The Physics of the SuperKEKB/Belle II Super Flavor Factory

Research in flavor physics is an essential component of the future US program in particle physics. Here we discuss US participation in Belle II, a Super B flavor factory experiment based in Tsukuba, Japan at the upgraded KEKB accelerator. The design luminosity of SuperKEKB is $8 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, approximately forty times higher than what has been achieved at the KEKB accelerator[1]. This will allow a data sample with an integrated luminosity of 50 ab^{-1} to be accumulated by 2021. This can be compared to the 1 ab^{-1} data sample obtained over a decade of Belle[2] running with KEKB.

Belle together with BaBar established the existence of large CP violation (i.e. matter-antimatter asymmetry) in the b quark system in agreement with the prediction of Kobayashi and Maskawa (KM)[3]. In contrast to the kaon system (strange quarks), the observed CP violation effects for b quarks are of order one rather than 10^{-3}. This critical experimental contribution of the B factories was explicitly recognized in the citation of the 2008 Physics Nobel Prize awarded to Kobayashi and Maskawa[4].

The B factory results show most of standard model CP violation can be explained by the single irreducible complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) weak interaction coupling matrix. Nevertheless, the possibility of contributions from new physics that are O(10%) of the size of the standard model contribution are not ruled out. Moreover, the matter-antimatter asymmetry of the universe[3],[5] cannot be explained by the KM phase alone. The standard model KM explanation of the baryon asymmetry of the universe falls short by ten orders of magnitude. This demonstrates that there must be new sources of CP violation and new heavy particles, which remain to be discovered.

The Belle II experiment is part of a broad-based search for new physics. The LHC, which is now operating with high luminosity at a center of mass energy of 7 TeV, is designed to search for new physics at the *energy* frontier, i.e., its high center-of-mass energy may allow it to produce heavy, as-yet-undiscovered particles such as Higgs bosons and supersymmetric partners of quarks and leptons or new particles linked to extra dimensions. The SuperKEKB/Belle II facility searches for new physics using very high *luminosity*, i.e., by precisely measuring and comparing with theory branching fractions, angular distributions, CP asymmetries, forward-backward asymmetries, and a host of other observables that are difficult or unfeasible to measure at the LHC. Deviations of experimental results from the SM predictions can then be interpreted in terms of NP.

At the LHC and in the future at the ILC, the particles that are responsible for the electroweak force in the Standard Model will be studied. These include the W, Z^0 and perhaps soon the Higgs boson. In the upcoming round of neutrino and muon experiments properties of leptons will be explored; there will be improved measurements of neutrino mixing angles and a determination of whether future neutrino CP violation experiments are feasible. However, only Super Flavor Factories and LHCb will explore the new physics possibilities of the flavor and heavy quark sector.

In the past, measurements of processes involving internal loops have given access to high mass scales before accelerators were available to directly probe these scales. For example, the suppression of $K_L \to \mu^+\mu^-$ decays allowed theorists to infer the existence of the charm quark; the charm quark mass was subsequently estimated from the observed rate of K^0-$\overline{K}^0$

oscillations. The unexpected observation of CP violation in K^0 meson decays was used to predict the existence of a third generation of quarks. The unexpected discovery of large B^0-$\overline{B}^0$ oscillations indicated that the top quark was very heavy, contrary to the theoretical prejudice at the time (and contrary to where experiments were looking). These processes, as well as the violation of charge-parity (CP) symmetry, are quantum mechanical phenomena sensitive to very high energy scales, which have revolutionized how we think about extensions of the Standard Model. To continue this paradigm-shifting pursuit of flavor physics, about two orders of magnitude more data is now needed. Such a data set would tell us whether the CP violation effects observed in B decays are consistent with the Standard Model. Searching for flavor-changing neutral-currents (FCNC) with such a data set would probe mass scales of 1-100 TeV, which is mostly beyond the reach of direct searches at the LHC. If supersymmetry is discovered during LHC operation at either 7 or 14 TeV, a Super B Factory could help determine how the supersymmetry was broken [9]. This feature of a Super B factory sensitivity is illustrated in Fig. 1.

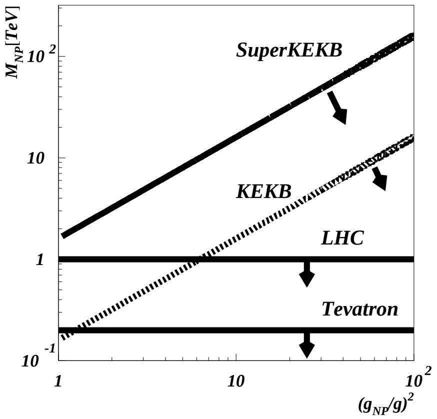

Figure 1: *New Physics (NP) Reach in terms of NP particle mass and in terms of NP coupling strength[8] at the energy and intensity frontiers.*

To be more concrete, we list below several big questions that can only be addressed by further studying loop processes and rare decays at a Super B factory.

