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Upgrading SuperKEKB with polarized e^- beams

J. Michael Roney[a,1,*]

[a] *University of Victoria,*
3800 Finnerty Road, Victoria, Canada

E-mail: mroney@uvic.ca

Upgrading the SuperKEKB e^+e^- collider with a polarized electron beam is under consideration as it enables a new program of precision electroweak and other physics at 10.6 GeV, thereby opening exciting new windows in search of new physics. Measurements of left-right asymmetries (A_{LR}) of e^+e^- transitions to pairs of muons, c- and b-quarks would yield substantial improvements to the determinations of the neutral current vector coupling of those final states and hence $\sin^2\theta_W$. Combining A_{LR} measurements from all final-state lepton-pairs would determine $\sin^2\theta_W$ with the Z-pole precision but at much lower energy. These will probe the running and universality of neutral current couplings with unprecedented precision. Other tau and QCD physics is also enhanced. A discussion of the physics enabled by beam polarization is presented, as well as the necessary upgrades to SuperKEKB: polarized e^- source, precision polarimetry, and spin rotators, all of which must be introduced while maintaining the high luminosity.

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[1] On behalf of the Belle II SuperKEKB e^- Polarization Upgrade Working Group
[*] Speaker

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With its high design luminosity of 8×10^{35} cm^{-2} s^{-1}, the SuperKEKB e$^+$e$^-$ collider at a centre-of-mass energy of 10.58 GeV can access unexplored avenues of discovery with the Belle II experiment if SuperKEKB is upgraded to have a longitudinally polarized electron beam. SuperKEKB/Belle II has a target integrated luminosity of 50 ab^{-1}[1] and currently is projected to reach that goal by 2031. SuperKEKB, upgraded to have electron beams with left and right longitudinal polarization of approximately 70% at the Belle II interaction point, would become a unique and versatile facility for probing new physics with precision electroweak measurements that no other experiments, current or planned, can achieve.

As described in Reference [2], with polarized electron beams e$^+$e$^-$ $\rightarrow f\bar{f}$ processes at 10.58 GeV, left-right cross-section asymmetries, which arise from $\gamma - Z$ interference, are sensitive to the product of the neutral current vector coupling constant, g_V^f, of the final-state fermion, f, and the neutral current axial-vector coupling constant of the initial state fermion, the electron, g_A^e. Within the framework of the Standard Model (SM) g_V^f is related to the weak mixing angle, θ_W, through the relation $g_V^f = T_3^f - 2Q_f \sin^2\theta_W$, where T_3^f is the 3rd component of weak isospin of f, Q_f is its electric charge in units of electron charge and the notational conventions of Reference [3] are used. Belle II would determine g_V^f by measuring the left-right asymmetry, A_{LR}^f, for each identified final-state fermion-pair. At lowest order

$$A_{LR}^f(Pol) = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{sG_F}{\sqrt{2}\pi\alpha Q_f} g_A^e g_V^f \langle Pol\rangle \tag{1}$$

where $g_A^e = T_3^e = -\frac{1}{2}$, G_F is the Fermi coupling constant, s is the square of the centre-of-mass energy, and

$$\langle Pol\rangle = \frac{1}{2}\left[\left(\frac{N_{eR} - N_{eL}}{N_{eR} + N_{eL}}\right)_{\mathbf{R}} - \left(\frac{N_{eR} - N_{eL}}{N_{eR} + N_{eL}}\right)_{\mathbf{L}}\right] \tag{2}$$

is the average electron beam polarization, where N_{eR} is the number of right-handed electrons and N_{eL} the number of left-handed electrons in the event samples where the electron beam bunch is left polarized or right polarized, as indicated by the '**L**' and '**R**' subscripts. Note that calculations at next-to-leading-order have recently been published for muon-pair [4] and electron-pair [5] final states.

Although the SM asymmetries are small (-6×10^{-4} for muons and taus, $+2\times10^{-4}$ for electrons, -5×10^{-3} for charm and -2% for the b-quarks), unprecedented precisions can be achieved because of the combination of both the high luminosity of SuperKEKB and a 70% beam polarization measured with a relative precision of better than ±0.5%.

