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KLEVER: An experiment to measure BR($K_L \to \pi^0 \nu \bar{\nu}$) at the CERN SPS

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Precise measurements of the branching ratios for the flavor-changing neutral current decays $K \to \pi \nu \bar{\nu}$ can provide unique constraints on CKM unitarity and, potentially, evidence for new physics. It is important to measure both decay modes, $K^+ \to \pi^+ \nu \bar{\nu}$ and $K_L \to \pi^0 \nu \bar{\nu}$, since different new physics models affect the rates for each channel differently. The goal of the NA62 experiment at the CERN SPS is to measure the BR for the charged channel to within 10%. For the neutral channel, the BR has never been measured. KOTO, an experiment at J-PARC, should have enough data for the first observation of the decay by about 2021. We are designing the KLEVER experiment to measure BR($K_L \to \pi^0 \nu \bar{\nu}$) to ~20% using a high-energy neutral beam at the CERN SPS starting in Run 4. The boost from the high-energy 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. On the other hand, the layout poses particular challenges for the design of the small-angle vetoes, which must reject photons from K_L decays escaping through the beam pipe amidst an intense background from soft photons and neutrons in the beam. Background from $\Lambda \to n \pi^0$ decays in the beam must also be kept under control. We present findings from our design studies, with an emphasis on the challenges faced and the potential sensitivity for the measurement of BR($K_L \to \pi^0 \nu \bar{\nu}$).

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The branching ratios for the decays $K \to \pi\nu\bar{\nu}$ are among the observables in the quark-flavor sector most sensitive to new physics. The Standard Model (SM) rates for these decays are BR($K^+ \to \pi^+\nu\bar{\nu}$) $= (8.4 \pm 1.0) \times 10^{-11}$ and BR($K_L \to \pi^0\nu\bar{\nu}$) $= (3.4 \pm 0.6) \times 10^{-11}$, with non-parametric theoretical uncertainties of about 3.5% and 1.5%, respectively [1]. Because these decays are strongly suppressed and their rates are calculated very precisely in the SM, their BRs are potentially sensitive to mass scales of hundreds of TeV, surpassing the sensitivity of B decays in most SM extensions [2]. Observations of lepton-flavor-universality-violating phenomena are mounting in the B sector [3]. Measurements of the $K \to \pi\nu\bar{\nu}$ BRs are critical to interpreting the data from rare B decays, and may demonstrate that these effects are a manifestation of new degrees of freedom such as vector leptoquarks [4].

The goal of the NA62 experiment at the CERN SPS is to measure BR($K^+ \to \pi^+\nu\bar{\nu}$) to within 10% [5]. NA62 has recently presented the preliminary result BR($K^+ \to \pi^+\nu\bar{\nu}$) $< 14 \times 10^{-10}$ (95%CL), with 1 observed candidate event [6]. This result is based on 2% of the combined data from running in 2016–2018. Additional running is contemplated for 2021–2022. In order to distinguish between different new-physics scenarios, it is necessary to measure BR($K_L \to \pi^0\nu\bar{\nu}$) as well [7]. KOTO, an experiment at J-PARC, has recently obtained the limit BR($K_L \to \pi^0\nu\bar{\nu}$) $<$ 3.0×10^{-9} (90%CL), with an expected background of 0.42 ± 0.18 events and no candidate events observed [8]. KOTO should be able to make the first observation of the $K_L \to \pi^0\nu\bar{\nu}$ decay by the early 2020s [9], but a next-generation experiment is needed in order to measure the BR. We are designing the KLEVER experiment to use a high-energy neutral beam at the CERN SPS to achieve 60-event sensitivity for the decay $K_L \to \pi^0\nu\bar{\nu}$ at the SM BR with an S/B ratio of 1. Data taking

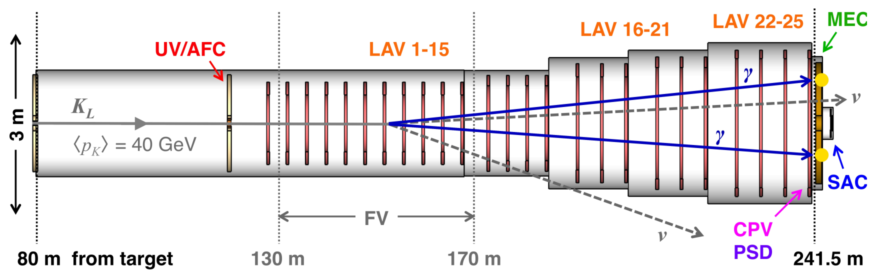

Figure 1: KLEVER experimental apparatus: upstream veto (UV), active final collimator (AFC), large-angle photon vetoes (LAV), main electromagnetic calorimeter (MEC), small-angle calorimeter (SAC), charged particle veto (CPV), pre-shower detector (PSD).

would start in LHC Run 4 (2026). The layout is sketched in Figure 1.

