CP Violation and the Future of Flavor Physics

Christian Kiesling

Max-Planck-Institute for Physics, Munich, Germany

Abstract. With the nearing completion of the first-generation experiments at asymmetric $e^+e^-$ colliders running at the $\Upsilon(4S)$ resonance (“B-Factories”) a new era of high luminosity machines is at the horizon. We report here on the plans at KEK in Japan to upgrade the KEKB machine (“SuperKEKB”) with the goal of achieving an instantaneous luminosity exceeding $8 \times 10^{35} \text{cm}^{-2} \text{s}^{-1}$, which is almost two orders of magnitude higher than KEKB. Together with the machine, the Belle detector will be upgraded as well (“Belle-II”), with significant improvements to increase its background tolerance as well as improving its physics performance. The new generation of experiments is scheduled to take first data in the year 2013.

Keywords: CP violation, high luminosity B-Factories, SuperKEKB, Belle-II

PACS: 12.15.Hh, 13.20.He, 13.25.Gv, 13.35.Dx, 14.40.Nd

INTRODUCTION

The Belle Collaboration, together with BaBar, has made essential contributions to establish the theory of Kobayashi and Maskawa, who explain all known CP violation phenomena within the framework of the Standard Model (SM) by a single irreducible phase appearing in the quark mixing matrix. For their outstanding achievement Kobayashi and Maskawa were awarded the Nobel Prize of 2008. Although the SM has been extremely successful in describing virtually all data, most importantly the CP violation phenomena of the $K$- and the $B$-systems (for a comprehensive overview see, e.g. [1]), there are a number of arguments why the SM cannot be the regarded as a complete theory. In fact, there is clear evidence for physics beyond the SM, as suggested by the non-vanishing mass of the neutrinos, the matter-antimatter asymmetry observed in the universe, and the apparent necessity for dark matter. Most likely, the effects mentioned have to do with CP violation of a yet undiscovered source. The “New Physics” (NP) generating these sources is expected to appear at large, so far unreached (multi-TeV) energy scales. While the discovery and exploration of New Physics is the central motivation for the LHC program, flavor physics is expected to play a key role in unraveling possible NP at this scale and to solve the puzzle of CP violation.

Colliding $e^+$ and $e^-$ beams with different (“asymmetric”) energies to produce the $\Upsilon(4S)$ resonance, with just enough energy for the creation of a pair of $B$-mesons (or background with other quark flavors), is an alternative approach to the high-energy frontier experiments at the LHC. With high luminosity, and consequently large statistics, as achieved in the next generation of flavor factories (“Super Flavor Factory”, SFF) [2, 3], very large energy scales can be reached, when quantum loop corrections to the SM are considered (see fig. 1). Depending on the flavor changing couplings of the NP particle spectrum, the sensitivity to large mass scales in a SFF may be from many hundred GeV up to tens of TeV. In this respect a SFF is truely complementary to the
FIGURE 1. Example of a SM process at the quantum loop level (“penguin diagram”, left) with “New Physics” contributing (right) to $B$-meson decay amplitudes.

LHC. A recent review of the physics potential of a future high luminosity B factory can be found, e.g., in [4]. One should note here that the discovery potential of a future SFF is indeed extraordinary and might reach even beyond the LHC.

There are several distinct approaches to look for NP at SFF’s: Many of them concentrate on the precise measurement of the angles and sides of the unitarity triangle for $B$-meson couplings, derived from the Cabibbo-Kobayashi-Maskawa (CKM) matrix which connects the mass eigenstates to the flavor eigenstates of the down-type quarks. Within the SM the CKM matrix is unitary and their elements describe the coupling strengths of the flavor changing currents at the quark level, such as $b \rightarrow c$ or $b \rightarrow u$. The unitarity of the CKM matrix gives rise to a total of six so-called unitarity triangles, one of them involving the $b$-quark couplings (“$B$-triangle”). All triangles have the same area, but the $B$-triangle has all three sides of the same order, corresponding to large angles and thus giving rise to large CP violating effects. Within the SM the $B$-triangle is highly over-constrained (5 observables for only 2 independent quantities), so a precise measurement of all the three angles and the two sides is a crucial check of the validity of the SM: If the $B$-triangle “does not close”, New Physics must be the reason. One should mention that all present measurements of the CKM unitarity are in agreement with the SM, although a few “tensions” have become noticeable (for details see, e.g. [5]).