A 20 ab^{-1} data sample with a 70% polarized electron beam will yield weak neutral current vector coupling constants of the b-quark, c-quark and muon with unprecedentedly high precision. The ratios of the vector couplings are precisely predicted in the SM assuming universality, and the g_V^b/g_V^c ratio will be measured to 0.3%, more than an order-of-magnitude higher precision than currently exists. With 40 ab^{-1}, combining the three leptonic final state measurements enables Belle II to measure $\sin^2\theta_W$ with a statistics-dominated uncertainty of ±0.00016, equivalent to the uncertainty on the world average from the five LEP+SLD experiments at the Z^0-pole [3] and more than twice as precise as the current world average from LHC [6]. As this will be measured at a much lower energy, it is sensitive to the running of $\sin^2\theta_W$ and new physics processes that might shift that running from that of the SM. Figure 1(left) shows the determinations of $\sin^2\theta_W$

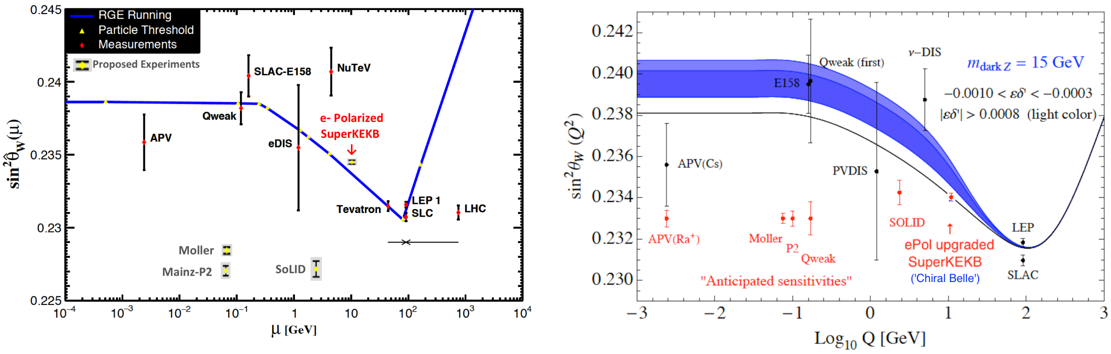

Figure 1: Left: Existing measurements of $\sin^2\theta_W$ and projected measurements at future experimental facilities as a function of energy scale, adapted from [10]. Right: Dark blue band indicates the Q^2-dependent shift in $\sin^2\theta_W$ caused by a 15 GeV mass dark Z, adapted from [9].

as a function of energy scale at present and future experimental facilities including SuperKEKB upgraded with a polarized electron beam. Moreover, the neutral current electroweak program with 40 ab^{-1} of polarized electron beams in SuperKEKB would provide the highest precision tests of neutral current vector coupling universality for all available final-state fermions with an error dominated by statistics, since the measured polarization, the dominant systematic error source, cancels in the ratio of the couplings. In addition, the right-handed b-quark couplings to the Z, which are currently in tension with the SM expectation by nearly 3σ, can be experimentally probed with high precision at Belle II with polarized beams.

Measurements with the projected precision allows Belle II to measure parity violation induced by the exchange of heavy particles such as a hypothetical TeV-scale Z' boson(s). If these bosons only couple to leptons, they will not be produced at the LHC. This upgrade renders SuperKEKB/Belle II unique in the ability to probe parity violation in the lepton sector mediated by light and very weakly coupled particles often referred to as “Dark Forces”. These forces have been entertained as a possible connecting link between normal and dark matter [7, 8]. SuperKEKB with polarization would be uniquely sensitivity to “Dark Sector” parity-violating light neutral gauge bosons, particularly if Z_{dark} is off-shell having a mass between $\sim$10 and 35 GeV [9] or even up to the Z^0 pole, or if it couples more to the 3rd generation (see Figure 1(right)).

