B}_+ \rangle = 0$

Since $B_-$ and $\tilde{B}_+$ are linear combinations of flavor eigenstates,

$$\left| \tilde{B}_+ \right> = \tilde{N}_+ \left[ \left| B^0 \right> - \alpha \left| \bar{B}^0 \right> \right], \quad \left| B_- \right> = N_- \left[ \left| B^0 \right> + \delta \left| \bar{B}^0 \right> \right] \quad \alpha = \frac{\langle J/\psi\pi\pi \big| T \big| B^0 \rangle}{\langle J/\psi\pi\pi \big| T \big| \bar{B}^0 \rangle}$$

$$\langle \tilde{B}_+ \big| B_- \rangle = \tilde{N}_+ N_- [1 - \alpha \delta] = 0 \Rightarrow \alpha \delta = 1 \Rightarrow \delta = \alpha^* \quad \text{if} \quad |\alpha| = 1$$

Analogously, the state $B_+$ is defined by the B decay to $J/\psi K_L$ [a CP-even final state at $O(10^{-3})$],

$$\left| \tilde{B}_- \right> = \tilde{N}_- \left[ \left| B^0 \right> - \beta \left| \bar{B}^0 \right> \right], \quad \left| B_+ \right> = N_+ \left[ \left| B^0 \right> + \beta^* \left| \bar{B}^0 \right> \right] \quad \beta = \frac{\langle J/\psi K_L \big| T \big| B^0 \rangle}{\langle J/\psi K_L \big| T \big| \bar{B}^0 \rangle}$$

\text{if} \quad |\beta| = 1
Properties of the $B_+$ and $B_-$ states (cont’d)

- $\tilde{B}_+$ and $B_+$, and $\tilde{B}_-$ and $B_-$ have to be the same states in order to define processes and their T-transformed counterparts, so $\beta = -\alpha^*$
- It then follows that $B_+$ and $B_-$ are too orthogonal,
\[ \langle B_+ | B_- \rangle = N_+ N_- \left[ 1 + \alpha^* \beta^* \right] = 0 \]

- Property 1: $B_+$ and $B_-$ are orthogonal linear combinations of flavor eigenstates, not necessarily defined through CP final states
- Property 2: $B_+$ and $B_-$ states defined through the B decays to $J/\psi K_L$ and $J/\psi \pi\pi$ final states are orthogonal iff
  - We neglect the $J/\psi \pi\pi$ component in $J/\psi K_L$ final states, i.e. neglect CPV in $K^0$-$\overline{K}^0$ mixing, $O(10^{-3})$
  - $|\alpha| = |\beta| = 1$, i.e., there is no direct CPV in the B decay to $J/\psi K^0$ (one single weak decay amplitude)

Next largest amplitude ($\lambda^2$) has same weak phase
Other CKM corrections are Cabibbo suppressed $O(\lambda^4)$
Data sample
and fitting strategy
530 fb$^{-1}$ recorded in the 9 years of operation

\begin{itemize}
  \item 14.5 fb$^{-1}$ \(\Upsilon(nS)\) \(\Gamma=54\text{KeV}\), \(\sigma_{\text{vis}}=7\text{nb}\)
  \item 30.2 fb$^{-1}$ \(\Upsilon(nS)\) \(\Gamma=20\text{KeV}\), \(\sigma_{\text{vis}}=4\text{nb}\)
  \item 430 fb$^{-1}$ \(\Upsilon(nS)\) \(\Gamma=20\text{MeV}\)
  \item 54 fb$^{-1}$ Off-\(\Upsilon(nS)\)
  \item 4 fb$^{-1}$ above \(\Upsilon(4S)\)
\end{itemize}

\begin{align*}
  \approx 470 \times 10^6 & \, \B\Bbar (0.5 \times \text{Belle}) \\
  \approx 690 \times 10^6 & \, \c\cbar \\
  \approx 500 \times 10^6 & \, \tau^+\tau^- \\
  \approx 121 \times 10^6 & \, \Upsilon(3S) \, (7 \times \text{Belle+Cleo}) \\
  \approx 99 \times 10^6 & \, \Upsilon(2S) \, (0.5 \times \text{Belle+Cleo})
\end{align*}
Select $B$ candidates using

- Beam-energy substituted mass
  \[ m_{ES} = \sqrt{E_{beam}^* - |\vec{p}_B|^2} \]
  where $E_B^* \rightarrow E_{beam}^*$ and $\vec{p}_B^* \approx 300$ MeV/c