Another way of gaining sensitivity at the SFF to NP is the study of rare decays of $B$ mesons and $\tau$ leptons. Some examples should illustrate this point, such as $B \rightarrow X_d \nu \bar{\nu}$ or $\tau \rightarrow \mu \gamma$. These decays involve (several) neutral particles in the final state and can therefore only be measured at SFF’s. Such decays are highly suppressed (in the $B$ case) or even completely forbidden (the $\tau$ case). With a SFF, branching fractions down to several $10^{-9}$ can be probed. More details on rare decays and their potential to search for New Physics can be found in the proposals for the SFFs [2,3].

One of the flagship measurements at the SFF is the precise determination of the time-dependent CP violating asymmetries. These asymmetries are measured by observing the decay rate $\Gamma$, as function of time, of a $B^0$ meson decaying into a specific CP eigenstate $f_{CP}$, as compared to the same final state coming from the $\bar{B}^0$. The CP violating time-dependent asymmetry is defined as:

$$A(f_{CP}, \Delta t) = \frac{\Gamma(\bar{B}^0 \rightarrow f_{CP}; \Delta t) - \Gamma(B^0 \rightarrow f_{CP}; \Delta t)}{\Gamma(B^0 \rightarrow f_{CP}; \Delta t) + \Gamma(\bar{B}^0 \rightarrow f_{CP}; \Delta t)},$$

where $\Delta t$ is the time difference between the two decay events.
where $\Gamma$ is the decay rate of the $B^0(\bar{B}^0)$ into the CP eigenstate $f_{CP}$ (“CP side”) within some time interval $\Delta t$, to be explained below. In order to determine which of the two flavors ($B^0$ or $\bar{B}^0$) has decayed into the common final state $f_{CP}$, the other $B$-decay (“tag side”) is analyzed for a specific flavor, using, e.g., semi-leptonic decays ($B^0 \to Xl^-\bar{\nu}, \bar{B}^0 \to Xl^+\nu$). The charge of the lepton uniquely identifies (“tags”) the flavor of the $B$ meson, where a positive (negative) lepton signals a $\bar{B}^0$ ($B^0$). Since the two $B$ mesons are produced in an entangled state by virtue of the quantum numbers of the $\Upsilon(4S)$, the tag side uniquely determines the flavor of the $B$-meson that decayed into the CP eigenstate. The time difference $\Delta t$ is given by the difference in decay times between the tag side and the CP side. Note that $\Delta t$ can be positive or negative.

Depending on the CP eigenstate chosen, any of the three angles $\phi_1 (\beta), \phi_2 (\alpha)$ or $\phi_3 (\gamma)$ of the $B$-triangle can be measured. Chosing, e.g., the final state $J/\psi K^0$, the angle $\phi_1$ (or $\beta$) is determined. A recent measurement of the time-dependent CP asymmetry for the $J/\psi K^0$ channel is shown in fig. 2. Here, the asymmetry is given for both odd ($J/\psi K_S$) and even ($J/\psi K_L$) CP final states. Since the $\Delta t$ distributions for the CP eigenstates are different, CP violation is established. Recent summaries on the measurements of the angles $\phi_1, \phi_2, \phi_3$ ($\alpha, \beta, \gamma$) have been presented at this conference.

**MACHINE UPGRADE: SUPERKEKB**

While no significant deviations from the SM predictions have been observed so far, there are some tantalizing hints for possible New Physics in $B$ decays (see, e.g., [9]). Clarification can only come with a new generation of SFF’s, which should aim at

---

1 strictly speaking, the quantum entanglement is broken when the first of the $B$-mesons decays. From then on the other $B$-meson is freely oscillating between $B^0$ and $\bar{B}^0$, but with a known time dependence.
integrated luminosities in excess of 50 /ab (the present world record KEKB accelerator is about to accumulate 1 /ab). Such large integrated luminosities require an equally large increase of the instantaneous luminosity $\mathcal{L}$ which, in its simplified form, is given by

$$\mathcal{L} = \frac{N_1 N_2 f}{4\pi \sigma_x \sigma_y}.$$ 

Here, $N_i$ are the numbers of particles in each of the two colliding bunches, $f$ is the bunch collision frequency, and $\sigma_{x,y}$ are the transverse dimensions of the colliding bunches.

