

## KEK B FACTORY- AN EXPERIMENTAL STUDY FOR CP VIOLATION

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**Abstract:** Violation of matter-antimatter symmetry, the so-called CP violation, was only observed as a small effect in the decays of neutral K-meson in 1964. In the early of 1980s, it was pointed out that in the B meson decay the CP violation could be observed most significantly. In order to study the long-standing puzzle about the origin of the CP violation, the KEK B-factory has been constructed at High Energy Accelerator Research Organization (KEK) in Japan. Using the KEKB factory and the BELLE detector, an experimental study of the production and decay of B mesons is being carried out. In this paper the design, construction and expected experimental performance of the BELLE detector have been described.

**Keywords:** CP violation, B-Factory Detector, B-meson decay, KEKB .

### Introduction

Almost all the phenomena observed in high-energy experiments can explained by the Standard Model (SM) (Salam, 1968). However, for example, Higgs particle has not been understood yet perfectly. It is stated that the CP violation is one of the three necessary ingredients in explaining that the universe is made of matter, not antimatter (Sakharov, 1967 and Halzen and Martin, 1984). The first observation of the CP violation in the  $K^0$  meson was in 1964. In spite of many attempts, over the last three and a half decades, the CP violation has not been observed in any decay modes other the K decay. A large number of theoretical works have been done to understand the phenomenon. There are two competitive theoretical explanation of CP violation in the K meson system: the super-weak model (Wolfenstein, 1983) and Kobayashi-Maskawa model (Kobayashi and Maskawa, 1973). The Kobayashi-Maskawa model explains the source of the CP violation in terms of the complex phases in the quark mixing parameter. According to this model, the CP violation should occur not only in the K decay, but also in several different decay modes of the B system (Carter and Sanda, 1980 and Bigi and Sanda, 1981). The magnitudes of the effects are completely determined by the quark mixing parameters. As a result the CP violation in the B decay is expected to be three orders of magnitude larger than in the K decay. Since quark-mixing parameters determine every aspect of quark transitions, these provide constrained predictions about the CP violation effects in the B decay. Any deviations must be understood either in terms of higher order terms in the existing theory, which is yet unknown to us, or in terms of new Physics.

Each channel in the B decay has a small branching fraction. Also the decay multiplicity of it is much larger than K decay, making full reconstruction of the final state difficult. It is these difficulties that have been preventing high precision studies of the B decay in spite of its crucial importance.

In order to study the long standing puzzle about the origin of the CP violation, an  $e^+e^-$  asymmetric collider referred to as "KEKB" or "KEK B-factory" has been constructed which will produce about  $10^8$  B mesons per year at KEK (BELLE Collaboration, 1995). Using the KEK B-factory and the BELLE detector, an experimental study on the production and decay of B mesons is now being carried out. Similar studies will also be made by BABAR (BABAR Collaboration, 1995) and CLEO collaboration (Battle, 1993). In the following sections the design, construction and prospects of the BELLE detector have been described.

### KEK B-Factory

Detailed studies of the B physics require a large number of B mesons. The B-factory at KEK, referred to as "KEKB", is an experimental facility where a large number of B mesons will be produced through the  $\Upsilon(4S)$  resonance at the center of mass energy of 10.58 GeV. The  $\Upsilon(4S)$  is the first resonance above the B meson production threshold, decaying to a pair of  $B^+B^-$  or  $B^0\bar{B}^0$  in an approximately equal decay rate. The  $B\bar{B}$  production cross-section at the peak of  $\Upsilon(4S)$  is 1.15 nb. Detection of the decay products of  $B\bar{B}$  produced from  $\Upsilon(4S)$  will be performed with the BELLE detector.

### CKM Matrix and CP Violation in the Standard Model

There are three well-known discrete symmetries: parity (P), charge conjugation (C) and time reversal (T) symmetries. A process in which the sign of all the internal quantum numbers (such as charge, baryon number, lepton number and flavor) of a particle changes while leaving mass, energy, momentum and spin untouched is called "charge conjugation". The replacement of a process by its mirror reflected process is called the "parity". Charge conjugation and parity are known to be drastically violated by the weak interactions (Wu et al., 1957).