KLEVER will make use of the 400-GeV SPS proton beam to produce a neutral secondary beam at an angle of 8 mrad with a mean K_L momentum of 40 GeV and a K_L yield of 2×10^{-5} K_L per proton on target (pot). Collection of 60 SM events in 5 years would require a total primary flux of 5×10^{19} pot, corresponding to an intensity of 2×10^{13} protons per pulse (ppp) under NA62-like slow-extraction conditions. This is a six-fold increase in the primary intensity relative to NA62, the feasibility of which is under study. Preliminary indications are positive: there is general progress on issues related to the slow extraction of the needed intensity to the North Area (including duty cycle optimization); a workable solution for transport of the beam from the primary target to the experimental beamline has been identified; and the ventilation in the target and secondary beam cavern appears to be sufficiently hermetic, obviating the need for potentially expensive upgrades.

The target and dump collimator (TAX) may have to be upgraded or rebuilt. A four-collimator neutral beamline layout for ECN3 has been developed and simulation studies with FLUKA and Geant4 are in progress to quantify the extent and composition of beam halo, muon backgrounds, and sweeping requirements. According to the simulation, there are 140 MHz of K_L in the beam and 440 MHz of neutrons [10]. A tungsten converter in the TAX followed by sweeping magnets in the beamline eliminates all but 40 MHz of the photons in the beam with energy greater than 5 GeV.

Most of the subdetector systems for KLEVER will have to be newly constructed. Early studies indicated that the NA48 liquid-krypton calorimeter (LKr) [11] currently used in NA62 could be reused as the MEC. Indeed, the efficiency and energy resolution of the LKr appear to be satisfactory for KLEVER. However, the LKr would measure the event time in KLEVER with 500-ps resolution, while the total rate of accidental vetoes (dominated by the rate in the SAC) could be 100 MHz. We are investigating the possibility of replacing the LKr with a shashlyk-based MEC patterned on the PANDA FS calorimeter (in turn, based on the KOPIO calorimeter [12]). We envisage a shashlyk design incorporating "spy tiles" for longitudinal sampling of the shower development, resulting in additional information for γ/n separation. A first test of this concept was carried out with a prototype detector at Protvino in April 2018.

The upstream veto (UV), which rejects $K_L \to \pi^0\pi^0$ decays upstream of the fiducial volume, would use the same shashlyk technology as the MEC. The active final collimator (AFC), inserted into the hole in the UV for passage of the beam, is a LYSO collar counter with angled inner surfaces. This provides the last stage of beam collimation while vetoing photons from K_L that decay in transit through the collimator itself.

Because of the boost from the high-energy beam, it is sufficient for the large-angle photon vetoes (LAVs) to cover polar angles out to 100 mrad. The 25 new LAV detectors for KLEVER are lead/scintillating-tile sampling calorimeters with wavelength-shifting fiber readout [13]. Extensive experience with this type of detector (including in prototype tests for NA62) demonstrates that the low-energy photon detection efficiency will be sufficient for KLEVER [14].

The small-angle calorimeter (SAC) sits directly in the neutral beam and must reject photons from K_L decays that would otherwise escape via the downstream beam exit. The veto efficiency required is not intrinsically daunting (inefficiency $< 1\%$ for 5 GeV $< E_\gamma <$ 30 GeV and $< 10^{-4}$ for $E_\gamma <$ 30 GeV; the SAC can be blind for $E_\gamma <$ 5 GeV), but must be attained while maintaining insensitivity to more than 500 MHz of neutral hadrons in the beam. In addition, the SAC must have good longitudinal and transverse segmentation to provide γ/n discrimination. An intriguing solution is to construct the SAC as a compact, Si-W sampling calorimeter with crystalline tungsten tiles as the absorber material, since coherent interactions of high-energy photons with a crystal lattice can lead to increased rates of pair conversion relative to those obtained with amorphous materials [15]. The effect is dependent on photon energy and incident angle; in the case of KLEVER, one might hope to decrease the ratio $X_0/\lambda_{\rm int}$ by a factor of 2–3. The same effect could be used to efficiently convert high-energy photons in the neutral beam to e^+e^- pairs at the dump collimator for subsequent sweeping, thereby allowing the use of a thin converter to minimize the scattering of hadrons from the beam. Both concepts were tested in summer 2018 in the SPS H2 beam line, in a joint effort together with the AXIAL collaboration.

For the rejection of charged particles, K_{e3} is a benchmark channel because of its large BR and because the final state electron can be mistaken for a photon. Simulations indicate that the needed rejection can be achieved with two staggered planes of charged-particle veto (CPV) each providing 99.5% detection efficiency, supplemented by the $\mu^\pm$ and $\pi^\pm$ recognition capabilities of the MEC (assumed in this case to be equal to those of the LKr) and the current NA62 hadronic calorimeters and muon vetoes.

