CP-Violation Results from the BaBar Collaboration

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University of British Columbia

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Outline

Measuring CP Violation in the B-Meson System

PEP-II B-Factory and BaBar Detector

Analysis and Results

Prospects
CP Violation

Particle Physics (pre–1964)
   Energy $\leftrightarrow$ Equal amounts of Matter and Antimatter
   Matter and Antimatter have identical properties (CP is conserved)

Astrophysics
   The Universe contains negligible antimatter
   The Universe was created in a hot Big Bang

Where did all the antimatter go?

Cronin-Fitch Experiment (1964)
   Long-lived neutral kaon (CP-odd) sometimes decays to $\pi^+ \pi^-$ (CP-even)
   CP is violated!

Kobayashi-Maskawa (1973)
   Weinberg-Salam with 3 quark generations has “natural” CP violation
   “Predicts” that CP is violated

Experimental question: is the Kobayashi-Maskawa explanation the right one?
Mixing and CP Violation

Mixing of Neutral Mesons
Weak interactions allow neutral mesons ($K^0$, $D^0$, $B^0$) to “oscillate” into their own antiparticles and back again.
We can write CP-even and CP-odd particle-anti-particle combinations.
If CP is conserved, these are the mass eigenstates, with different decays.
In the $K^0$ case, the lifetimes are very different ($K^0_{\text{LONG}}, K^0_{\text{SHORT}}$).

Three kinds of CP violation
Direct: $B \rightarrow X \neq \bar{B} \rightarrow \bar{X}$
Mixing: mass eigenstate is not CP-eigenstate has “CP-forbidden” decays
Interference: $B \rightarrow CP$ and $\bar{B} \rightarrow CP$ so they can interfere
makes decay rates time-dependent.

CP Violation in $B^0$ system
Small lifetime difference makes purely mixing CP violation small.
Direct CP-violation expected to be large in some rare modes but also suffers from hadronic uncertainties.
Interference CP-violation is the preferred measurement for both theoretical and experimental reasons.
Measuring CP Violation in $B^0$ System

Requirements for measuring CP violation through interference
Isolation of exclusive decays to particular CP-eigenstates
“Tagging” of whether it was created as a $B^0$ or anti-$B^0$
Measurement of decay time (not always required but always helpful)

Golden Mode: $B^0 \rightarrow J/\psi K_S^0$, $J/\psi \rightarrow e^+e^-(\mu^+\mu^-)$, $K_S^0 \rightarrow \pi^+\pi^-$
Minimal number of particle tracks (less combinatoric background)
Two leptons, separated K-decay vertex, 3 mass constraints
Theoretically clean

Cleanest source of $B^0$ events is $e^+e^-$ collisions at $Y(4S)$ resonance
$Y(4S)$ is an excited $b\bar{b}$ bound state that decays only to $B^0\bar{B}^0$ and $B^+B^-$
At resonance, $\approx 20\%$ of all events are $Y(4S)$ with no extra particles
$B^0\bar{B}^0$ are created with a small fixed kinetic energy in the $Y(4S)$ frame
Measuring CP Violation in $B^0$ System (2)

Problems with $Y(4S)$ for CP measurement

$B^0 B^0$ created in entangled state so integrated CP-asymmetry vanishes (time-dependent asymmetry is still present)

Velocity of $B^0 B^0$ in $Y(4S)$ frame is too slow to resolve time dependence

Solution:

Collide $e^+ e^-$ with different energies

$Y(4S)$ and thus $B^0$ and anti-$B^0$ are moving in lab frame

Fully reconstruct one exclusive CP eigenstate

typical branching ratio of $\ll 10^{-3}$

Partially reconstruct the other $B$ decay

“Tag” event by decay products of other $B$: lepton or $K$ charge

Resolve time-dependence using silicon detector technology
PEP-II Performance

PEP-II collides 1 Ampere of 9.0 GeV e\(^-\) with 2 Amperes of 3.1 GeV e\(^+\) at the Y(4s)

Design luminosity was 3.0 x 10\(^{33}\) cm\(^{-2}\) sec\(^{-1}\), record luminosity is now 4.3 x 10\(^{33}\)

Best Shift \hspace{1cm} 102 pb\(^{-1}\)
Best 24 hours \hspace{1cm} 278 pb\(^{-1}\)
Best 7 days \hspace{1cm} 1758 pb\(^{-1}\)
Best Month \hspace{1cm} 6038 pb\(^{-1}\)