In contrast to this their product (CP), thought to be conserved until 1964, is violated very slightly ( $\sim 0.002$ ) in the decays of neutral kaons (Wu et al., 1957). Till now, no observation of this phenomenon has been observed in other systems. Therefore, it is necessary to make a confirmation whether CP violation phenomena also occur in other decays in the framework of Standard Model.

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Non-conservation of CP symmetry has been introduced in the SM in 1973 by Kobayashi-Maskawa (Kobayashi and Maskawa, 1973) requiring at least six quark flavors. In the early 1980s pointed out that sizeable CP asymmetries are expected in certain decay modes of B mesons. The Cabibbo-Kobayahi-Maskawa (CKM) matrix is symbolically written as

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

**Direct CP Violation**

The simplest manifestation of CP violation is the difference in the decay rate between  $B \rightarrow f$  and  $\bar{B} \rightarrow \bar{f}$ . In the standard model the origin of the CP violation is the fact that the CKM matrix is complex. Thus the interference between several decay amplitudes involving these complex elements may produce CP violating effects, which are referred to as direct CP violation. Let us illustrate this by assuming that two amplitudes  $A_1$  and  $A_2$  contribute to the decay  $B^+ \rightarrow f$ , where  $f$  is a particular final state. The conjugate process of this decay is  $B^- \rightarrow \bar{f}$ . The asymmetry between these processes is defined as

where  $\Gamma$  indicates the partial widths. Finally one may observe an asymmetry between the two processes given by (Khan, 1999)

$$A = \frac{\Gamma(B^+ \rightarrow f) - \Gamma(B^- \rightarrow \bar{f})}{\Gamma(B^+ \rightarrow f) + \Gamma(B^- \rightarrow \bar{f})}$$

where  $\psi$  and  $\alpha$  indicates the CKM phases and strong phases, respectively.

$$A = \frac{2|A_1||A_2|\sin(\psi_1 - \psi_2)\sin(\alpha_1 - \alpha_2)}{|A_1|^2 + |A_2|^2 + 2|A_1||A_2|\cos(\psi_1 - \psi_2)\cos(\alpha_1 - \alpha_2)}$$

**Indirect CP Violation**

Indirect CP violation occurs when  $B^0$  and  $\bar{B}^0$  decay into same final state, which is a CP eigenstate, through  $B^0 - \bar{B}^0$  mixing. The term mixing or oscillation represents the transitions of the type of  $B^0 \leftrightarrow \bar{B}^0$ . The time dependent asymmetry  $A_f$  is expressed as (Khan, 1999)

Where  $\phi_m$  is the mixing phase,  $(t-t')$  is the time difference between the state  $B^0$  and  $\bar{B}^0$ .

$$A_f = \frac{\Gamma(B^0 \rightarrow f) - \Gamma(\bar{B}^0 \rightarrow \bar{f})}{\Gamma(B^0 \rightarrow f) + \Gamma(\bar{B}^0 \rightarrow \bar{f})} = \sin 2\phi_m \sin\{\Delta m(t - t')\}$$

**KEK B-Factor Accelerator**

The primary goal of the KEK B-factory experiment is to detect the CP violating effects in B meson decays and to provide definitive information regarding the mechanism of CP violation (BELLE Collaboration, 1995). KEK B-factory is an asymmetric electron-positron collider of energies  $8.0 \times 3.5$  GeV, which aims to provide electron positron collision at a center of mass energy of 10.58 GeV which corresponds to the  $\Upsilon(4S)$  resonance. In this experiment the luminosity is one of the important parameter, which can affect significantly on the CP violation study in the B system. The typical branching ratio of the decay of B mesons into some final states is very low ( $10^{-4} \sim 10^{-5}$ ). Therefore, for the precise measurement of the CP violation about  $10^7 \sim 10^8$  B mesons will be required. In order to collect  $10^8$  B mesons the machine has to provide the luminosity of  $10^{34} \text{cm}^{-2}\text{s}^{-1}$ . The luminosity of an  $e^+e^-$  collider is expressed by the expression (Kurokawa, 1991)

$$L = 2.17 \times 10^{34} \cdot \xi(1+r) \left(\frac{IE}{\beta_y^*}\right)_{+/-} \dots \dots \dots (1)$$

where  $\xi$  is the beam-beam tune shift,  $r$  the ratio of the vertical to horizontal beam size at the collision point,  $I$  the circulating current in Ampere,  $E$  the beam energy in GeV, and  $\beta_y^*$ , the vertical beta function at the interaction point in cm. The subscript, + or -, means that both the current and the beam energy can be taken from either of the two rings. High luminosity requires high current beams which gives rise to couple bunch instability. In order to reduce this coupled bunch instability, a new type of a normal conducting RF cavity, AERS (Accelerator Resonantly coupled with Energy Storage), was developed for the KEK B-factory.

