Snowmass 2021 Letter of Interest: Charm Physics at Belle II

on behalf of the U.S. Belle II Collaboration

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■ (RF01) Weak Decays of b and c
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Abstract:

The Belle II experiment is expected to record 50 ab^{-1} of data in e^+e^- collisisons over the next decade. This data sample will result in almost 10^{11} D meson decays in a relatively low-background environment. As such, Belle II will pursue an extensive study of charm physics, with the goal of uncovering new physics. Here we briefly discuss several topical areas of this program: measuring charm mixing and CP violation; measuring leptonic and semileptonic decays to determine $|V_{cd}|$, $|V_{cs}|$, and test lattice QCD calculations; and studying charm baryon decays.

The Belle II experiment has a diverse physics program, the goal of which is to uncover new physics (NP) beyond the Standard Model (SM). One especially promising area of study is charm physics, which played a prominent role in the physics programs of the B-factory experiments Belle and BaBar. These experiments were the first to observe D^0-$\overline{D}^0$ mixing; the first to observe the anomalous states $X(3872)$, $Y(4260)$, $D_{sJ}(2317)$, and $D_{sJ}(2460)$ (among others); and, along with CLEO and BESIII, the first to test precise lattice QCD (LQCD) calculations with measurements of the decay constant f_{D_s}. At an e^+e^- experiment, backgrounds are low, the trigger efficiency is high and uniform, and the initial state is fully known. These features allow one to measure, in both neutral and charged final states, a wide variety of observables — branching fractions, CP asymmetries, isospin asymmetries, polarization, $SU(3)$ sum rules, etc. — in the search for NP. The Belle II experiment plans to record 50 ab^{-1} of data at the $\Upsilon(4S)$ resonance. Such a sample is about 50 times that recorded by Belle and would yield almost 10^{11} D meson decays. The resulting charm physics program will be extensive and cover a wide range of measurements: mixing, CP and T violation, leptonic and semileptonic decays, charm baryons, and charm spectroscopy. This LOI discusses the first five topics; a separate LOI discusses spectroscopy. Details of these topics are provided in the Belle II Physics Book.[1]

The first evidence for D^0-$\overline{D}^0$ mixing was obtained by Belle[2] and BaBar[3] using $D^0 \to K^+K^-/\pi^+\pi^-$ and $D^0 \to K^+\pi^-$ decays, respectively. Since then, mixing has been measured in several other decay modes by Belle, BaBar, CDF, and LHCb; the current world averages[4] for the mixing parameters $x \equiv \Delta m/\Gamma$ and $y \equiv \Delta\Gamma/(2\Gamma)$ are $(0.37 \pm 0.12)\%$ and $(0.68 \pm 0.07)\%$, respectively. While y is clearly non-zero and known to 10% precision, x still has significant uncertainty. One decay mode that would help resolve this is $D^0 \to K_S\,\pi^+\pi^-$; a Dalitz plot analysis of this final state has good sensitivity to both x and y, free of strong phases. Belle analyzed this mode with 0.92 ab^{-1} of data;[5] Belle II, with 50 ab^{-1} of data, is expected to measure x with more than twice better precision including systematic uncertainties, and y with more than three times better precision. Comparing D^0 and $\overline{D}^0$ decays, Belle II can measure the indirect CP-violating parameters $|q/p|$ and $\mathrm{Arg}(q/p) \equiv \phi$; the precision expected for the latter is less than 4°. This precision is better than that of the current global mixing fit by the Heavy Flavor Averaging Group.[4] Indirect CP violation is predicted to be small in the D^0-$\overline{D}^0$ system and has not yet been observed; such an observation could be the first sign of NP. The most sensitive measurements of mixing and indirect CP violation are based on fitting decay-time distributions; it is thus noteworthy that the decay-time resolution of Belle II is a factor of two more precise than that of Belle or BaBar.

