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THE K12 BEAMLINE FOR THE KLEVER EXPERIMENT

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Abstract

The KLEVER experiment is proposed to run in the CERN ECN3 underground cavern from 2026 onward. The goal of the experiment is to measure BR($K_L \to \pi^0 \nu\bar{\nu}$), which could yield information about potential new physics, by itself and in combination with the measurement of BR($K^+ \to \pi^+ \nu\bar{\nu}$) of NA62. A full description will be given of the considerations in designing the new K12 beamline for KLEVER, as obtained from a purpose made simulation with FLUKA. The high intensities required by KLEVER, 2×10^{13} protons on target every 16.8 s, with 5×10^{19} protons accumulated over 5 years, place stringent demands on adequate muon sweeping to minimize backgrounds in the detector. The target and primary dump need to be able to survive these demanding conditions, while respecting strict radiation protection criteria. A series of design choices will be shown to lead to a neutral beamline sufficiently capable of suppressing relevant backgrounds, such as photons generated by π^0 decays in the target, and $\Lambda \to n\pi^0$ decays, which mimic the signal decay.

INTRODUCTION

The measurement of the branching ratio BR($K_L \to \pi^0 \nu\bar{\nu}$) offers enticing prospects for testing several potential models for new physics [1]. The KLEVER experiment would be the capstone in the CERN kaon program, following the NA31, NA48 and NA62 experiments. This paper will briefly lay out the physics case for KLEVER, and then focus on the challenges the proposed measurement poses for the adaptations required in the K12 beamline.

MOTIVATION

NA62 has recently found a first signal candidate; the first step to measuring BR($K^+ \to \pi^+ \nu\bar{\nu}$) [2]. KLEVER is under design to measure the neutral equivalent: BR($K_L \to \pi^0 \nu\bar{\nu}$). These measurements together constitute a method of determining the Cabibbo-Kobayashi-Maskawa (CKM) unitarity triangle, independently of B-physics. A large advantage is that their values in the Standard Model have been calculated to high precision. The combination of the expected measurements from NA62 and KLEVER forms a particularly powerful probe of several potential new physics scenarios; as summarized in Fig. 1.

EXPERIMENTAL LAYOUT

KLEVER can be separated into the beamline and the detectors surrounding the decay volume. The experiment

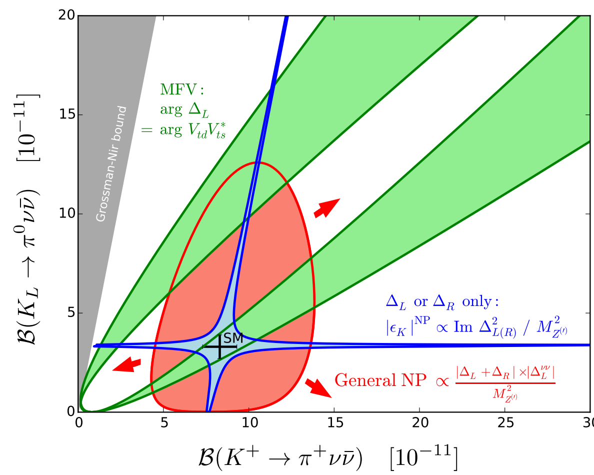

Figure 1: SM prediction for BR(K $\to \pi\nu\bar{\nu}$) with new physics scenarios overlaid, from [1]: CKM-like models with minimal flavour violation (green), models with flavour-violating interactions in which left-handed or right-handed couplings dominate (blue) and more general models (e.g., Randall-Sundrum, red).

requires an intense beam of K_L mesons, which is generated by a 400 GeV/c proton beam derived from the SPS that is incident on a target at a downwards vertical angle. The closer to zero the angle is, the higher the rate of K_L per solid angle. The angle of incidence was set to 8 mrad following a series of studies on the spectra of all neutral particles produced. A key background for KLEVER is from the Λ baryon decaying as $\Lambda \to n\pi^0$ with the neutron potentially undetected. This decay resembles the KLEVER signal decay: a single π^0 with significant missing momentum. This background was suppressed heavily by going to an 8-mrad angle of incidence, because the production of Λ falls off quicker as a function of angle than the K_L. The Λ momentum spectrum also falls off much more quickly at higher angles. Because of the long lifetime of the K_L relative to the Λ, this greatly reduces the number of Λs that decay in the fiducial volume. The residual Λ background is removed by means of kinematic cuts.