Fig.-1 shows the schematic layout of KEKB accelerator. The two rings, a high-energy ring (HER) for 8.0 GeV electrons and a low-energy ring (LER) for 3.5 GeV positrons, were built side by side which has a circumference of about 3 kilometers. Beams are injected from a linac and are collided at a finite angle of  $\pm 11$  mrad at the interaction point (IP) in the Tsukuba experimental hall at KEK where the BELLE detector is installed. The large

current, small  $\beta_y^*$  and the finite beam crossing angle are the salient features of KEK B-factory. A high beam current is required to achieve the desired luminosity. A brief description of the BELLE detector is given in the next sub-section.

**BELLE Detector**

Decay vertices of the B mesons are reconstructed by a silicon vertex detector (SVD). Charge particle tracking is provided by a central drift chamber (CDC) that is coaxial with the beam. Particle identification is provided by  $dE/dx$  measurements in the CDC, the aerogel Cherenkov counter (ACC) and the time of flight (TOF) counter arrays. The TOF and ACC are located radially out of the CDC. Electromagnetic showers are detected in a nine thousand array of CsI(Tl) crystals located inside the solenoid coil. Muons and  $K_L$  mesons are identified by arrays of detectors interspersed in the iron return yoke of the magnet. The brief description of the sub-detectors is given below.

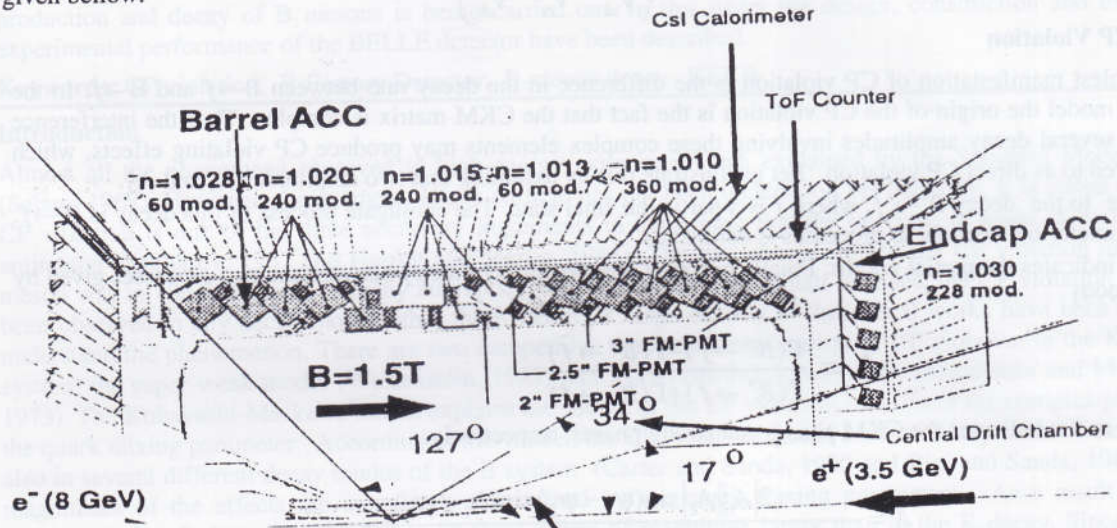


Fig. -1. Side view of the BELLE detector.

