Rare decays at the CERN high-intensity kaon beam facility

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Precision measurements of the branching ratios (BRs) for rare kaon decays can provide unique constraints on CKM unitarity and may reveal the existence of new physics. The BRs for two of these decays, $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$, are strongly suppressed in the Standard Model (SM), while their rates can be calculated with very small theoretical uncertainties [1]. These decays are potentially sensitive to mass scales of hundreds of TeV [2] and several models of new physics predict large deviations from the SM [3, 4, 5, 6, 7, 8, 9]. While evidence for lepton-flavor-universality (LFU) violation in B decays is mounting [10, 11, 12, 13], most explanations predict strong third-generation couplings and thus significant changes to the $K \to \pi\nu\bar{\nu}$ BRs through couplings to final states with τ neutrinos [14]. Measurements of the $K \to \pi\nu\bar{\nu}$ BRs may demonstrate that LFU violation is a manifestation of new degrees of freedom such as leptoquarks [15, 16]. Anomalously high apparent values for the $K \to \pi\nu\bar{\nu}$ BRs might also be interpreted as evidence for the existence of hidden-sector particles, such as a dark scalar X produced in place of the $\nu\bar{\nu}$ pair [17]. Because the K^+ and K_L decays have different sensitivity to new sources of CP violation, measurements of both BRs would be useful not only to uncover evidence of new physics in the quark-flavor sector but also to shed light on its nature.

Much progress has been made recently in the measurement of the $K \to \pi\nu\bar{\nu}$ BRs. The KOTO experiment at J-PARC [18] has achieved a preliminary single-event sensitivity (SES) for $K_L \to \pi^0\nu\bar{\nu}$ decays of 7.1×10^{-10}, corresponding to 0.04 SM signal events collected in 2016–2018. The collaboration has observed 3 candidate events, with an estimated background of 1.05 ± 0.28 events, dominantly from K^+ charge-exchange, techniques for the suppression of which are under development. KOTO expects to reach the SES for the SM decay by about 2025. A possible KOTO Step-2 upgrade thereafter would require construction of a planned extension of the J-PARC hadron hall, as well as of a completely new detector several times larger than the present detector [19]. Meanwhile, the NA62 experiment at the CERN SPS [20] has announced preliminary results from 2018 data taking: 17 candidate events for the $K^+ \to \pi^+\nu\bar{\nu}$ decay were observed, with an expected SM signal of 7.6 ± 0.8 and an expected background of $5.3^{+1.0}_{-0.7}$ events [21]. In combination with the smaller data set collected in 2016-2017 (three candidate events) [22, 23], NA62 obtains $\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = (11.0^{+4.0}_{-3.5} \pm 0.3) \times 10^{-11}$, improving on the previous bounds from the Brookhaven E787 and E949 experiments [24] and giving the first significant evidence ($> 3\sigma$) for this rare decay. NA62 expects to attain ~10% precision on the BR with data to be collected in 2021–2024.

Following upon NA62's successful application of the in-flight technique to measure $\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})$, we envision a comprehensive program for the study of the rare decay modes of both K^+ and K_L mesons, to be carried out with high-intensity kaon beams from the CERN SPS in multiple phases, including both an experiment to measure $\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})$ at the 5% level and an experiment to measure $\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu})$ at the 20% level, which together with the KOTO measurement will push the precision below 15%. The detectors could also be reconfigured to allow measurements of K_L decays with charged particles, such as $K_L \to \pi^0\ell^+\ell^-$.

The success of this program depends on the delivery of a high-intensity, slow-extracted 400-GeV/c proton beam from the SPS to the current NA62 experimental hall, which is ideally suited for next-generation kaon experiments. Up to 10^{19} protons on target per year will be required. Studies indicate that, with duty-cycle optimization, sufficient proton fluxes can be delivered to allow a high-intensity kaon experiment to run as part of a robust fixed-target program [25]. The upgrades to the primary beamline tunnel, target gallery, and experimental cavern to handle an intensity of up to six times that in NA62 has been studied as part of the Physics Beyond Colliders initiative at CERN [26, 27].