Are there new CP violating phases?

This will require new much more precise measurements of time-dependent CP violation in $b \to s$ modes such as $B \to \phi K^0$, $B \to \eta' K^0$ and $B \to f_0 K_S$ with a data sample of order 50 ab^{-1}. The expected accuracies of these measurements are given in Table I. If there is new physics in $b \to d$ transitions, precise measurements of Cabibbo-Kobayashi-Maskawa (CKM) parameters in mixing and in tree processes will be required. For example, the measurement of $B_d \to J/\psi K_S$ should be consistent with measurements of V_{ub}/V_{cb} and other constraints.

New measurements of B_s properties and perhaps CP-violating asymmetries in B_s decays might be possible with long runs at the $\Upsilon(5S)$. The feasibility of B_s studies at the $\Upsilon(5S)$

has been demonstrated recently by Belle [10], which has recorded a 121 fb^{-1} data sample. These can explore B_s decays with neutral particles or neutrinos in contrast to hadronic experiments. Some examples of expected accuracies at Belle II are given in Table I.

Are there new operators with quarks enhanced by new physics?

Experimentally, it is important to measure forward-backward asymmetries $A_{FB}(q^2)$ as a function of the q^2 of the dilepton in $b \to sl^+l^-$ decays. Although there are now rough measurements of $A_{FB}(q^2)$ using data samples at the B factories as well as from LHCb and CDF, the zero-crossing point of $A_{FB}(q^2)$ is sensitive to new physics and is an observable that will be accessible at a Super B factory. In particular, measurement of inclusive processes such as $b \to s\ell^+\ell^-$ and the inclusive forward-backward asymmetry are possible only at a Super B factory. Another example of this approach to new physics is measuring the rates and asymmetries in the full complement of neutral and charged $B \to K\pi$ decays to a precision that can determine whether or not there are enhanced electroweak penguins [11]. The sensitivity is shown in Fig. 2. Note that measurements of the CP asymmetry in $B \to K_S^0\pi^0$ are especially critical here.

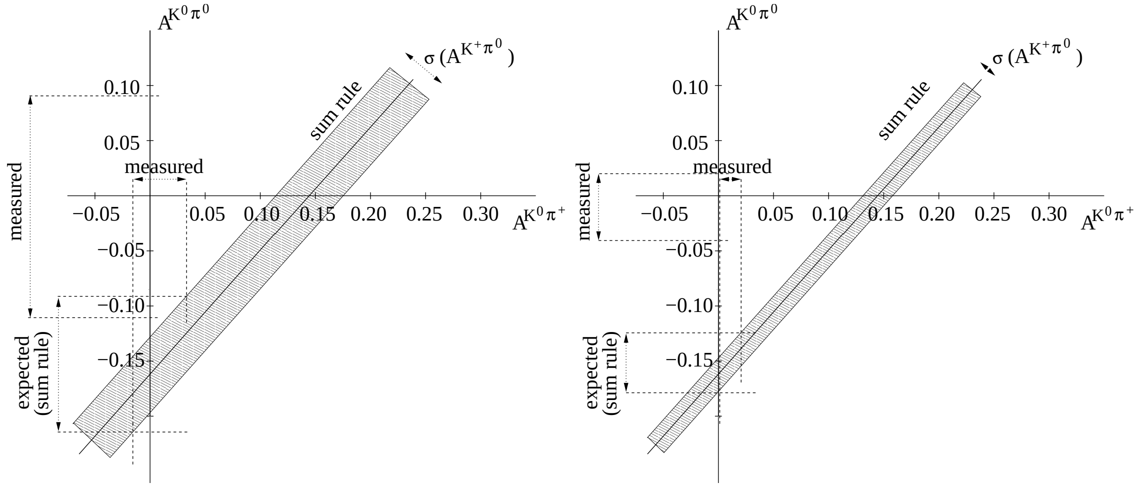

Figure 2: *Sensitivity of tests for new physics electroweak penguins using the isospin sum rule and measurements of CP asymmetries in $B \to K\pi$ modes (with current world averages (left) and at 50 ab^{-1} (right)). Note that neutral detection is required for $A_{CP}(B \to K^0\pi^0)$.*

Are there right-handed currents from new physics?