**Silicon Vertex Detector (SVD)**

The primary goal of the vertex detector in BELLE is the measurement of an asymmetry in the proper time distribution when one of the BB pair decays into a CP eigenstate. The proper time distribution is given by

$$\Delta t \cong \Delta_z / c\beta\gamma = (z' - z) / c\beta\gamma \dots\dots\dots(2)$$

where  $\beta\gamma$  is the Lorentz boost factor due to the asymmetric beam energies and  $\Delta_z$  is the distance between the decay vertices of the two B mesons along the beam direction. For the CP measurement  $\Delta_z$  should be measured with an accuracy better than  $1/2$  of average B lifetime  $\tau_B$ . The SVD is located between the Be beam pipe and the inner wall of CDC. The SVD covers a polar angle  $21^\circ$  and  $140^\circ$  in laboratory system. A rather good signal to noise (S/N) ratio of  $\geq 15$  is expected.

**Central Drift Chamber**

The efficient reconstruction of charged track and precise determination of their momenta are essential ingredients to all of the measurements planned for the B-factory experiment. The central drift chamber (CDC) provides charged particle tracking and  $dE/dx$  measurements over the  $17^\circ \leq \theta \leq 150^\circ$  angular region as well as fast charged-track information for the trigger. The CDC consists of 50 cylindrical layers of drift cells. In the CDC a gas mixture of 50% He-50%  $C_2H_6$  is used.

**Time of Flight and Aerogel Cherenkov Counter**

In addition to the  $dE/dx$  information from the CDC, the BELLE particle identification system comprises an array of TOF counters covering the flavor tagging momentum range,  $p \leq 1.2 GeV/c$ , augmented by an aerogel Cherenkov counter system (ACC) that extends the coverage upward to the kinematic limit of two-body B-decays such as  $B^0 \pi^+ \pi^-$ , i.e., to  $p=2.5-3.5 GeV/c$ , depending on the polar angle  $\theta$  of the emitted particles with respect to the beam axis. The barrel part of the ACC consists of 960 aerogel counters; 16-fold segmentation in  $z$  and 60-fold segmentation in  $\phi$ . Fig.-2 shows a single counter module of the barrel ACC. Five different indices of refraction,  $n=1.01, 1.013, 1.015, 1.020$  and  $1.028$  are used for the five different  $\theta$  regions. Each barrel counter is viewed by one or two fine-mesh photo-multipliers (FM-PMTs) through an air gap. The endcap counter is viewed with one FM-

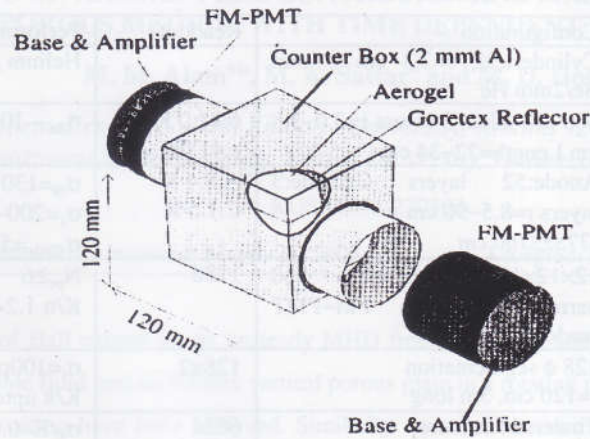


Fig. -2. A single counter module of the barrel ACC

PMT. Number of readout channel is 1560 in the barrel and 228 in the endcap. The detail construction and expected performance can be obtained from the references (Khan *et.al.*, 1998, Khan, 1999 and Suda, 1998).

The barrel TOF consists of 128 plastic scintillation counters forming a cylindrical structure located at a radius of 120 cm between the barrel ACC and the CsI calorimeter.

### Electromagnetic Calorimeter

Most of the physics goals of the B-factory experiments require the full reconstruction of decaying B mesons. Since approximately one third of the final state particle in the B meson decays are  $\pi^0$ s, it is essential to have high quality  $\gamma$ -ray detection. Good energy and angular resolutions are necessary for efficient detection of mass peaks with a good signal to noise ratio. The energy region of interest is from 20 MeV to 4 GeV.

The BELLE electromagnetic calorimeter (ECL) is based on the thallium-doped CsI scintillating crystals read out by the photodiodes. The crystal has a tower-like shape with a front face of  $5.5\text{cm} \times 5.5\text{cm}$  and length of 30 cm. The CsI calorimeter covers the polar angle region  $17^\circ \leq \theta \leq 150^\circ$ . A silicon PIN photodiode attached at the rear surface of the crystal reads out each CsI counter. The typical  $\gamma$  detection efficiency and the  $\pi^0$  reconstruction efficiency of the ECL are about 70 % and 40 %, respectively according to the GEANT simulation results.

