Recent results from Belle

- (No) Introduction
- KEKB accelerator and Belle detector
- Observation of CP violation in B system

Nobu Katayama
KEK, Japan
Oct. 9th, 2001
Siena2001
Physics Motivation of Belle

- Observe CP violation in B meson system
- Try to establish the mechanism of the CP violation
  - In particular, we must know whether the measurements (of the CP violation) are consistent with the description given by the CKM matrix of weak interactions in the standard model
  - Otherwise we need to find the new CP violating interaction
The Cabibbo-Kobayashi-Maskawa quark mixing matrix

- A unitary matrix which relates the mass eigenstates to eigenstates of weak force.
- The strength of the weak interaction is proportional to $V_{q_i q_j}$.
- Wolfenstein parameterization is the most popular approximation, writing in terms of the powers of $\lambda$; sine of Cabibbo angle $V \approx \begin{pmatrix} 1 - \lambda^2 / 2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2 / 2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$.
The Unitarity Triangle

Unitarity ($U^\dagger U=1$) of the CKM matrix applied to the first and third columns yields:

$$V_{ub}V_{ud} + V_{cb}^*V_{cd} + V_{tb}^*V_{td} = 0$$

In the Wolfenstein parameterization, it is simply

We would like to determine the sizes and angles of the triangle!
In the standard model, CP-violating processes/amplitudes involve the phase in the CKM matrix (Kobayashi-Maskawa)

- A 3x3 unitary matrix has one non-trivial phase

For CP-violating asymmetries of neutral B mesons decaying to CP eigenstates, there is a direct relationship between the magnitude of the asymmetry and $\sin(2\phi)$ (Bigi, Sanda, Carter)

- For example, asymmetry in the golden mode, $B_d^0(B_d^0) \rightarrow J/\psi K_S$ determines $\sin(2\phi_1)$
Other measurements ($\varepsilon$, $b \rightarrow u$, etc.) constrain the triangle in other ways.

The CKM matrix given in PDG2001
How to measure $\sin(2\phi_1)$ at Belle

1. Reconstruct one $B$ meson decay into the CP eigenstates
2. Tag the flavor of the other $B$ decay
3. Measure the signed time difference $\Delta t$
   - The asymmetry $A(\Delta t)$ will distribute as

$$A(\Delta t) = \frac{\Gamma(\Delta t) - \overline{\Gamma}(\Delta t)}{\Gamma(\Delta t) + \overline{\Gamma}(\Delta t)} \propto \xi_{CP} \sin 2\phi_1 \sin \Delta m_d \Delta t$$

Asymmetric e$^+$e$^-$ collider
↓↓↓↓
$B$ mesons are moving
High Energy Accelerator Research Organization

KEKB and Belle

ATLAS/LHC

K2K

JHF

...
KEKB accelerator system

- Asymmetric $e^+e^-$ collider (3.5GeV vs 8.0GeV)
- Reuse TRISTAN tunnel
- $L_{\text{goal}} = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

History
- First collision: 1999/5
- Runs used for this analysis

\[ \int Ldt = 33 \text{ fb}^{-1} \]
(as of July 2001)
One day performance

HER: 652.2 [mA] \(1.15 \times 10^5\) bunches
LER: 772.5 [mA] \(1.15 \times 10^5\) bunches
Luminosity: 3508 (now) \(4098\) (peak in 24H) \(\times 10^{30}/\text{cm}^2\text{sec}\)
Integ. Lumin. 6.7 (Fill) 92.0 (Day) 223.1 (24H) [pb]

06/16/2001 8:59 JST

Oct. 9, 2001

Nobu Katayama
KEKB performance

Luminosity of KEKB
July 1999 – July 2001

\[ \beta y^* = 7 \text{ mm} \]
\[ (\nu x, \nu y) = (0.52, 0.08) \]

- Installed 4 more SC Cavities, Belle VYD V1.5, LER V4 masks
- Peak Luminosity 4.49 /nb/s
- 232 /pb/day
- 1.50 /fb/7 days
- 33.1 /fb

Oct. 9, 2001
Nobu Katayama
The Belle Collaboration

World-Wide Activity Involving 50 Institutions

Australia
- Melbourne University
- University of Sydney

Austria
- Vienna*

China
- Beijing University
- Inst. for HEP
- Univ. of Sci. and Tech.