The experimental approach involves measurement of time-dependent CP violation in $B \to K^{*0}\gamma$ ($b \to s\gamma$) or related modes such as $B \to K_S\rho^0\gamma$ or $B \to K_S\phi\gamma$. Note that $B \to K^{*0}\gamma$ involves the reconstruction of the final state $B \to K_S\pi^0\gamma$ and precision vertexing of the pions from the K_S decay. Table I shows that the expected precision of Belle II suffices to explore the CP violation from NP in $B \to K_S\pi^0\gamma$ down to the level at which SM corrections are expected. Another interesting approach involves triple-product CP violation asymmetries in $B \to VV$ decays. Data samples with luminosity of order 50 ab^{-1} are required for either approach.

Are there flavor changing neutral currents (FCNC) beyond the Standard Model?

It is of great interest to measure $b \to s\nu\bar{\nu}$ transitions such as $B \to K^{(*)}\nu\bar{\nu}$. Belle's evidence for $B^+ \to \tau^+\nu$ is the first example of a new class of B decays with large missing energy. Extrapolations from this result indicate that the necessary sensitivity to a rare B mode with the same challenging experimental signature (a single track and missing energy) can be achieved at Belle II (see Table I).

Are the FCNCs observed in B decays consistent with those in kaon decays? One particularly interesting example is $B \to \rho\gamma$, which is a $b \to d$ radiative penguin. This mode has been observed at the B factories but detailed comparisons to theory expectations are not yet possible. In general, it is desirable to measure FCNC's with comparable accuracy in $b \to d$, $b \to s$ and $s \to d$ transitions. These will complement measurements of rare kaon modes such as $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$.

Neutrino experiments have found large mixing between the muon-neutrino and the tau-neutrino. Although the expected direct contribution from neutrino mixing is negligible, charged lepton flavor changing processes may be observable. This raises the possibility of flavor-changing processes such as $\tau \to \mu\gamma$. Searching for $\tau \to \mu\gamma$ at the $\mathcal{O}(3 \times 10^{-9})$ level would complement $\mu \to e\gamma$ searches and $\mu \to e$ conversion experiments, as $\tau \to \mu\gamma$ may have different sensitivity to new physics.

In 2007, Belle and BaBar obtained the first evidence for D^0-$\overline{D}^0$ mixing, which had been searched for for over thirty years. This discovery leads to the question of whether new physics enhances CP violation in the D^0-$\overline{D}^0$ system to an observable level (i.e., observable via D^0-$\overline{D}^0$ mixing). The Standard Model predicts a negligible effect, so observing CP violation in the D^0 system would be an unambiguous sign of new physics. (Recently, LHCb has reported 3.5σ evidence for direct CP violation in the neutral charm meson system [6]). Finally, the Belle II experiment would not only measure known CKM observables with unprecedented precision, but it would also measure new observables and decay modes that could shed light on new physics. The sensitivities for selected processes are given in Table I 1. More complete reviews of the physics program possible at a Super B factory are available in Refs. [7, 12, 13].

The SuperKEKB project in Japan has been approved by the Japanese government and has started construction. The machine uses nano-beams rather than very high beam currents to achieve the high luminosity. The vertical height of the beam is about 50 nanometers, which can be compared to the one micron level at KEKB. A large number of improvements to the machine are required including a new low energy ring beam pipe and a positron damping ring. The accelerator will begin commissioning in late 2014 with a special background detector.

The Belle II detector is an upgraded version of Belle that can handle the higher backgrounds that accompany the large increase in luminosity. The inner vertexing is based on DEPFET pixels. This is followed by double-sided silicon strips with a high speed readout matched to the higher brackground conditions. There will be a new small cell drift chamber. The particle identification system will be based on the detection of correlated time-space patterns of Cherenkov light produced (and internally reflected) in quartz bars. The barrel CsI(Tl) calorimeter will be retained. However, the readout will use waveform sampling to handle the larger backgrounds. The endcap K_L/muon detector as well as the first two layers of the barrel will be upgraded to a scintillator based device in order to handle larger beam related neutron backgrounds[8]. The Belle II detector plans to roll into the beamline in late 2015 after the background commissioning of SuperKEKB has been completed.

The US groups in Belle II [14] have chosen to focus their efforts on two areas of the detector that will have high impact on the new physics studies and that match their expertise and experience: high precision particle identification (especially at higher momenta) and muon/K_L identification. The high momentum particle identification is required to observe and separate from background the highly suppressed penguin loop processes that involve $b \to s$ or $b \to d$ transitions. These are likely to contain new sources of flavor mixing or new types of CP violation.

At the DOE intensity frontier review in 2010, Belle II was chosen as one of the two new high priority US intensity frontier experiments (along with g-2 at Fermilab). The DOE Mission Need Statement (CD-0) for the Next Generation B Factory Detector Systems was approved in August 2011 and the US Belle II groups are now preparing for the CD-1 review.