One can also search for direct CP violation ($dCPV$) in charm decays. In the SM, such $dCPV$ is expected to be negligible in Cabibbo-favored (CF) and doubly Cabibbo-suppressed (DCS) decays, but measureable in singly Caibbo-suppressed (SCS) decays.[6] LHCb[7] has recently observed $dCPV$ in the charged SCS final states K^+K^- and $\pi^+\pi^-$, and the asymmetry is consistent with theory predictions.[6] It would be of high interest to measure similar $dCPV$ in neutral final states such as $D^0 \to K^0\overline{K}^0$ and $D^0 \to \pi^0\pi^0$. Belle II has good reconstruction efficiency for such final states and will undertake a comprehensive search for $dCPV$ in neutral, charged, and mixed neutral-charged final states. Belle II will search for $dCPV$ in radiative decays such as $D^0 \to V\gamma$, where $V = \phi$, ρ^0, $\overline{K}^{*0}$. Some final states are especially promising for uncovering NP. For example, the decay $D^+ \to \pi^+\pi^0$ has no QCD-penguin amplitude as the $\Delta I = 1/2$ contribution to the decay amplitude is forbidden by Bose-Einstein statistics; thus, $dCPV$ in this final state should be neglibible, and observing it would be a strong indication of NP. The world's best constraint on this asymmetry was set by Belle with 0.92 ab^{-1} of data; the result was $(2.31 \pm 1.24 \pm 0.23)\%$.[8] The expected uncertainty from Belle II is 0.17%, including systematic uncertainties.

Another promising strategy for uncovering NP is searching for T violation in D decays; this would imply CP violation via the CPT theorem. It is challenging to search for T violation in particle decays, as an explicit test requires interchanging initial and final states, which is usually unfeasible. Alternatively, one can measure a non-zero value for a T-odd observable, i.e., a quantity that changes sign under time reversal.[9] One such observable is $C_T = \vec{p}_1 \cdot (\vec{p}_2 \times \vec{p}_3)$ in four-body $D \rightarrow p_1\, p_2\, p_3\, p_4$ decays. Belle, BaBar, and LHCb have performed such measurements for several CF and SCS decays. To subtract off a non-zero contribution that can arise from strong phases, the measurement is performed for both D^0 and $\overline{D}^0$ decays and the difference in C_T distributions calculated. To date, all such measurements have yielded null results. Belle II can significantly expand upon these measurements, both in statistical precision and in the variety of final states studied. In particular, Belle II can study final states that include neutral particles π^0, K^0, and $\eta^{(\prime)}$.

With regard to leptonic and semileptonic decays, Belle II will improve upon the measurements made by Belle and Babar with much higher statistics, and also include more decay channels. These improvements will leverage expected improvements in LQCD calculations. The decays $D^+ \rightarrow \ell^+\nu$ and $D \rightarrow K\ell^+\nu$, $\pi\ell^+\nu$ involve missing energy, and thus these measurements are well-suited to an e^+e^- experiment in which the initial state is known and several kinematic constraints can be used to determine the neutrino momentum. The branching fraction for leptonic decays depends on the decay constant f_D or f_{D_s}, whereas the rate for semileptonic decays depends on the form factor $f_+(q^2)$. Measuring these decays and taking either the value of f_D or the normalization $f_+(0)$ from LQCD calculations yields measurements of the CKM matrix elements $|V_{cd}|$ and $|V_{cs}|$. Alternatively, taking $|V_{cd}|$ and $|V_{cs}|$ from a global fit to all data assuming CKM unitarity yields measurements of f_D and $f_+(0)$; these can be compared to LQCD results. The first method provides the world's most precise measurements of $|V_{cd}|$ and $|V_{cs}|$, wherease the latter provides a stringent test of LQCD. With 50 ab^{-1} of data, Belle II should determine $|V_{cs}|$ from $D_s^+ \rightarrow \ell^+\nu$ decays with a statistical uncertainty similar to the uncertainty arising from LQCD. The precision on the product $f_D \cdot |V_{cd}|$ from measuring $D^+ \rightarrow \ell^+\nu$ decays is expected to be $\sim 1.4\%$, significantly better than that attained by CLEOc, and possibly better than that from BESIII. Belle II can search for lepton non-universality in $D \rightarrow X\ell^+\ell^-$ transitions, as both electrons and muons have similarly high reconstruction efficiencies.