These high precisions are possible because with 20 ab^{-1} Belle II can identify between 10^9 and 10^{10} final-state pairs of b-quarks, c-quarks, taus, muons and electrons with high purity and reasonable signal efficiency, and because all detector-related systematic errors can be made to cancel by flipping the laser polarization from **R** to **L** in a random, but known, pattern as collisions occur as was done at SLC. $\langle Pol\rangle$ would be measured in two ways. The first method uses a Compton polarimeter, which can be expected to have an absolute uncertainty at the Belle II interaction point of less than 1% and provides a ‘bunch-by-bunch’ measurement of $\left(\frac{N_{eR}-N_{eL}}{N_{eR}+N_{eL}}\right)_{\mathbf{R}}$ and $\left(\frac{N_{eR}-N_{eL}}{N_{eR}+N_{eL}}\right)_{\mathbf{L}}$. The uncertainty will be dominated by the need to predict the change in polarization between where it is measured, at the Compton polarimeter, and the interaction point. The second method measures the polar angle dependence of the polarization of τ-leptons produced in $e^+e^- \to \tau^+\tau^-$ events using the kinematic distributions of the decay products of the τ separately for the **R** and **L** data samples. The forward-backward asymmetry of the tau-pair polarization depends on $\langle Pol \rangle$ and therefore can be used to determine $\langle Pol \rangle$ to 0.5% at the Belle II interaction point in a manner entirely independent of the Compton polarimeter. The τ polarization method avoids the uncertainties associated with tracking the polarization losses to the interaction point and also automatically accounts for any residual positron polarization that might be present. In addition, it automatically provides a luminosity-weighted beam polarization measurement.

A polarized beam also improves the precision measurements of the tau electric dipole moment [11] and $g-2$. It can be used to reduce backgrounds in searches for $\tau \to \mu\gamma$ and $\tau \to e\gamma$, leading to improved sensitivities and can be used to distinguish left and right handed new physics currents [2]. In addition, polarized e^+e^- annihilation into a polarized Λ or a hadron pair experimentally probes dynamical mass generation in QCD.

The upgrade to SuperKEKB involves three hardware projects:

1. A low-emittance polarized electron source in which the electron beams would be produced via a polarized laser illuminating a "strained lattice" GaAs photocathode as was done for SLD [3]. The source would produce longitudinally polarized electron bunches whose spin would be rotated to be transversely polarized before it enters the SuperKEKB electron storage ring. The design calls for ~4 nC/bunch source with 20 mm-mrad vertical emittance and 50 mm-mrad horizontal emittance. The current focus is on a GaAs cathode with a thin Negative Electron Affinity (NEA) surface.

2. A pair of spin-rotators, one positioned before and the other after the interaction region, to rotate the spin to longitudinal prior to collisions and back to transverse following collisions. One configuration under consideration for the spin-rotator is a combined function magnet that replaces an existing dipole in the SuperKEKB electron beam lattice with a superconducting magnet that has both a dipole and solenoid [12] as well as six skew quads. Another concept is to install spin-rotator magnets in the existing SuperKEKB drift regions [13]. The challenge is to design the rotators to minimize couplings between vertical and horizontal planes and to address higher order and chromatic effects in the design to ensure the luminosity is not degraded.

3. A Compton polarimeter that measures the beam polarization before the beam enters the interaction region in real-time. Experience from Compton polarimeter designs at HERA at DESY and the QWeak experiment at Jefferson Lab is being deployed in the design of a SuperKEKB polarimeter, which will be installed outside the interaction region.

Also required is a reasonable de-polarization lifetime and it has been shown [13] that the depolarization lifetime for electrons with an energy of 7.15 GeV in the high energy ring (HER) of SuperKEKB is approximately 2 hours, which is twice the present HER beam lifetime. In addition, the HER beam is continously topped-up at 50 Hz. These initial studies are encouraging and more detailed conceptual design work is currently underway.

In summary, an electron beam polarization upgrade at SuperKEKB opens an exciting and unique discovery window with precision electroweak physics. Early feasibility studies are encouraging and are continuing, as discussed in the KEK Roadmap 2021-2026 submission to the Japanese

MEXT ministry. A growing international team is working on developing a conceptual design with a goal to realize the upgrade in order to begin taking Belle II data with polarized SuperKEKB electron beams as soon as possible after a 2026 shutdown scheduled for an upgrade of the Interaction Region.

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