- Energy difference $\Delta E = E_B^* - E_{beam}^*$

- Choose best $B$ candidates based on masses of daughters

Background rejection

- Depends on $B$ decay channel
- Veto dangerous or significant backgrounds
- Suppress continuum $u, d, s$ backgrounds using angular distributions and event shape variables

\[ m_{ES} = \sqrt{E_{beam}^* - p_R^*} \]
\[ \sigma_{m_{ES}} \sim \sigma_{beam} \sim 2.7 \text{ MeV} \]
Identical sample to that used in our most recent (canonical) CP violation measurement with $B \to c\bar{c}K^{(*)0}$ events, but excluding $\eta_c K_S$ and $J/\psi K^*(\to K_S\pi^0)$

7796 events, purity 87–96%

5813 events, purity $\approx 56%$
Fitting strategy

- Overall procedure very similar to that followed in the most recent CP violation study with $B \to c\bar{c}K^{(*)0}$ decays (PRD 79, 072009 (2009))

- Use the $B_{\text{flav}}$ sample to determine:
  - Decay time difference resolution model and parameters
  - Wrong-flavor ID fractions

- Perform simultaneous, unbinned ML fit to the 4 signal samples

\[
\begin{pmatrix} B^0, \bar{B}^0 \end{pmatrix} \times \begin{pmatrix} J/\psi K^0_S, J/\psi K^0_L \end{pmatrix}
\]

- Normalization is common for $B^0$, $\bar{B}^0$, and $\Delta t>0$ and $\Delta t<0$
- But independent for $c\bar{c}K_S$ and $J/\psi K_L$

- Signal and background probabilities defined as a function of $m_{ES}$ and $\Delta E$

- Sample composition and time-dependent background description identical to the CP violation analysis
  - 11 parameters allow for possible T and CP violation in background

- But the signal model is quite different…
  - Time ordering is the key!
Fitting strategy: signal model

- **Signal PDF**

\[ H_{\alpha,\beta}(\Delta t) \propto g^{+}_{\alpha,\beta}(\Delta t_{\text{true}}) \times H(\Delta t_{\text{true}}) \otimes \mathcal{R}(\delta t; \sigma_{\Delta t}) \]

- **Step function**

- **Resolution function**

\[ \delta t = \Delta t - \Delta t_{\text{true}} \]

- **Flavor tagged events (+)**

- **CP tagged events (−)**

\[ g^{\pm}_{\alpha,\beta}(\Delta \tau) \propto e^{-\Gamma \Delta \tau} \{1 + S^{\pm}_{\alpha,\beta} \sin(\Delta m_{d} \Delta \tau) + C^{\pm}_{\alpha,\beta} \cos(\Delta m_{d} \Delta \tau)\} \]

- **Fit has to unfold** \( \Delta t_{\text{true}}>0 \) and \( \Delta t_{\text{true}}<0 \) events (mixed due to limited time resolution), to obtain **8 sets of S, C parameters**

\[ (\Delta t > 0, \Delta t < 0) \times (B^0, \bar{B}^0) \times (J/\psi K_s^0, J/\psi K_{L}^0) \]

- **Flavor misID fractions** \( w \) (not shown here) dilute the S,C parameters by a factor (1-2\( w \))

- **In practice,** we directly fit to the T-, CP- and CPT-violating parameters

\[ \Delta S_T^{\pm}, \Delta C_T^{\pm}, \Delta S_{CP}^{\pm}, \Delta C_{CP}^{\pm}, \Delta S_{CPT}^{\pm}, \Delta C_{CPT}^{\pm} \]

- **In canonical CP violation studies (assume CPT and \( \Delta \Gamma=0 \), one single S, C set**

- **In SM,** \( S \sim \sin2\beta = 0.679 \pm 0.020 \) (HFAG winter’12) and \( C \sim 0 \) (e.g. PRD 79, 072009 (2009))
Results and interpretation
Results

T-violating parameters

\[ \Delta S_T^+ = S^-_{\ell^-, K^0_L} - S^+_{\ell^+, K^0_S} \quad -1.37 \pm 0.14 \pm 0.06 \]
\[ \Delta S_T^- = S^+_{\ell^-, K^0_L} - S^-_{\ell^+, K^0_S} \quad 1.17 \pm 0.18 \pm 0.11 \]
\[ \Delta C_T^+ = C^-_{\ell^-, K^0_L} - C^+_{\ell^+, K^0_S} \quad 0.10 \pm 0.14 \pm 0.08 \]
\[ \Delta C_T^- = C^+_{\ell^-, K^0_L} - C^-_{\ell^+, K^0_S} \quad 0.04 \pm 0.14 \pm 0.08 \]