In the past several years, the study of charmed baryons has undergone a renaissance, with many new measurements from Belle, LHCb, and BESIII of Λ_c^+, Σ_c^0, $\Xi_c^{(+)}$, and Ω_c baryons, and excited Ξ_c and Ω_c^0 states. The doubly charmed Ξ_{cc}^{++} baryon has been observed,[10] and DCS $\Lambda_c^+ \rightarrow pK^+\pi^-$ decays have been measured.[11] A first search for CP violation has been performed, in $\Lambda_c^+ \rightarrow pK^+K^-$ and $\Lambda_c^+ \rightarrow p\pi^+\pi^-$ decays.[12] These studies and more will continue at Belle II. Charm baryon decays into neutral particles such as π^0's, K^0's, and η's are largely unexplored and will be systematically measured by Belle II. To give one example, the SCS decays $\Xi_c^+ \rightarrow \Sigma^+K^+K^-$, $\Sigma^+\pi^+\pi^-$ $(\Sigma^+ \rightarrow p\pi^0)$ will be searched for; these are analogous to $\Lambda_c^+ \rightarrow ph^+h^-$ $(h = K, \pi)$ decays but have not yet been observed.

In summary, the Belle II experiment will have a rich charm physics program, and Belle II is expected to make a wide range of forefront measurements with discovery potential.

References

[1] E. Kou *et al.*, *The Belle II Physics Book*, Prog. Theor. and Exp. Phys. **12**, 123C01 (2019).

[2] M. Staric *et al.* (Belle Collaboration), *Evidence for D^0-$\overline{D}^0$ Mixing*, Phys. Rev. Lett. **98**, 211803 (2007).

[3] B. Aubert *et al.* (BaBar Collaboration), *Evidence for D^0-$\overline{D}^0$ Mixing*, Phys. Rev. Lett. **98**, 211802 (2007).

[4] Y. Amhis *et al.* (Heavy Flavor Averaging Group), *Averages of b-hadron, c-hadron, and τ-lepton properties as of 2018*, arXiv:1909.12524 (to appear in Eur. Phys. Jour. C), and online update at https://hflav.web.cern.ch/content/charm-physics.

[5] T. Peng *et al.* (Belle Collaboration), *Measurement of D^0-$\overline{D}^0$ mixing and search for CP violation in $D^0 \to K^0_S \pi^+\pi^-$ decays*, Phys. Rev. D **89**, 091103 (2014).

[6] Y. Grossman, A. L. Kagan, and T. Nir, *New physics and CP violation in singly Cabibbo suppressed D decays,* Phys. Rev. D **75**, 036008 (2007).
H.-Y. Cheng and C.-W. Chiang, *Direct CP violation in two-body hadronic charmed meson decays,* Phys. Rev. D **85**, 034036 (2012).

[7] R. Aaji *et al.* (LHCb Collaboration), *Observation of CP violation in charm decays*, Phys. Rev. Lett. **122**, 211803 (2019).

[8] V. Babu *et al.* (Belle Collaboration), *Search for CP violation in the $D^+ \to \pi^+\pi^0$ decay at Belle*, Phys. Rev. D **97**, 011101 (2018).

[9] W. Bensalem and D. London, *T-Odd Triple-Product Correlations in Hadronic b Decays*, Phys. Rev. D **64**, 116003 (2001).

[10] R. Aaji *et al.* (LHCb Collaboration), *Observation of the Doubly Charmed Baryon Ξ^{++}*, Phys. Rev. Lett. **119**, 112001 (2017).

[11] . S. B. Yang *et al.* (Belle Collaboration), *First Observation of the Doubly Cabibbo-Suppressed Decay of a Charmed Baryon: $\Lambda_c^+ \to pK^+\pi^-$*, Phys. Rev. Lett. **117**, 011801 (2016).

[12] R. Aaji *et al.* (LHCb Collaboration), *A measurement of the CP asymmetry difference between $\Lambda_c^+ \to pK^-K^+$ and $\Lambda_c^+ \to p\pi^-\pi^+$*, JHEP **03**, 182 (2019).