The beamline consists of a combination of magnets and collimators to select the neutral beam. A strong magnet is placed directly after the target to sweep the primary protons further downward and dump them on the combined dump/collimator (TAX). The beam is derived in a horizontal line from the target, passes through the TAX collimator, and subsequently encounters the defining and cleaning collimators. The defining collimator is the narrowest relative to the beam divergence. The cleaning collimator removes

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particles generated by interactions on the defining collimator. Together these collimators allow for a 0.4 mrad opening angle relative to the target. Each of these three collimators is followed by a magnetic element to eject charged particles generated by interactions in the collimator. At 120 m from the target the upstream veto (UV), an electromagnetic calorimeter, defines the upstream edge of the fiducial volume. Its function is to screen particles upstream of it from the decay volume. The UV has a central passage of 10 cm radius. The inside of this passage (radius 6 to 10 cm) is lined with LYSO crystals and makes up the active final collimator (AFC). Magnetic sweeping is not needed after the AFC since it is an active detector. A schematic overview of the beamline can be seen in Fig. 2.

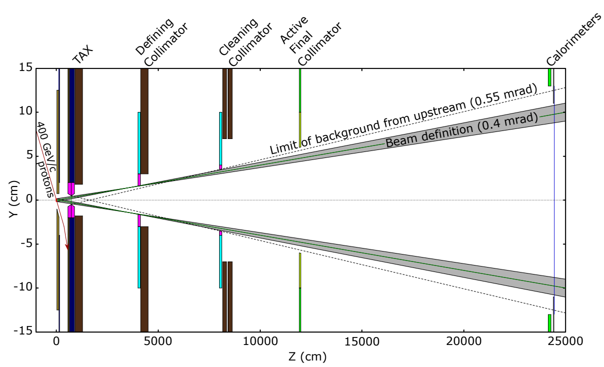

Figure 2: Layout of the K12 beamline for KLEVER, with the four-collimator system for selecting the neutral beam.

The fiducial volume for the experiment extends from 130 m to 170 m. The decay volume is lined with large-angle veto detectors (LAVs) hermetically sealing it for angles up to 100 mrad relative to the beam axis. A series of detectors is placed near the end of the decay volume at 240 m. The charged particle veto (CPV) removes events from K_L decays with charged particles in the final state. The pre-shower detector (PSD) adds efficiency to the vetoing of the neutral channel $K_L \to \pi^0\pi^0$, one of the most difficult tasks in removing background. It does so by providing independent measurements of the angles of incident photons. The main electromagnetic calorimeter (MEC) allows for signal events to be recognized by reconstruction of $\pi^0 \to \gamma\gamma$ decays on the beam axis and determination of the transverse momentum of the π^0. The small-angle calorimeter (SAC) is placed on-axis and has to screen all the photons from the beam while still remaining sensitive to photons generated from K_L decays. The full layout of the KLEVER detectors is shown in Fig. 3.

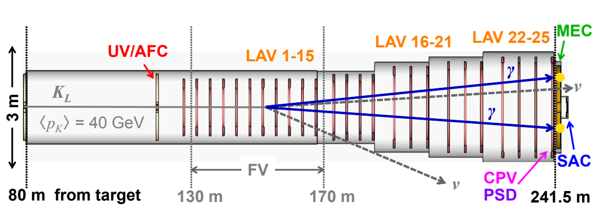

Figure 3: Layout of the detectors for KLEVER.

MUON SWEEPING

Over the distance between the target and the detectors, significant quantities of muons are generated, mostly from decays of pions and kaons. These can form substantial backgrounds in the detector, and a series of simulations has been performed in FLUKA [3,4] to quantify and then reject these. The field setting of the magnet following the target is maximized and fixed to dump the primary protons with as much downward angle as possible. The magnets following the collimator stations can be set in strength and orientation as needed. Care was taken to include the return fields in the yoke, which are important for assessing the muon backgrounds.

It has been assumed that the sweeping would be most effective with maximized field strengths. To select the optimal orientation of the magnets a simulation was performed, iterating all three (sets of) magnet orientations over four cardinal directions. The optimal configuration was found by orienting the first magnet such that it sweeps positive particles to negative X. The second and third (sets of) magnets sweep positive particles to positive X. The rates for positive and negative muons at the UV for this magnet configuration are shown in Figure 4. In total, 2.5 MHz of muons with $P > 1$ GeV/c pass through the UV and 4.9 MHz through the MEC. The increase in muons in the MEC relative to the UV is attributed to its larger area and particles decaying in the decay volume. This background is rather small compared to the 40 MHz design criterion that was set for beam photons detected in the small angle calorimeter.