Large significance for T violation

(0,0) = no violation

68%

95%
Results (cont’d)

CP-violating parameters

\[ \Delta S_{CP}^+ = S_{\ell-,K^0_S}^+ - S_{\ell+,K^0_S}^- \quad -1.30 \pm 0.11 \pm 0.07 \]
\[ \Delta S_{CP}^- = S_{\ell-,K^0_S}^- - S_{\ell+,K^0_S}^+ \quad 1.33 \pm 0.12 \pm 0.06 \]
\[ \Delta C_{CP}^+ = C_{\ell-,K^0_S}^+ - C_{\ell+,K^0_S}^- \quad 0.07 \pm 0.09 \pm 0.03 \]
\[ \Delta C_{CP}^- = C_{\ell-,K^0_S}^- - C_{\ell+,K^0_S}^+ \quad 0.08 \pm 0.10 \pm 0.04 \]

CP violation significance largest than for T violation

CPT-violating parameters

\[ \Delta S_{CPT}^+ = S_{\ell+,K^0_L}^- - S_{\ell+,K^0_S}^+ \quad 0.16 \pm 0.21 \pm 0.09 \]
\[ \Delta S_{CPT}^- = S_{\ell+,K^0_L}^+ - S_{\ell+,K^0_S}^- \quad -0.03 \pm 0.13 \pm 0.06 \]
\[ \Delta C_{CPT}^+ = C_{\ell+,K^0_L}^+ - C_{\ell+,K^0_S}^- \quad 0.14 \pm 0.15 \pm 0.07 \]
\[ \Delta C_{CPT}^- = C_{\ell+,K^0_L}^- - C_{\ell+,K^0_S}^+ \quad 0.03 \pm 0.12 \pm 0.08 \]

No sign of CPT violation

Observed T violation as due to compensate CP violation

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Cross checks

- Study using simulation data shows asymmetry parameters $\Delta S^\pm_T$, $\Delta C^\pm_T$ are unbiased and have Gaussian errors.
- Studies of data segmented by running period or flavor mode are consistent.
- With appropriate constraints, obtain same $S,C$ parameters as the latest BaBar CP violation study.  
  \textit{PRD 79, 072009 (2009)}
- Fitting $B \to c\bar{c}K^\pm$ and $B \to J/\psi K^{*\pm}$ control samples yield asymmetry parameters consistent with zero.

```
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta C^-_{C\bar{P}}$</td>
<td>$0.036 \pm 0.050$</td>
</tr>
<tr>
<td>$\Delta C^-_{C\bar{P}T}$</td>
<td>$-0.0042 \pm 0.068$</td>
</tr>
<tr>
<td>$\Delta C^-_T$</td>
<td>$-0.0405 \pm 0.073$</td>
</tr>
<tr>
<td>$\Delta C^+_{C\bar{P}}$</td>
<td>$0.0044 \pm 0.049$</td>
</tr>
<tr>
<td>$\Delta C^+_{C\bar{P}T}$</td>
<td>$-0.1586 \pm 0.070$</td>
</tr>
<tr>
<td>$\Delta C^+_T$</td>
<td>$-0.0237 \pm 0.073$</td>
</tr>
<tr>
<td>$\Delta S^-_{C\bar{P}}$</td>
<td>$0.088 \pm 0.054$</td>
</tr>
<tr>
<td>$\Delta S^-_{C\bar{P}T}$</td>
<td>$-0.1035 \pm 0.083$</td>
</tr>
<tr>
<td>$\Delta S^-_T$</td>
<td>$0.041 \pm 0.089$</td>
</tr>
<tr>
<td>$\Delta S^+_{C\bar{P}}$</td>
<td>$0.041 \pm 0.053$</td>
</tr>
<tr>
<td>$\Delta S^+_{C\bar{P}T}$</td>
<td>$0.030 \pm 0.086$</td>
</tr>
<tr>
<td>$\Delta S^+_T$</td>
<td>$0.155 \pm 0.094$</td>
</tr>
</tbody>
</table>
```

- $B \to c\bar{c}K^\pm$ used as $J/\psi K_S$.
- $B \to J/\psi K^{*\pm}$ used as $J/\psi K_L$.

\[ (\Delta S_T^-, \Delta C_T^-) \]
\[ (\Delta S_T^+, \Delta C_T^+) \]

68% 95%
Systematic uncertainties are evaluated similarly as in our last CP analysis.