At KEK, an extremely strong accelerator research program is focusing on an asymmetric $e^+ e^-$ collider with instantaneous luminosities in excess of $8 \times 10^{35}$ cm$^{-2}$ s$^{-1}$ (which is about 40 times the present world record luminosity of $2.11 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, reached in May 2009 with KEKB). The new machine, called “SuperKEKB”, is an upgrade of the present KEKB machine and should start producing luminosity by the year 2013. According to the current plan the KEKB accelerator should stop running by the end of 2009, so that the construction work for SuperKEKB can start in 2010. The expected luminosity development of the SuperKEKB machine is shown in Fig. 3.

Two options for the SuperKEKB machine have been discussed: The “high-current” (HC) option and the “nano-beam” (NB) option (see Table 1). Initially, the HC option was favored. It was characterized by a mild decrease of the beta function in the low energy ring (LER), and a dramatic increase of the beam current in the LER and the high energy ring (HER). In addition, an ingenious scheme was developed to counteract the luminosity loss due to the finite angle under which the two colliding bunches cross each other, i.e., the crab crossing scheme. In this scheme special crab cavities before and after the interaction region rotate the bunches, so that they collide head-on, instead of at an angle. The crab crossing scheme was verified with the running KEKB accelerator, increasing the instantaneous luminosity by about 20 percent to a new world record.
TABLE 1. Comparison of parameters for the two high luminosity options of the SuperKEKB machine, compared to the presently running KEKB factory. The high current option for SuperKEKB has been discarded recently (see text) and the nano-beam option is now the baseline.

|                         | KEKB Design | KEKB achieved (): with crab | SuperKEKB High-Current Option | SuperKEKB Nano-Beam Option |
|-------------------------|-------------|-----------------------------|-------------------------------|-----------------------------|
| $\beta_y^*$ (mm) (LER/HER) | 10 / 10     | 6.5/5.9 (5.9/5.9)          | 3 / 6                         | 0.26 / 0.26                 |
| $\varepsilon_x$ (nm)    | 18 / 18     | 18 / 24                     | 24 / 18                       | 2.8 / 2.0                   |
| $\sigma_x$ (\(\mu\)m) | 1.9         | 1.9 (0.94)                  | 0.85 / 0.73                   | 0.073 / 0.097               |
| $\xi_y$                 | 0.052       | 0.108/0.057 (0.129/0.090)   | 0.3 / 0.51                    | 0.079 / 0.079               |
| $\sigma_y$ (\(\mu\)m) | 4           | 7                           | 5 (LER) / 3 (HER)             | 5                           |
| $I_{\text{beam}}$ (A)   | 2.6/1.1     | 1.66/1.34 (1.64/1.19)       | 9.1 / 4.1                     | 3.84 / 2.21                 |
| $N_{\text{bunches}}$    | 5000        | 1388 (1585)                 | 5000                          | 2252                        |
| Luminosity ($10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$) | 1           | 1.76 (2.11)                 | 53                            | 80                          |

However, it became apparent that a new effect would make the HC option difficult: For the crab crossing to work efficiently the bunch length must be smaller than the $\beta$ function at the interaction point (IP), i.e. $\sigma_z < \beta_y^*$. This condition, imposed to avoid the so-called hour-glass effect, creates no problems at low beam currents. However, at the large beam currents of the HC option (see Table 1) coherent synchrotron radiation becomes an issue which has the effect of lengthening the bunch, thus running into the hour-glass effect. The unavoidable bunch lengthening leads to a decrease of the obtainable maximum luminosity to slightly over $50 \times 10^{34}$. Failing the goal of $\mathcal{L} \geq 80 \times 10^{34}$, this option is disfavored now.

Following the ideas of the final focus system envisaged for a future linear collider, transferred to a circular machine as laid down in [3], the NB option has become the baseline [10]. Here, the key parameters are a factor of two increase in the beam currents with respect to the present KEKB, but strongly reduced $\beta$ functions at IP (factor of about 20 smaller than in the HC option). In addition, low emittance beams are necessary to achieve the desired small (less than 100 nano meters) transverse bunch sizes. Such a beam size has been achieved at the ATF damping ring facility at KEK. While a low emittance electron beam can be prepared by virtue of a carefully designed injection system, the transverse phase-space of the positrons needs to be cooled in a special new damping ring.