References

[1] S. Kurokawa and E. Kikutani, Nucl. Instrum. Methods Phys. Res., Sect. A **499**, 1 (2003), and other papers included in this volume.

[2] A. Abashian et al. (Belle Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **479**, 117 (2002).

[3] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).

[4] See `http://www.nobelprize.org/nobel_prizes/physics/laureates/2008/advanced.html`

[5] A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. **5**, 32 (1967); JETP Lett. bf 5, 24 (1967); Sov. Phys. Usp **34**, 392 (1991); Us. Fiz. Nauk **161**, 61 (1991).

[6] LHCb Collaboration, LHC-CONF-2011-061 (2011).

[7] T. Aushev *et. al.* (Belle II Physics Study), arXiv:1002.5012.

[8] K. Abe *et al.*, KEK report 04-4, hep-ex/0406071. The Belle Technical Design Report (TDR), edited by Z. Dolezal and S. Uno, T. Abe et al., (Belle II collaboration), arXiv: 1011.0352.

[9] See for example: A. J. Schwartz, "Complementarity: Flavor Physics in the LHC Era," invited talk at the Tenth Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2009), arXiv:0909.4344.

[10] R. Louvot et al. (Belle collab.), arXiv:0809.2526; J. Wicht et al. (Belle collab.) Phys. Rev. Lett 100, 121801 (2008); A. Drutskoy et al. (Belle collab.) Phys. Rev. D 76, 012002 (2007); A. Drutskoy et al. (Belle collab.) Phys. Rev. Lett. 98, 052001 (2007).

[11] S-W Lin et al. (Belle collab.), Nature 452, 332 (2008).

[12] T. E. Browder, T. Gershon, D. Pirjol, A. Soni and J. Zupan, hep-ph/0710.3799. Published in RMP 81, 2009.

[13] T. E. Browder, M. Ciuchini, T. Gershon, M. Hazumi, T. Hurth, Y. Okada, and A. Stocchi, JHEP 0802: 110 (2008).

[14] The US groups currently collaborating in Belle II are: Pacific Northwest National Lab (PNNL), Virginia Polytechnic Institute, Wayne State University, University of South Alabama, University of Cincinnati, University of Hawaii at Manoa, University of Indiana

Observable	Belle II sensit. ($50\ \mathrm{ab}^{-1}$)	SM[1]	comment
Hadronic $b \to s$ transitions			
$S(B \to \phi K_S)$	0.03	0.03 ± 0.02	
$S(B \to \eta' K_S)$	0.02	0 ± 0.015	
$S(B \to f_0 K_S)$	0.03	0 ± 0.015	
Radiative/electroweak $b \to s$ transitions			
$S(B \to K_S \pi^0 \gamma)$	0.03	-0.04 ± 0.1	
$Br(B \to X_s \gamma)$ $(\times 10^{-4})$	0.13	3.2 ± 0.2	inclusive Br
$Br(B \to K \nu \bar{\nu})$ $(\times 10^{-6})$	1.0	3.6 ± 0.5	
$A_{FB}(B \to K^* \ell^+ \ell^-)$	0.03	-0.10 ± 0.02	for $0 \leq q^2 \leq 4.3\ \mathrm{GeV}^2$
Radiative $b \to d$ transitions			
$S(B \to \rho \gamma)$	0.15	< 0.05	
Leptonic B decays			
$Br(B \to \tau \nu)$ $(\times 10^{-3})$	0.04	1.1 ± 0.2	
LFV in τ decays (U.L. at 90% C.L.)			
$Br(\tau \to \mu \gamma)$ $(\times 10^{-9})$	3	0	
B_s physics			
$Br(B_s \to \gamma \gamma)$ $(\times 10^{-6})$	0.3	0.7 ± 0.3	with $5\ \mathrm{ab}^{-1}$ of data
A_{SL} $(\times 10^{-3})$	5	0.23 ± 0.06	at $\Upsilon(5S)$
D meson mixing and CPV			
x $(\times 10^{-4})$	4		SM expectations
y $(\times 10^{-4})$	3		difficult to
$\lvert q/p \rvert$	0.03		estimate due to the
$\mathrm{Arg}(\lvert q/p \rvert)$ $(^\circ)$	1.5		LD contributions
$A_{CP}(D^0 \to K^+ K^-)$ $(\times 10^{-4})$	6		

Table 1: Some expected accuracies of *selected* physics observables at Belle II with a $50\ \mathrm{ab}^{-1}$ data sample. The second column gives approximate expectations within the SM along with theoretical uncertainties.