<table>
<thead>
<tr>
<th>Systematic source</th>
<th>$\Delta S^+_T$</th>
<th>$\Delta S^-_T$</th>
<th>$\Delta C^+_T$</th>
<th>$\Delta C^-_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interaction region</td>
<td>0.011</td>
<td>0.035</td>
<td>0.02</td>
<td>0.029</td>
</tr>
<tr>
<td>Flavor misID probabilities</td>
<td>0.022</td>
<td>0.042</td>
<td>0.022</td>
<td>0.022</td>
</tr>
<tr>
<td>$\Delta t$ resolution</td>
<td>0.030</td>
<td>0.050</td>
<td>0.048</td>
<td>0.062</td>
</tr>
<tr>
<td>$J/\psi K^0_L$ background</td>
<td>0.033</td>
<td>0.038</td>
<td>0.052</td>
<td>0.010</td>
</tr>
<tr>
<td>Background fractions and CP content</td>
<td>0.029</td>
<td>0.021</td>
<td>0.020</td>
<td>0.026</td>
</tr>
<tr>
<td>$m_{ES}$ parameterization</td>
<td>0.011</td>
<td>0.002</td>
<td>0.005</td>
<td>0.002</td>
</tr>
<tr>
<td>$\Gamma_d$ and $\Delta m_d$</td>
<td>0.001</td>
<td>0.005</td>
<td>0.011</td>
<td>0.008</td>
</tr>
<tr>
<td>CP violation for flavor ID categories</td>
<td>0.018</td>
<td>0.019</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Fit bias</td>
<td>0.010</td>
<td>0.072</td>
<td>0.013</td>
<td>0.010</td>
</tr>
<tr>
<td>$\Delta \Gamma_d/\Gamma_d$</td>
<td>0.004</td>
<td>0.003</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>PDF normalization</td>
<td>0.013</td>
<td>0.019</td>
<td>0.005</td>
<td>0.004</td>
</tr>
<tr>
<td>Total</td>
<td>0.064</td>
<td>0.112</td>
<td>0.08</td>
<td>0.077</td>
</tr>
</tbody>
</table>

Effect of treating $c\bar{c}K_S$ and $J/\psi K_L$ as orthogonal states negligible.
Significance of T violation

- Repeat the standard fit, applying constraints to the parameters for T-conjugate processes
- Difference in likelihood with the standard fit yields the significance of T violation
  \[ \Delta \chi^2 = -2 \left( \ln L_{\text{No TRV}} - \ln L \right) \]
  \[ \Delta \nu = 8 \text{ degrees of freedom} \]
- CP and CPT significance can be estimated this way using appropriate constraints
- Include systematics variations in significance estimations

\[ m_j^2 = -2 \left[ \ln L(q_j, o_j) - \ln L(p_0) \right] / s_{\text{stat},j}^2 \]
- Take \( \max(m_j^2) \), scale significance by \( [1+\max(m_j^2)] = 1.61 \)

\[ \begin{array}{|c|c|c|}
\hline
\text{T-inv. constraints} & \Delta S_T^\pm = \Delta C_T^\pm = 0 \\
\hline
\Delta S_{CP}^\pm = \Delta S_{CPT}^\pm & \Delta C_{CP} = \Delta C_{CPT} \\
\hline
\end{array} \]

**Significance**

<table>
<thead>
<tr>
<th></th>
<th>(-2\Delta \ln L)</th>
<th>Signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T)</td>
<td>226</td>
<td>&gt; 10 (\sigma)</td>
</tr>
<tr>
<td>(CP)</td>
<td>307</td>
<td>&gt; 10 (\sigma)</td>
</tr>
<tr>
<td>(CPT)</td>
<td>5</td>
<td>0.33 (\sigma)</td>
</tr>
</tbody>
</table>

(Includes systematics)
Building raw $T$ asymmetries

- Construct asymmetry for each of the four reference transitions
  
  $\bar{B}^0 \rightarrow B_-$ \quad $\bar{B}^0 \rightarrow B_+$ \quad $B_+ \rightarrow B^0$ \quad $B_- \rightarrow B^0$

- For the 1st reference (and similarly for the other three)

\[
A_T(\Delta t) = \frac{H_{\ell^- x, J/\psi K^0_L}(\Delta t) - H_{\ell^+ x, c\bar{c}K^0_S}(\Delta t)}{H_{\ell^- x, J/\psi K^0_L}(\Delta t) + H_{\ell^+ x, c\bar{c}K^0_S}(\Delta t)}
\]

where

\[
H_{\alpha, \beta}^{\pm}(\Delta t) = H_{\alpha, \beta}(\pm \Delta t) H(\Delta t)
\]