Table II gives an overview of the machine parameters for the presently running KEKB accelerator, and for both the HC and NB options (status of July 2009). Note that the presently achieved luminosity of KEKB is a factor of two larger than the original design value. Part of it is due to the new crab crossing scheme, which is being successfully tested with the running machine. It should be noted, however, that the luminosity increase predicted in simulation for the crab crossing scheme has not yet been reached in
the real machine. The discrepancy is attributed to so-called “machine errors” which may result from a finite precision in aligning the focusing quadrupoles along the ring. Small (unknown) deviations from the ideal position can lead to a coupling of the horizontal and vertical betatron oscillations and therefore to an increase in the vertical beam size at the IP, reducing the luminosity. During the last winter shutdown some errors of this kind have been diagnosed and corrected for by installing a set of so-called “skew sextupoles” around the ring. As a consequence, the luminosity could be immediately increased by more than 15 percent, leading to new world records for the instantaneous luminosity (see table 1).

Preliminary parameters of both collision schemes for the SuperKEKB machine are given in the table [10]. Intense optimization studies for the new machine are going on, concentrating now mainly on the NB option. One should note, however, that the parameters given in the table have not yet been consolidated. In addition, the so-called crab waist scheme, as proposed in [3], has not yet been included in the present design. While the crab waist scheme is expected to improve the instantaneous luminosity only by a few percent, it is very effective in reducing the coupling between vertical and horizontal betatron oscillations and is therefore quite useful to stabilize the machine operation.

Some of the virtues of the NB option are quite evident: There is no need to have short bunches (the condition $\sigma_z < \beta_y^*$ vital for the HC option to avoid the hour glass effect does not apply here), and the beam-beam parameter $\xi_y$ can be relaxed substantially (it should be noted that the large $\xi_y$ parameter required for the HC option has never been reached so far). Also the synchrotron radiation is less of an issue due to the smaller beam currents. This is certainly good news for the detectors close to the beampipe (e.g. the silicon detectors). On the other hand, a new source of background may arise from the Touschek effect [11], a kind of intra-beam Coulomb scattering, which couples betatron and synchrotron oscillations. Due to this effect particles may be sent to off-momentum orbits, causing particle loss and a severe decrease of the beam lifetime. To counteract the shorter lifetimes (order of a few minutes) an elaborate scheme is envisaged for SuperKEKB which keeps the bunch currents almost constant by permanent re-injection at a rate of about 50 Hertz. With the NB option another important physics parameter may be chosen more favorably, i.e. the radius of the beampipe, which may be as small as roughly 1 cm, whereas in the HC option 1.5 cm had to be chosen. It is expected that the final design for the SuperKEKB machine in its nano-beam version will be completed in the fall of 2009.

**DETECTOR UPGRADE: BELLE-II**

Parallel to the machine studies, a Letter of Intent [6] for the Belle upgrade was issued in the year 2004, with a recent update from 2008 [12]. The main (re)design goals are to cope with the much higher physics rates and the much larger backgrounds to be expected, as well as improving the overall physics performance.

A comparison of Belle and its upgraded version (“Belle-II”) is shown in a sideview in fig. 4. We will first give a short overview of the different detector components and then pick out two specific systems which will be very important for the precise measurement
of the CP quantities. As a general side condition, the performance of the new Belle-II detector should be as good or better than Belle. This is a non-trivial requirement in view of the anticipated very high background at the SuperKEKB machine, which is estimated to be roughly an order of magnitude larger as compared to the present KEKB machine (for details, see [12]).