Total 1999 \hspace{1cm} 1620 pb\(^{-1}\)
Total 2000 \hspace{1cm} 23760 pb\(^{-1}\)
Total 2000-1 \hspace{1cm} 59040 pb\(^{-1}\)
Projected 2001-2 \hspace{1cm} 77000 pb\(^{-1}\)
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CP-Violation from BaBar

T. Mattison

Coral Gables 2001
BaBar Detector

SVT: 97% efficiency, 15µ hit resolution in Z for inner layers

Tracking: \( \sigma(p_t)/p_t = 0.13\%p_t + 0.45\% \)

DIRC: K-π separation > 3.4σ for P< 3.5 GeV/c

EMC: \( \sigma_E/E = 2.3\%E^{-1/4} \oplus 1.9\% \)

IFR: Muon and \( K_{L0}^0 \) identification

CP-Violation from BaBar
Exclusive $B^0 \rightarrow J/\Psi K_S$ Reconstruction

Form $\pi\pi$ combinations with decay vertex $\rightarrow K^0$

Form $e e$ and $\mu\mu$ combinations $\rightarrow J/\Psi$

Combine $K^0$ and $J/\Psi$ combinations $\rightarrow B^0$

$$M_{ES} = \sqrt{\left( E_{beam}^* \right)^2 - \left( P_\perp^* \right)^2}$$

$$\Delta E = E_{candidate}^* - E_{beam}^*$$

Form $\pi\pi$ combinations with decay vertex $\rightarrow K^0$

Form $e e$ and $\mu\mu$ combinations $\rightarrow J/\Psi$

Combine $K^0$ and $J/\Psi$ combinations $\rightarrow B^0$
Published CP Sample    PRL 87, 091801 (2001)

Events: 441
Purity: 97%

J/ψ K_S

K_S → π^+ π^−

Events: 95
Purity: 87%

K_S → π^0 π^0

Events: 85
Purity: 96%

ψ(2S) K_S

Events: 41
Purity: 95%

χ_c1 K_S

Events: 56
Purity: 74%

J/ψ K^*

1999-2001 data
32×10^6 BB pairs,
29 fb^{-1} on peak

Events: 257
Purity: 60%

J/ψ K_L

CP-Violation from BaBar

T. Mattison

Coral Gables 2001
Time Dependence from Other B Vertex

- **Reconstruct** $B_{\text{rec}}$ vertex from
  - charged $B_{\text{rec}}$ daughters ($\sigma_z(B_{\text{rec}}) = 65 \, \mu m$)
- **Determine** $B_{\text{Tag}}$ vertex from
  - charged tracks not belonging to $B_{\text{rec}}$
  - $B_{\text{rec}}$ vertex and momentum
  - beam spot and $Y(4S)$ momentum
“Tagging” with the Other B Decay

Charge of lepton (e or µ) with highest p*
  p* > 1.0 GeV/c for e, 1.1 GeV/c for µ
reduces B→D→lepton background

Charge of decay kaon
identified by Cherenkov angle, dE/dx

Neural net
  Charge and p* of highest p* track
  Subnet for soft pion from D* decay,
  Subnets for lepton and kaon ID
  Most discrimination from
  unrecognized leptons and D* pions

Use lepton tag if available
  (and not contradicted by kaon tag)
Then use kaon tag if available
Strong (NT1) and weak (NT2) neural net tags
Δt Resolution and Mistag Dilution

\[ f_{CP_{\pm}} = \left\{ \frac{\exp(\Delta t/\tau_B)}{2\tau_B} \times \left[ 1 - 2w_{\text{tag}} \sin(2\beta) \sin(\Delta m \Delta t) \right] \right\} \otimes R(\Delta t) \]

- \( w_{\text{tag}} \) is dilution of asymmetry from tags with wrong sign.
- \( R(\Delta t) \) is smearing due to finite vertex resolution (mostly from tag vertex).
Raw CP Asymmetry

\[ B^0 \rightarrow J/\psi K_S^0 \]
\[ B^0 \rightarrow \psi(2S) K_S^0 \]
\[ B^0 \rightarrow \chi_{c1} K_S^0 \]

246 \( B^0 \) tags
234 \( B^0 \) tags
Calibration with “Flavor” Modes

Use the much larger sample of decays that are “self-tagged” as B or anti-B to determine the time-resolution and mis-tag rates.