Germany
- Frankfurt*

India
- Panjab University
- Tata Institute*
- Utkal University

Korea
- Gyeongsang Nat’l Univ
- Koryong University
- Kyungpook Nat’l Univ
- Seoul National University
- Sung Kyun Kwan Univ
- Yonsei University

Japan
- Aomori University
- Chiba University
- Chuo University
- Hiroshima IT
- Kanagawa University
- KEK
- Kyoto University
- Nagasaki Inst. of A.S.
- Nagoya University
- Nara Women’s Univ.
- Niigata University
- Nihon Dental College
- Osaka University
- Osaka City University
- Saga University

Slovenia
- Ljubljana*

Switzerland
- Lausanne*

Taiwan
- Academia Sinica
- National Central Univ
- Nat. Kaohsing Nor. Univ.
- Nat Lien-Ho College
- National Taiwan Univ

United States
- University of Cincinnati
- University of Hawaii
- Princeton University
- Virginia Polytechnic

Poland
- Krakow Inst. of Nucl Phy.

Russia
- Budker Inst of Nucl Phy.
- ITEP Moscow

~250 authors

Oct. 9, 2001
Nobu Katayama
Belle detector

- SVD: 3-lyr silicon detector
- CDC: 50-lyr drift chamber
- ACC: Aerogel Cherenkov counter

- TOF: 4-cm Scint. Counter
- ECL: 16 rad. len. CsI
- KLM: 14-lyr RPC

SVD

CDC

TOF

ECL

B (1.5Tesla)

ACC
In this analysis we used a data sample of 29.1 fb$^{-1}$ taken from Oct. 1999 to July 2001.
How to measure $\sin(2\phi_1)$ at Belle

1. Reconstruct one B meson decay into the CP eigenstates
2. Tag the flavor of the other B decay
3. Measure the signed time difference
   - The asymmetry $A(\Delta t)$ will distribute as
     $$A(\Delta t) = \frac{\Gamma(\Delta t) - \bar{\Gamma}(\Delta t)}{\Gamma(\Delta t) + \bar{\Gamma}(\Delta t)} \propto \xi_{CP} \sin 2\phi_1 \sin \Delta m_d \Delta t$$
   - Experimental concerns
     - Resolution function
     - Wrong tagging fraction
     - Backgrounds

Asymmetric collision

B meson is moving

Must understand these very well
1. Reconstruct CP eigenstates
   - Background function: $f_{BG}$

2. Tag flavor of the other B
   - Wrong tag fraction: $w$

3. Measure decay-time difference
   - Resolution function: $R_{res}$

4. Maximum Likelihood fit
   - $\sin 2\phi_1$

$A^{CP}(t) \equiv \frac{\Gamma(B_d^0(t) \to f_{CP}) - \Gamma(B_d^0(t) \to \bar{f}_{CP})}{\Gamma(B_d^0(t) \to f_{CP}) + \Gamma(B_d^0(t) \to \bar{f}_{CP})}$

$= -\xi_f \sin 2\phi_1 \sin \Delta m_B t$
Reconstruction of $B$ to $f_{cp}$

Use low background $cc\bar{K}^0$ modes

- $J/\psi$ ($\rightarrow l^+l^-$) + $K_S$ ($\rightarrow \pi^+\pi^- \ & \pi^0\pi^0$)
- $\psi(2S)$ ($\rightarrow l^+l^- \ & \ J/\psi\pi^+\pi^-$) + $K_S$
- $\chi_{c1}$ ($\rightarrow J/\psi\gamma$) + $K_S$
- $\eta_c$ ($\rightarrow K_SK^+\pi^- \ , \ K^+K^-\pi^0$) + $K_S$
- $J/\psi \ K_L$
- $J/\psi \ K^{*0}$ ($\rightarrow K_S\pi^0$)

\[
\xi_f = -1 \quad \text{CP odd}
\]

\[
\xi_f = +1 \quad \text{CP even}
\]

(81\% $\quad \xi_f = +1$)

[ full angular analysis ]

Oct. 9, 2001 Nobu Katayama 19
Reconstruction of $K_S$

$K_S \rightarrow \pi^{+} + \pi^{-}$
- CDC($\sigma_{r\phi} \sim 100 \mu m$)
- SVD($\sigma_{r\phi} \sim 30 \mu m$)

$\sigma_{pt} = 0.19 pt \oplus 0.34/\beta\%$

$\sigma_{M}=4.1\text{ MeV}/c^2$

same $p$ cut with $J/\psi K_S$ events

$K_S \rightarrow \pi^0 + \pi^0$
- Electromagnetic Calorimeter

$\sigma_{E}/E=1.34 \oplus 0.066/E \oplus 0.81/E^{1/4}(\%)$

$\sigma_{M}=9.3\text{ MeV}/c^2$

in inclusive $J/\psi$ events

Oct. 9, 2001

Nobu Katayama
An example of $J/\psi (l^+l^-) + K_s (\pi^+\pi^-)$

$B^0 \rightarrow J/\psi + K_s$

$\mu^+\mu^- \pi^+\pi^-$

The Golden mode (large b.r. low b.g.)
The $J/\psi + K_s(\pi^+\pi^-)$ event sample