The tracking system in the “old” Belle detector consisted of 4 layer of Si strip vertex detectors (SVD), followed by a Central Drift Chamber (CDC). Due to the largely increased background, strip detectors are no longer an option for the innermost Si layers. Instead a two-layer pixel detector (PXD) for the innermost Si layers is planned (see below). The SVD will be replaced entirely as well as the CDC: due to the harsh backgrounds the inner radius of the CDC has to be moved out and the two outer layers of the new SVD will cover the gap. The momentum resolution of charged particles will be improved by extending the CDC to a larger radius. Since the magnet and the barrel part of the electromagnetic calorimeter (ECL) will not be changed, the particle identification system has to be replaced by a thinner, low material budget detector (see below). In the endcap parts of the ECL the present CsI(Tl) crystals will be replaced by pure CsI that provide faster signals, and the forward part of the KLM ($K_L$ and muon detector) in the iron flux return yoke will be instrumented by scintillator strips with SiPM readout, replacing the present RPCs.

To extend the physics reach for Belle-II, the $K/\pi$ separation ability will be improved
by a new particle identification (PID) system. Two types of detectors are being proposed, one is a time-of-propagation (TOP) counter for the barrel region (Barrel PID), and the other a proximity-focussing Cherenkov ring imaging counter with aerogel radiators (ARICH) for the endcap region (Endcap PID). The present time-of-flight and aerogel Cherenkov counters in the barrel region of Belle are replaced by a TOP counter made from quartz radiator bars (thickness 2 cm), in which the time of propagation of Cherenkov photons is measured, which are internally reflected and focussed onto micro-channel plate (MCP) PMTs at the end surfaces of the quartz bars. The MCP-PMTs have an excellent time resolution of about 50 ps, so that the difference in arrival times of the Cherenkov photons, radiated by pions or kaons, can be determined. This time difference results from the different Cherenkov emission angles (for equal particle momenta) and consequently different path lengths for the photons which undergo multiple internal reflections on their way to the ends of the quartz bars.

The ARICH counters are located in front of the endcap ECL, where the space is quite limited. For this reason a proximity focussing scheme is envisaged for the Cherenkov photons, with an expansion thickness of only 20 cm. In the present design three layers of silica aerogel, each 10 mm thick, are foreseen, with refractive indices varying between 1.045 and 1.055, so that the photons emitted from the three regions produce overlapping images on the photon detector surface. Since the photon detectors have to work in a strong magnetic field of 1.5 Tesla, candidates are a hybrid avalanche photon detector (HAPD) or a MCP-PMT.

An example of the expected performance of the new PID system relative to the present Belle ACC system is shown in fig. 5. Here, the decay $B^0 \rightarrow \rho^0 \gamma$ is studied at the $\Upsilon(4S)$ resonance and the distribution of the quantity $\Delta E = E_{\text{beam}} - E_{B^0}$ is chosen for reference, where $E_{\text{beam}}$ is the beam energy in the $\Upsilon(4S)$ center-of-mass system and $E_{B^0}$ is the energy of the $B$ meson, reconstructed from the two pions forming the $\rho$ and the photon. An overwhelming background from $B \rightarrow K^* \gamma$ is expected due to the CKM couplings (about a factor 40). While for the case of Belle (left side) the background from misidentified kaons is very large, the improved PID in Belle-II (right) largely reduces the background and shows a much clearer signal.
A second example for the improved instrumentation at Belle-II is the new two-layer Si pixel detector, located closest to the beampipe, for precise vertexing. As mentioned above, the expected strong increase of background relative to the present KEKB machine, proportional to $1/r^2$ where $r$ is the radial distance from the interaction region, creates large occupancies within the strip detectors, making an efficient reconstruction of tracks and vertices impossible. The solution is to use a pixel detector which intrinsically provides three-dimensional space points. However, pixel segmentation is not the only requirement to be fulfilled at Belle-II. Due to the small (transverse) momenta of the $B$ decay products, the momentum and vertex resolutions are dominated by multiple scattering, so a pixel sensor should have a very low material budget. Furthermore, the harsh radiation environment at the SuperKEKB factory requires low-noise and radiation-hard technology, and the limited space between the beampipe and the strip detector requires a low power consumer. Finally, a pixel detector should be operational from the start of the Belle-II running, which is envisaged for the year 2013.