Finally, a pre-shower detector (PSD) featuring a $0.5X_0$ converter and two planes of tracking with $\sigma_{x,y} \sim 100$ μm (assumed to be large-area MPGDs) would allow angular reconstruction of at least one γ from $K_L \to \pi^0\pi^0$ events with two lost γs in 50% of cases, providing $\gamma\gamma$ vertex reconstruction (with the nominal beamline) with $\sigma_z \sim 10$ m or better. Information from the PSD will be used for bifurcation studies of the background and for the selection of control samples.

Simulations of the experiment carried out with fast-simulation techniques (idealized geometry, parameterized detector response, etc.) show that the target sensitivity is achievable (60 SM events with $S/B = 1$). Fig. 2 illustrates the scheme for differentiating signal events from $K_L \to \pi^0\pi^0$

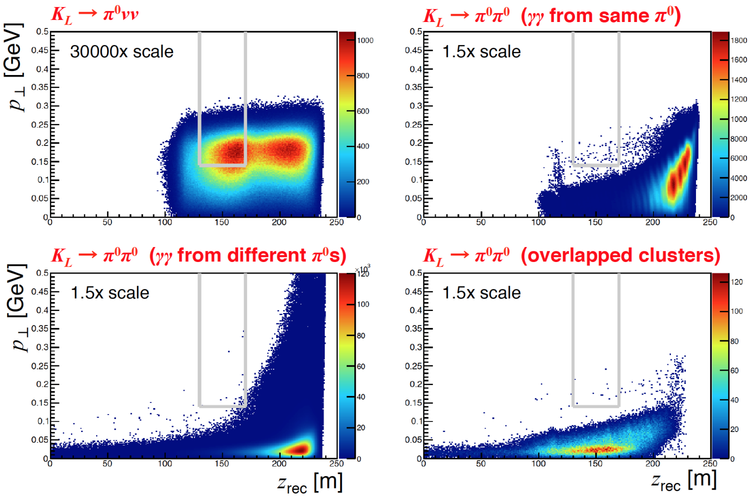

Figure 2: Distributions of events in plane of $(z_{\rm rec}, p_\perp)$ after basic event selection cuts, from fast MC simulation, for $K_L \to \pi^0\nu\bar{\nu}$ events (top left) and for $K_L \to \pi^0\pi^0$ events with two photons from the same π^0 (top right), two photons from different π^0s (bottom left), and with two or more indistinguishable overlapping photon clusters (bottom right).

background. Events with exactly two photons on the MEC and no other activity in the detector are selected. The clusters on the MEC from both photons must also be more than 35 cm from the beam axis (this helps to increase the rejection for events with overlapping clusters). If one or both photons convert in the PSD, the reconstructed vertex position must be inside the fiducial volume. The plots show the distributions of the events satisfying these minimal criteria in the plane of $p_\perp(\gamma\gamma)$ vs. $z_{\rm rec}(\gamma\gamma)$ for the π^0, where the distance from the π^0 to the MEC is reconstructed from the transverse separation of the two photon clusters, assuming that they come from a π^0 ($M_{\gamma\gamma} = m_{\pi^0}$). This scheme is far from final and there is room for improvement with a multivariate analysis, but is does demonstrate that it should be possible to obtain $S/B \sim 1$ with respect to other K_L decays. Background from $\Lambda \to n\pi^0$ and from decays with charged particles is assumed to be eliminated on the basis of studies with more limited statistics. Besides the length from the target to the fiducial volume and the choice of production angle carefully optimized to balance K_L flux against the need to soften the Λ momentum spectrum, background from $\Lambda \to n\pi^0$ ($p^* = 104$ MeV) can be effectively eliminated by cuts on $p_\perp$ and in the θ vs. p plane for the π^0.

An effort is underway to develop a comprehensive simulation and use it to validate the results obtained so far. Of particular note, backgrounds from radiative K_L decays, cascading hyperon decays, and beam-gas interactions remain to be studied, and the neutral-beam halo from our more detailed FLUKA simulations needs to be incorporated into the simulation of the experiment. Preliminary studies indicate that the hit and event rates on most of the detectors are on the order of a few tens of MHz, a few times larger than in NA62, with the notable exception of the SAC, which will require an innovative readout solution to handle rates of 100 MHz.

KLEVER would aim to start data taking in LHC Run 4. To be ready for the 2026 start date, detector construction would have to begin by 2021 and be ready for installation by 2025, leaving three years from the present for design consolidation and R&D. Many institutes currently participating in NA62 have expressed support for and interest in the KLEVER project. Input to the update process for the European Strategy for Particle Physics and an Expression of Interest to the SPS program committee (SPSC) are in preparation. Successfully carrying out the KLEVER experimental program will require the involvement of new institutions and groups, and we are actively seeking to expand the collaboration at present.

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