$B^0 \rightarrow J/\psi + K_s(\rightarrow \pi^+\pi^-)$

457 events

$\sim 3\%$ background

Energy difference

$$\Delta E \equiv E_{J/\psi} + E_{K_s} - E_{CM} / 2$$

Beam constrained mass

$$m_{bc} = \sqrt{(E_{CM} / 2)^2 - (\vec{p}_{J/\psi} + \vec{p}_{K_s})^2}$$

Oct. 9, 2001
Oct. 9, 2001  Nobu Katayama  24

**Summing up all modes but J/ψK_L**

### All modes except for J/ψK_L
- **Signal(+BG)**: 747 events (purity: 92%)
- **Background**: ~59 events

### B^0 \rightarrow J/ψ K_S (→π^+π^-)
- **Signal(+BG)**: 457 events (purity: 97%)
- **Background**: ~12 events

### Other modes
- **Signal(+BG)**: 290 events (purity: 84%)
- **Background**: ~46 events

Oct. 9, 2001

Nobu Katayama
**Selection procedure**

1. Find $J/\psi \rightarrow l^+l^-$
2. Assume $B^0 \rightarrow J/\psi K_L$ and calculate the $K_L$ direction
3. Find ECL/KLM cluster within $45^\circ$ cone
4. Cut on a likelihood based on kinematical and shape quantities
5. Calculate $P_B^*$
**P_B^* distribution in B^0 → J/ψ K_L**

- **P_B^*:** If B^0 → J/ψ K_L, peaks at around ~340 MeV/c

- **B^0 → J/ψ K_L**
  - Signal(+BG) 569
  - Background~223 (purity:61%)

- **Total of 1316 events (incl.BG) in all CP=±1 modes**

Oct. 9, 2001
Nobu Katayama
Tag flavor of the other B

Would like to know the flavor of the B meson which decayed into the CP eigenstate.

We can flavor tag the other B meson:
- Lepton from B, D
- Kaon from $b \rightarrow c \rightarrow s$
- Slow pion from $D^*$
- Fast pion from B

Combine into a two layered likelihood function.

Would like to know the flavor of the $B^0$ or $B^0$ ?

Flavor tagging: $B^0 \rightarrow D^{(*)-} \pi^+$, $D^{(*)-} \rho^+$, etc.

Vertexing

Reconstruction of $f_{CP}$

Oct. 9, 2001

Nobu Katayama
Lepton identification

- Electron ID by E/p, CsI shower shape, dE/dx, track matching, TOF and ACC
- Muon ID: by KLM
  - 14 layers of glass resistive plate chambers (RPC) in iron yoke

Electron efficiency vs. $P_{lab}(GeV/c)$
- 90% efficiency
- 1% fake rate

Muon efficiency vs. $P_{lab}(GeV/c)$
- 90% efficiency
- 2% pion fake rate

Oct. 9, 2001
Nobu Katayama
We measure efficiency, fake rate using D*s

- Kaon efficiency
- $\pi$ contamination

$dE/dx$ (CDC)
TOF (Barrel)
Barrel ACC
Endcap ACC

$\Delta dE/dX \sim 6.9\%$
$\Delta T \sim 95$ ps (r = 125cm)
n = 1.010 - 1.028
n = 1.030 (for flavor tagging)

Efficiency

Counts / 0.02/track

Oct. 9, 2001 Nobu Katayama
Wrong tagging fraction: $w_k$

Get $w_k$ from $B\bar{B}$ mixing amplitude using $B\to D^*\ell\nu$ events

$$A(\Delta t) \equiv \frac{P_{\text{Opposite-Flavor}}(\Delta t) - P_{\text{Same-Flavor}}(\Delta t)}{P_{\text{Opposite-Flavor}}(\Delta t) + P_{\text{Same-Flavor}}(\Delta t)}$$

$$\approx (1 - 2w) \cos(\Delta m_B \Delta t) \quad (r: \text{to categorize events})$$

Efficiency $\sim 100\%$

Effective efficiency is $27.0 \pm 1.2\%$
\[ \Delta t = \Delta z / \beta \gamma c \] is measured by