- **N_{B^0/B^0} \approx 9400**
  - purity 83%

- **N_{B^+/B^-} \approx 8500**
  - purity 85%

---

**perfect**
- flavor tagging & time resolution
- UnMixed
- Mixed

**realistic**
- mis-tagging & finite time resolution
- UnMixed
- Mixed
Fitting Method

Unbinned maximum likelihood fit to 29 fb\(^{-1}\) of data:
- B lifetime and mixing-rate were fixed to PDG values
- Fit flavor-mode data for mistag-rates for different tag classes
- Fit flavor- and CP-modes for \(\Delta t\) resolution
- Fit sidebands for additional mistag and \(\Delta t\) resolution parameters

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<tr>
<th>Tagging category</th>
<th>(\varepsilon_i) (%)</th>
<th>(w_i) (%)</th>
<th>(Q_i) (%)</th>
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<td>Lepton</td>
<td>10.9 ± 0.3</td>
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<td>7.4 ± 0.5</td>
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<tr>
<td>Kaon</td>
<td>35.8 ± 0.5</td>
<td>17.6 ± 1.0</td>
<td>15.0 ± 0.9</td>
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<td>NT1</td>
<td>7.8 ± 0.3</td>
<td>22.0 ± 2.1</td>
<td>2.5 ± 0.4</td>
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<td>NT2</td>
<td>13.8 ± 0.3</td>
<td>35.1 ± 1.9</td>
<td>1.2 ± 0.3</td>
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<td><strong>ALL</strong></td>
<td><strong>68.4 ± 0.7</strong></td>
<td><strong>26.1 ± 1.2</strong></td>
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Mistag probabilities from fit

\(\Delta t\) core resolution \(\approx 1.27\) ps

Fit CP-modes for \(\sin(2\beta)\)
CP Fit Results

Positive-asymmetry modes

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<tr>
<th>$B^0 \rightarrow J/\psi K_S^0$</th>
<th>$B^0 \rightarrow \psi(2S) K_S^0$</th>
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Negative-asymmetry mode

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\[
\sin(2\beta) = 0.59 \pm 0.14_{\text{stat}}
\]
Systematic Errors on $\sin(2\beta)$

$\pm 0.03$  
Signal Resolution and Vertexing  
Resolution model, outliers, SVT residual misalignment

$\pm 0.03$  
Tagging  
Possible differences between mistag for CP and flavor samples

Backgrounds  
Amount, shape, and CP asymmetry of background

$\pm 0.02$  
$K^0_{\text{SHORT}}$

$\pm 0.09$  
$K^0_{\text{LONG}}$

$\pm 0.11$  
$K^*$

Sample  
$K^0_{\text{SHORT}}$  
$K^0_{\text{LONG}}$  
$K^*$  
Full

Systematic  
0.05  
0.10  
0.16  
0.05

Statistical  
0.15  
0.34  
1.01  
0.14

$\sin(2\beta) = 0.59 \pm 0.14_{\text{stat}} \pm 0.05_{\text{syst}}$

Prob. of this result if CP is conserved : $< 3 \times 10^{-5}$
Prob. of this result if CP is conserved ($\eta_{CP} = -1$) : $< 2 \times 10^{-4}$
Systematic Errors on $\sin(2\beta)$

$\pm 0.03$  Signal Resolution and Vertexing
Resolution model, outliers, SVT residual misalignment

$\pm 0.03$  Tagging
Possible differences between mistag for CP and flavor samples

Amount, shape, and CP asymmetry of background

$\pm 0.02$  $K^0_{\text{SHORT}}$

$\pm 0.09$  $K^0_{\text{LONG}}$

$\pm 0.11$  $K^*$

$\pm 0.05$  Systematic error when modes are combined with statistical weights

$\sin(2\beta) = 0.59 \pm 0.14_{\text{stat}} \pm 0.05_{\text{syst}}$

Prob. of this result if $CP$ is conserved : $< 3 \times 10^{-6}$
Prob. of this result if $CP$ is conserved ($\eta_{CP} = -1$) : $< 2 \times 10^{-4}$
Comparison to Other Measurements

![Graph showing measurements of sin2β for OPAL, CDF, ALEPH, BELLE, BABAR, and the average. The graph indicates that the average value is 0.79 ± 0.10.](image)

- OPAL: $3.20^{+1.8}_{-2.0} \pm 0.5$
- CDF: $0.79^{+0.41}_{-0.44}$
- ALEPH: $0.84^{+0.82}_{-1.04} \pm 0.16$
- BELLE: $0.99 \pm 0.14 \pm 0.06$
- BABAR: $0.59 \pm 0.14 \pm 0.05$
- Average: $0.79 \pm 0.10$
Cabibbo-Kobayashi-Maskawa Matrix and Wolfenstein Parameters