It turns out that there is only one mature technology at present fulfilling all these requirements: The DEPFET pixel sensor [13], invented and developed at the Max-Planck-Institute for Physics (MPI) in Munich, Germany. The name DEPFET stands for DEPleted Field Effect Transistor and combines detection and amplification. The DEPFET principle of operation is shown in fig. 6. A MOS field effect transistor is integrated onto a fully depleted silicon substrate forming the detector. By means of an additional $n$-implant underneath the transistor channel a potential minimum for electrons is created. This potential well can be considered as an internal gate of the transistor. A particle entering the detector creates electron-hole pairs in the fully depleted silicon substrate. The electrons ("signal") are collected and stored in the internal gate. The electron charges change the potential of the internal gate, resulting in a modulation of the transistor channel current. After readout of the channel current, the signal electrons are removed by a positive voltage at the clear contact. Another read cycle then establishes the baseline which is subtracted from the current readout before the clear. The whole readout cycle (read-clear-read) takes about 80 ns. Because of the small capacitance of the internal gate, the noise in the DEPFET is very low, about 100-200 electrons are expected when operating at Belle-II.

For a real detector a matrix of DEPFET pixels must be constructed. Such matrices, using the SOI technique, where the sensor wafer is bonded to a “handling” wafer, have
already been built and subjected to extensive beam tests. Matrices up to 512 × 512 pixels have been obtained, with pixel sizes of about 17 × 13 μm². For the DEPFET pixel detector (“PXD”) at Belle-II typical pixel sizes would be around 50 × 50 μm². An additional asset of the DEPFET technology is the fact that the detector can be thinned down to about 50 μm thickness. The thinning procedure of the handling wafer has already been demonstrated at the MPI semiconductor laboratory. With such a thin sensor still a signal to noise ratio of about 40:1 can be reached. Finally, the radiation hardness of the DEPFET matrix has been tested and found to be satisfactory for a few years of running at SuperKEKB with full luminosity. Further details of the DEPFET project at Belle-II can be found elsewhere [14].

CONCLUSIONS

Complementary to the LHC, a new generation of Super Flavor Factories is being planned, probing the Standard Model at energy scales beyond tens of TeV. Flavor physics continues to be the key to the puzzle of the observed matter-antimatter asymmetry in the universe, intimately connected to CP violation. The SuperKEKB project, together with a substantially upgraded detector, Belle-II, will contribute to this fascinating chapter of particle physics, taking first data in the year 2013, with the prospect of accumulating 50 times the presently available data by the year 2020.

ACKNOWLEDGMENTS

The author would like to acknowledge the extremely stimulating and pleasant atmosphere created by the organizers, especially Marvin Marshak, of the CIPANP 2009 Conference. He also wishes to thank Tom Browder, Yoshihiro Funakoshi, Katsunobu Oide, and Yoshi Sakai for their careful reading of the manuscript and their valuable advice.

REFERENCES

1. see, e.g., A. J. Buras, Flavour Physics and CP Violation, TUM-HEP-590/05.
2. S. Hashimoto et al., LoI for KEK Super B Factory, Part I: Machine, KEK-Report 2004-4, 2004.
3. M. Bona et al., SuperB, a High-Luminosity Heavy Flavor Factory, INFN/AE-07/2, 2007.
4. T. E. Browder et al., hep-ph/0802.3201.
5. CMK Fitter Group, J. Charles et al., http://ckmfitter.in2p3.fr
6. K. Abe et al., LoI for a KEK Super B Factory, Part II: Detector, KEK-Report 2004-4 (2004).
7. Belle Collaboration, K. Chen et al., PRL 98 (2007) 031802.
8. see, e.g., J. Hirschauer (φ₁(β)), A. Bevan (φ₂(α)), T. Aushev (φ₁(γ)), these proceedings.
9. see, e.g., T. E. Browder, in “Hints for New Physics in Flavor Decays”, KEK, March 20-21, 2009.
10. K. Oide, et al., “Few Issues on the Upgrade of KEKB B-Factory”, talk at PAC09, MO3RAI01, May 4-8, 2009, Vancouver, BC, Canada (2009); K. Oide & Y. Funakoshi, private communication.
11. C. Bernardini et al., Phys. Rev. Lett. 10 (1963) 407.
12. I. Adachi et al., sBelle Design Study Report, KEK Report 2008-7 (2008).
13. J. Kemmer, G. Lutz et al., NIM A253 (1987) 356; NIM A288 (1990) 92.
14. see the webpage of the DEPFET Collaboration: http://www.depfet.org