**SVD**: 3 layers of Double Sided Silicon Detectors (DSSD)

- \[ \sigma_f = 19 \oplus 50 / p \beta \sin^{3/2} \theta (\mu m) \]
- \[ \sigma_z = 36 \oplus 42 / p \beta \sin^{5/2} \theta (\mu m) \]

- For CP-side, use \( J/\psi \rightarrow e^+e^- \)
  - \( \sigma_{z_{CP}} \approx 75 \mu m \)
  - \( \varepsilon \approx 92\% \)

- For Tag-side,
  - use tracks other than those in CP side
  - iterate: discard worst track
  - \( \sigma_{z_{tag}} \approx 140 \mu m \) \( \Leftarrow \) Charm effect
  - \( \varepsilon \approx 91\% \)

- Require \(|z_{CP} - z_{tag}| < 2 mm (\gg 10 \tau_B)\)

Oct. 9, 2001

Nobu Katayama
Resolution function $R(\Delta t - \Delta t')$

Measured $\Delta t$: smeared by detector resolution & charm lifetimes

Resolution function: a sum of two Gaussians

$$R(\Delta t - \Delta t') = (1 - f_{\text{tail}}) \times G_1(\Delta t - \Delta t'; \mu_{\text{main}}, \sigma_{\text{main}}) + f_{\text{tail}} \times G_2(\Delta t - \Delta t'; \mu_{\text{tail}}, \sigma_{\text{tail}})$$

- $\sigma/\mu$
  - Calculated event by event from vertex fit errors
- Average $\Delta t$ error: 1.5ps

After vertexing, total of 1137 events left

SVD vertex resolution
Charmed meson lifetime

- Poorly reconstructed tracks

$J/\psi K_S$ events

$log R$

$G_1$

$G_2$

$f_{\text{tail}} = 0.03$

$\mu_{\text{main}} = -0.24\text{ps}$
$\sigma_{\text{main}} = 1.49\text{ps}$
$\mu_{\text{tail}} = 0.18\text{ps}$
$\sigma_{\text{tail}} = 3.85\text{ps}$

Oct. 9, 2001
Nobu Katayama
Validation for R: B lifetimes

B lifetimes are measured using the same R

\[ \tau_{B^0} = 1.55 \pm 0.02\text{ps} \]
(PDG: 1.55 ± 0.03ps)

\[ \tau_{B^+} = 1.64 \pm 0.03\text{ps} \]
(PDG: 1.65 ± 0.03ps)

Agree very well with the world averages

Very small error
Maximum likelihood fit for $\sin 2\phi_1$

Estimate $\sin 2\phi_1$ using event by event likelihood $f$.

$$L_{\text{event}} = \int ((1 - f_{BG})PDF_{\text{sig}} + f_{BG}PDF_{BG}) \times R(\Delta t - \Delta t')d\Delta t'$$

$f_{BG}$ : background function, $R$ : resolution function

PDF : Probability density function

PDF$_{\text{sig}} = \frac{e^{-|\Delta t|/\tau_B}}{2\tau_B} \left( 1 - \xi_f q(1 - 2w) \sin 2\phi_1 \sin \Delta m_B \Delta t \right)$

$\xi_f : \pm 1$ for CP = $\pm 1$

PDF$_{BG} = f_{\tau} \frac{e^{-|\Delta t|/\tau_{BG}}}{2\tau_{BG}} + (1 - f_{\tau}) \delta(\Delta t)$

$q$ : tagged flavor

$W$ : wrong tag fraction

$\Delta m_B$, $\tau_B$ : from PDG

$\tau_{BG}$, $f_{\tau}$ : MC and side band data

$\sin 2\phi_1$ is the only free parameter in the fit
What we want to observe

\[ \Delta t \approx \Delta z/c\beta\gamma \]

Oct. 9, 2001  Nobu Katayama
Result of the fit: $\sin^2 \phi_1$

Maximizing $\log L$ sum, we obtained

$$\sin^2 \phi_1 = 0.99 \pm 0.14 \text{(stat)} \pm 0.06 \text{(sys)}$$

We observed CP violation in $B$ meson system

- Curves are from the result of unbinned fit
- $q_{\xi_f} +1$ and $-1$ are shown separately
\[ \Delta t \text{ dependent (binned) asymmetry} \]

\[ \propto \frac{\Gamma(B_d^0(\Delta t) \rightarrow f_{CP=\xi_f}) - \Gamma(B_d^0(\Delta t) \rightarrow f_{CP=-\xi_f})}{\Gamma(B_d^0(\Delta t) \rightarrow f_{CP=\xi_f}) + \Gamma(B_d^0(\Delta t) \rightarrow f_{CP=-\xi_f})} \]

\[ = -\xi_f \sin 2\phi_1 \times \sin \Delta m_B \Delta t \]

\[ \Delta t \text{ dependence as expected from the max. likelihood fit} \]