CKM Matrix describes charged-current weak couplings between quarks

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

Wolfenstein noted that $|V_{cb}| \approx |V_{us}|^2$ and suggested the parameterization

\[
\begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix}
\]
Unitarity Triangle

Unitarity \[\Rightarrow\] \[V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0\]

Can be represented as a triangle in the complex plane with unit base, and apex at \((\rho, \eta)\)

CP-violation means that there is an irreducible phase in the CKM matrix so the triangle doesn’t collapse to a line.

CP-violation in different processes depends different angles of triangle

Sides of triangle determine weak coupling strengths
BaBar Result Compared

Combination of CP-violation in $K^0$ system, B-mixing rate, and rate of charmless B-decays makes a prediction of $(\rho, \eta)$ and thus $\sin(2\beta)$.

BaBar result is quite consistent with this prediction.
Conclusion

BaBar has established CP-violation in the $B^0$ system at 4 $\sigma$ level

$$\sin(2\beta) = 0.59 \pm 0.14 \pm 0.05$$

Probability to observe such a large value
in the absence of CP-violation is less than $3 \times 10^{-5}$

PEP-II is running superbly, and we already have twice as much data
as was reported here and published, and we will continue to run
essentially continuously until Summer 2002.

We are also working on measuring $\sin(2\alpha)$ through $B^0 \to \pi\pi$

BaBar is also contributing to measurements of the sides of the
Unitarity Triangle through non-CP processes

There is a long range program of upgrades to PEP-II
to raise the luminosity even higher

Along with BELLE, the Tevatron, and eventually the LHC,
BaBar is bringing the world a new regime of precision tests
of the CKM explanation of CP-violation
Fitting Method

Unbinned maximum likelihood fit to 29 fb$^{-1}$ of data:
B lifetime and mixing-rate were fixed to PDG values
Run 1 flavor- and CP-modes for $\Delta t$ resolution (3 Gaussians, 8 parameters)
Run 2 flavor- and CP-modes for $\Delta t$ resolution (3 Gaussians, 8 parameters)
All flavor-mode data for mistag-rates for 4 $B^0$ tag classes
All flavor-mode data for mistag-rates for 4 anti-$B^0$ tag classes
Sidebands for mistag (8 parameters) and $\Delta t$ shape (12 parameters)
CP-modes for $\sin(2\beta)$

Total of 45 parameters

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$\Delta t$ core resolution $\approx$ 1.27 ps
Systematic Errors on $\sin(2\beta)$

- **Signal resolution and vertexing = 0.03**
  - Resolution model, outliers, SVT residual misalignment
- **Tagging = 0.03**
  - Studies of possible differences between $B_{\text{CP}}$ and $B_{\text{flavor}}$ samples
- **Backgrounds = 0.02 (overall)**
  - Signal probability, peaking background, $CP$ content of background
  - Total 0.093 for $J/\Psi K_L$ channel; 0.11 for $J/\Psi K^{*0}$
  - **Total = 0.05 for full sample**

<table>
<thead>
<tr>
<th></th>
<th>$K_S$</th>
<th>$K_L$</th>
<th>$K^{*0}$</th>
<th>Full</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Sys</td>
<td>0.05</td>
<td>0.10</td>
<td>0.16</td>
<td>0.05</td>
</tr>
<tr>
<td>Total Stat</td>
<td>0.15</td>
<td>0.34</td>
<td>1.01</td>
<td>0.14</td>
</tr>
</tbody>
</table>

$\sin(2\beta) = 0.59 \pm 0.14_{\text{stat}} \pm 0.05_{\text{syst}}$

Prob. of this result if $CP$ is conserved: $< 3 \times 10^{-5}$
Prob. of this result if $CP$ is conserved ($\eta_{CP} = -1$): $< 2 \times 10^{-4}$
Fit Results By Decay Mode

Errors are statistical only
Fit Results By Decay Mode and Run

Result for modes used in first paper differs by 1.8 σ between Runs 1 and 2
Fit Results By $\Delta t$ Bin

$\sin 2\beta$

$\eta_f = -1$ modes

$0.56 \times \sin \Delta m_{B_d} \Delta t$

$\Delta t$ (ps)

$\sin 2\beta \sin \Delta m_{B_d} \Delta t$

$\Delta t$ (ps)