### Solenoid Magnet

A superconducting solenoid magnet provides a magnetic field of 1.5 T in a cylindrical volume of 3.4 m diameter and 4.4 m in length. The coil is surrounded by a multilayer structure consisting of iron plates and calorimeter. A field analysis considering such a configuration shows the calculated stored energy is 34 MJ at 4400 A.

### $K_L$ and Muon Detector

The volume outside the superconducting solenoid is instrumented to identify  $K_L^0$  mesons and muons. It is intended to detect  $K_L^0$ s and muons above 600 MeV/c. The KL/MU detectors (KLM) consists of alternating layers of an absorber and a detector, with the absorber promoting hadronic interactions of  $K_L$  and penetrating  $\pi^+/K^\pm$ , and the detector sensing the passage of charged hadrons, muons and  $\delta$  rays. The KLM detector consists of a central barrel region and two endcap regions. As a detector element of KLM, glass of resistive plate counters (RPCs) is used. The iron plates are 47 mm thick, while the gaps are nominally 44 mm. The RPC gas is a mixture of argon, Butane and HFC-134a. The KLM's detection efficiency of  $K_L$  is a function of  $K_L$  momentum.

The expected performance of the BELLE detector is summarized in Table 1 below: The detail description of these sub-detectors, the BELLE data acquisition and the expected physics goals of the detector can be obtained from any of the references (BELLE Collaboration, 1995, Suda, 1998 and Khan, 1999).

### Conclusion

The study of CP violation and measurement of the KM matrix elements, including the complex phases, are very important for the development of a more fundamental understanding of nature. The BELLE detector at KEK in Japan will allow high energy physicists to understand the fundamental constituents of the universe as well the matter-antimatter asymmetry. Using the KEKB factory and the BELLE detector, an experimental study of the decay of B mesons is now being carried out. The analysis of the experimental data from BELLE will help us to understand the mechanism of CP violation as well as may produce new physics out of the Standard Model in the near future.

Table-1: Expected Performance Parameter of the BELLE Detector

Detector	Type	Configuration	Readout	Performance
Beam Pipe	Beryllium double-wall	Cylindrical, $r=2.3$ cm 0.5mm Be/2mm He		Helium gas cooled
SVD	Double Sided Si Strip	300 $\mu$ m thick, 3 layers $r=3.0-5.8$ cm Length=22-34 cm	$\phi$ :41.0 K z:41.0K	$\sigma_{\Delta z} \sim 105 \mu$ m
CDC	Small Cell Drift Chamber	Anode:52 layers Cathode:3 layers $r=8.5-90$ cm $-77 \leq z \leq 160$ cm	A:8.4 K C:1.5 K	$\sigma_{\phi}=130 \mu$ m $\sigma_z=200-400 \mu$ m $\sigma_{dE/dx}=5\%$
ACC	n:1.01-1.03 Silica Aerogel	12x12x12 $\text{cm}^3$ blocks 960 barrel/228 endcap FM-PMT readout	1788	$N_{pe} \geq 6$ $K/\pi$ 1.2 < p < 3.5 GeV/c
TOF	Scintillator	128 $\phi$ segmentation $r=120$ cm, 3m long	128x2	$\sigma_t=100$ ps $K/\pi$ upto 1.2 GeV/c
ECL	CsI	Towered structure $\sim 5.4 \times 5.5 \times 30 \text{ cm}^3$ crystals Barrel: $r=125-162$ cm Endcap: $z=-102$ and $+196$ cm	6624 1152(f) 960(b)	$\sigma_E/E=0.67\%/\sqrt{E} \pm 1.8\%$ $\sigma_{\text{pos}}=0.5 \text{ cm}/\sqrt{E}$ E in GeV
MAGNET	Super conducting	Inn.rad.=170 cm		B=1.5 T
KLM	Resistive Plate	14 layers (5cm Fe+4cm gap) two RPCs in each gap $\theta$ and $\phi$ strips	$\theta$ :16 K $\phi$ :16 K	$\Delta\phi=\Delta\theta=30$ mr for $K_L$ $\sigma_t=1$ ns 1% hadron fake

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