Result of global fit

\[ (\sin 2\phi_1 = 0.99) \]

Oct. 9, 2001

Nobu Katayama
CP=−1/CP=+1 fitted separately

\[ \sin^2 \phi_1 \]

\[ 0.84 \pm 0.17 \]

Statistical error

\[ \sin^2 \phi_1 \]

\[ 1.31 \pm 0.23 \]

Statistical error

Distribute oppositely
Agrees within errors
Control sample: non-CP modes

B^0 \rightarrow D(\ast)^{-}\pi^+, \ D^*-\rho^+, \ D^-/\nu, \ J/\psi K^*(K^+\pi^-)

\sim 17,000 \text{ events}

\Delta^+ (ps) \quad \text{No asymmetry observed}

\text{Statistical error only}

\langle \sin 2\phi_1 \rangle = 0.05 \pm 0.04
sin2φ₁ from various subsamples

- J/ψ Kₛ(GPM)
- Other CP=-1
- J/ψ Kₐ
- J/ψ K*₀

q=+1: 560 events
q=−1: 577 events

All (1137 events)

Statistical errors only
## Systematic errors

<table>
<thead>
<tr>
<th>Source of Error</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertexing algorithm</td>
<td>±0.04</td>
</tr>
<tr>
<td>Flavor tagging</td>
<td>±0.03</td>
</tr>
<tr>
<td>Resolution function</td>
<td>±0.02</td>
</tr>
<tr>
<td>$K_L$ background fraction</td>
<td>±0.02</td>
</tr>
<tr>
<td>Background shapes</td>
<td>±0.01</td>
</tr>
<tr>
<td>$\Delta m_d$ and $\tau_{B0}$ errors</td>
<td>±0.01</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>±0.06</td>
</tr>
</tbody>
</table>
Belle in the unitarity triangle

Unitarity triangle in PDG2001

Belle’s $1\sigma$ band

$\Delta M_{B_d}$

$|V_{cb}^* V_{cd}| \sim 0.0092$

Oct. 9, 2001

Nobu Katayama
Compare with other experiments

**BaBar** (32M BB) 0.59 ± 0.14 ± 0.05

**Belle** (31.3M BB) 0.99 ± 0.14 ± 0.06

**BaBar** (Osaka, 9/fb) 0.12 ± 0.37 ± 0.09

**Belle** (Osaka, 6.2/fb) 0.45 ± 0.43 ± 0.09

**CDF** (2000) 0.84 ± 0.82 ± 0.16

**ALEPH** (2000) 0.79 ± 0.41 -0.44

**Average**

0.79 ± 0.10

Oct. 9, 2001

Nobu Katayama
Prospects

Is Triangle triangle?

$V^*_{ub} V_{ud} + V^*_{cb} V_{cd} + V^*_{tb} V_{td} = 0$

$\phi_1 + \phi_2 + \phi_3 = \pi$

$B \rightarrow \pi/\nu$

$B \rightarrow D_{s\pi}$

$B^- \rightarrow D_{c p} K^-$

$B \rightarrow \pi\pi/K\pi$

$B \rightarrow 3$ body

$V^*_{ub} V_{ud}$

$V^*_{tc} V_{td}$

$V^*_{cb} V_{cd}$

$B^0 \rightarrow (cc)K^{(*)0}$

$B^0 \rightarrow D^{(*)-}/(K)$

$B^0 \rightarrow \eta' K_S, \phi K_S$

If $V^*_{ub} V_{ud} + V^*_{cb} V_{cd} + V^*_{tb} V_{td} \neq 0$

$\phi_1 + \phi_2 + \phi_3 \neq \pi$

$\phi_i(A) \neq \phi_i(B)$

New Physics!
Summary and conclusions

- KEKB accelerator has achieved $4.5 \times 10^{33}$ cm$^{-2}$s$^{-1}$
- Belle has analyzed $31 \times 10^6$ BB events and observed CP violation in the neutral B meson system
  - $\sin^2 \phi_1 = 0.99 \pm 0.14 \pm 0.06$ ($>6\sigma$ or $>99.999\%$!)
- KEKB/Belle plans to accumulate 300 fb$^{-1}$ in 5 years and 3,000 fb$^{-1}$ in 10 years and contribute to the physics of the flavor sector