- For perfect reconstruction, is

\[
A_T(\Delta t) \approx \frac{\Delta C_T^+}{2} \cos(\Delta m \Delta t) + \frac{\Delta S_T^+}{2} \sin(\Delta m \Delta t)
\]

Signal region:

- $5.27 < m_{ES} < 5.29$ GeV/c²
- $|\Delta E| < 0.010$ GeV

SLAC Seminar

Observing directly “the weak arrow of time”

F. Martínez-Vidal, IFIC-Valencia
The four independent T asymmetries
The four independent CP asymmetries

\[ A_{CP} \]

\[ \bar{B}^0 \to B_- \]

\[ \bar{B}^0 \to B^+ \]

\[ B^+ \to B^0 \]

\[ B^- \to B^0 \]
The four independent CPT asymmetries

\[ B_+ \rightarrow B^0 \]

\[ A_{\text{CPT}} \]

\[ \Delta t \text{ (ps)} \]

\[ B_+ \rightarrow \bar{B}^0 \]

\[ A_{\text{CPT}} \]

\[ \Delta t \text{ (ps)} \]

\[ B_- \rightarrow B^0 \]

\[ A_{\text{CPT}} \]

\[ \Delta t \text{ (ps)} \]

\[ B_- \rightarrow \bar{B}^0 \]

\[ A_{\text{CPT}} \]

\[ \Delta t \text{ (ps)} \]
Summary
has measured for the first time T-violating parameters in the time evolution of neutral B mesons, by comparing conjugate processes that can only be achieved by T reversal, not CP

This novel approach does not need CPT invariance to link T and CP violation

The significance of the effect exceeds 10σ level

The result is consistent with CP-violating measurements assuming CPT invariance

This is the first direct observation of Time Reversal Violation, in any system, through processes that can only be related by a T transformation

This somehow closes the cycle of the CPT theorem…
Observation of Time-Reversal Violation in the $B^0$ Meson System


(The BABAR Collaboration)

(Received 24 July 2012)

Although $CP$ violation in the $B$ meson system has been well established by the $B$ factories, there has been no direct observation of time-reversal violation. The decays of entangled neutral $B$ mesons into definite flavor states ($B^0$ or $\bar{B}^0$), and $J/\psi K^0_S$ or $c\bar{c}K^0_S$ final states (referred to as $B^+$ or $B^-$), allow comparisons between the probabilities of four pairs of $T$-conjugated transitions, for example, $\bar{B}^0 \to B_-$ and $B_+ \to B^0$, as a function of the time difference between the two $B$ decays. Using $468 \times 10^6$ $B\bar{B}$ pairs produced in $Y(4S)$ decays collected by the BABAR detector at SLAC, we measure $T$-violating parameters in the time evolution of neutral $B$ mesons, yielding $\Delta S^+ = -1.37 \pm 0.14$ (stat) $\pm 0.06$ (syst) and $\Delta S_T = 1.17 \pm 0.18$ (stat) $\pm 0.11$ (syst). These nonzero results represent the first direct observation of $T$ violation through the exchange of initial and final states in transitions that can only be connected by a $T$-symmetry transformation.

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Observing directly “the weak arrow of time”
F. Martínez-Vidal, IFIC-Valencia
Added bonus: article in The Economist (1st September)

A press release is now under review by SLAC and DOE, plan to release once the paper will be published online

Plan for an article in Physics Today

http://www.economist.com/node/21561111
Thank you for your attention
The BaBar detector

- **DIRC (PID)**
  - 144 quartz bars
  - 11000 PMs

- **1.5T solenoid**

- **EMC**
  - 6580 CsI(Tl) crystals

- **Drift Chamber**
  - 40 stereo layers

- **Silicon Vertex Tracker**
  - 5 layers, double sided strips

- **Instrumented Flux Return**
  - Iron / RPCs / LSTs (muon / neutral hadrons)

- **e^+ (3.1 GeV)**

- **e^- (8-9 GeV)**

- Asymmetric B-factory: $E_{\text{cms}} = 10.58$ GeV
- Performed a wide range of flavor physics results in B, Charm and tau sectors
- General purpose detector in $e^+e^-$ environment: precision tracking, photon/electron detection, particle ID, muon/KL identification. Very stable over the 9 years of operation