To measure BR($K^+ \to \pi^+ \nu\bar{\nu}$) with 5% precision, the experiment must be able to handle a beam intensity of four times that in NA62. The entire complement of NA62 detectors [20] would require substantial upgrades in order to provide clean event reconstruction at the expected rates. Development of the new detectors is synergistic with R&D efforts for HL-LHC. Ultrafast ($\sigma_t \sim 20$ ps) single-photon detectors, such as advanced devices making use of multi-channel plates, will be needed for use in the Cherenkov detectors for beam and secondary particle identification. Tracking of the K^+ beam will require a new Gigatracker with 50 ps time resolution, capable of operating at rates of up to 8 MHz/mm^2; possible solutions under exploration include silicon sensors incorporating LGAD technology [28] and 3D pixels with trench geometry [29]. Design work has started on a tracking system for secondary particles based on thin-walled ($\sim 20\ \mu$m), narrow-gauge (5 mm) straw tubes operating in vacuum, with a time resolution of ~6 ns per straw. This work, which builds on the NA62 straw-tracker design, is synergistic with R&D work for COMET phase-II at J-PARC [30].

The baseline design for the K_L experiment is the KLEVER project [31], presented as part of the Physics Beyond Colliders initiative [32]. The KLEVER goal is to measure BR($K_L \to \pi^0 \nu\bar{\nu}$) to within 20%. The measurement technique is complementary to that for KOTO: the boost from the high-energy neutral beam facilitates the rejection of background channels such as $K_L \to \pi^0\pi^0$ by detection of the additional photons in the final state. Background from $\Lambda \to n\pi^0$ decays in fiducial volume must be kept under control, and recent work has focused on the possibility of a beamline extension and other adaptations of the experiment to ensure sufficient rejection of this channel. The layout poses challenges for the design of the small-angle vetoes, which must reject photons from K_L decays escaping through the beam exit amidst an intense background from soft photons and neutrons in the beam. A notable feature of KLEVER is the exploitation of coherent interaction effects in oriented crystals [33, 34, 35] to remove high-energy photons from the neutral beam and, possibly, for the construction of small-angle photon vetoes with high conversion efficiency for photons but good transparency to beam neutrons.

Experiments with different kaon beams would run consecutively in the same experimental area and use interchangeable detectors. The forward calorimetry and photon veto systems would be the same for both experiments. Detector and beamline configuration between phases will be scheduled during an LHC shutdown period. As in NA62, the physics program of the high-intensity K^+ experiment is broad and includes studies of radiative kaon decays, tests of lepton-universality conservation, searches for lepton-flavor or lepton-number violating decays, decays of the kaon to hidden-sector particles [36], and other precision tests. In the $K_L \to \pi^0 \nu\bar{\nu}$ configuration, to optimize the measurement, the K_L experiment will have no secondary tracking and limited PID capability. As part of a broader physics program, however, we foresee the possibility of taking data with the downstream detectors configured for charged-particle measurements (calorimetry, secondary tracking and PID) but with a neutral beam. This will allow searches for radiative and lepton-flavor violating K_L decays, K_L decays to exotic particles, and particularly, measurements of the $K_L \to \pi^0 \ell^+ \ell^-$ BR, for which only limits exist at present [37, 38]. Measurement of these BRs would overconstrain the kaon unitarity triangle; to the extent that there is little constraint on the CP-violating phase of the $s \to d\ell^+\ell^-$ transition, measurement of the $K_L \to \pi^0 \ell^+ \ell^-$ BRs may reveal the effects of new physics [39]. The combination of data from multiple channels will yield a thorough investigation of new physics in the kaon sector.

The program described builds on a CERN tradition of groundbreaking experiments in kaon physics, following on the successes of NA31, NA48, NA48/1, NA48/2, and NA62. In the 2020 update of the European Strategy for Particle Physics, rare kaon decay measurements at CERN were identified as contributing to a diverse program of high-impact particle physics initiatives that is an essential part of the Strategy [40].

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