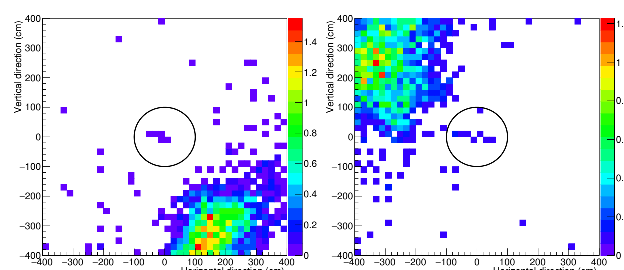

Figure 4: Rate per bin (MHz) for muons with $P > 1$ GeV/c passing through the UV, (left) for μ^+ and (right) for μ^-. The large muon populations shown move outward and away from the downstream detector planes.

TARGET & PHOTON ABSORBER

The photon absorber set into the center of the TAX fulfils a critical function for KLEVER: it cleans the high energy photons from the beam so that they do not overwhelm the SAC placed on-axis at the end of the K_L decay volume. The absorber is made from tungsten. Its thickness is chosen to obtain a rate of photons with $E > 5$ GeV at the SAC that is lower than 40 MHz. For this calculation, the beam rate assumed is 2×10^{13} protons on target over a 3 s spill. The actual length is 4.8 s; assuming it is shorter will account for

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fluctuations over the spill. It was found [5] that the use of a higher-Z material is a potentially interesting way to lower the photon content in the beam. Most of the prompt photons come from π^0 decays generated within the target. Higher-Z material promotes conversion of these photons to e^+e^- pairs. The effective conversion length in a given material due to pair conversion is $X_{eff} = \frac{9}{7}X_0$ [6]. The rate of photons at the SAC for beryllium, copper and tungsten targets (each with a nuclear interaction length equivalent to 400 mm Be) is shown in Fig. 5.

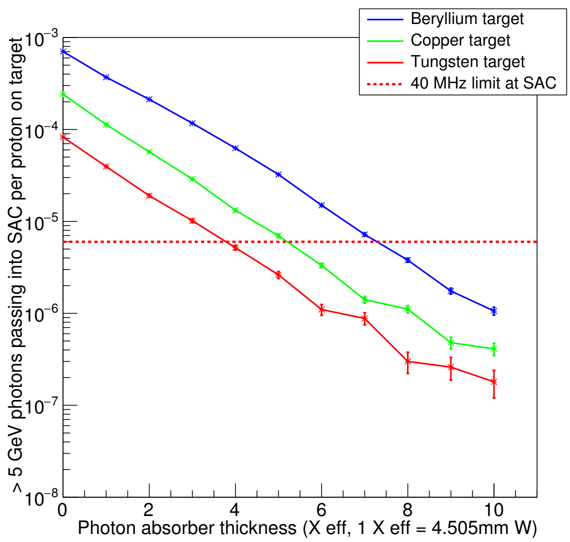

Figure 5: Rate of photons with $E > 5$ GeV per POT for varying thickness of photon absorber, for Be / Cu / W targets.

It was found that the required thicknesses of the absorber for equivalent targets made of Be / Cu / W are 7.3 / 5.2 / 3.8 X_{eff}. A thinner absorber leads to less scattering of the beam, resulting in an increase of 15% / 26% of the K_L content in the beam for a Cu / W target relative to a beryllium target. Changing the target material strongly impacts the target design, which is currently under study.

Another promising technique to further alleviate the impact of the photon content in the beam is to make the photon absorber crystalline. If the crystal axis is aligned with the direction of the incoming photons, the coherent effect of the crystal matrix promotes pair production, leading to an effective increase in the absorption length. A series of tests to this effect has been performed with a set of tungsten crystals at the CERN SPS in collaboration with the AXIAL collaboration [7]. A tungsten crystal of 10 mm thickness was targeted with a tagged photon beam. Between the off / on-axis orientations of the crystal the multiplicity of charged particles was found to be enhanced by a factor 1.5-2.2 in the range of 10-80 GeV photon energy, showing the aforementioned improvement. This result is preliminary; further analysis is in progress.

CONCLUSIONS & FUTURE PROSPECTS

The KLEVER project aims to measure BR($K_L \to \pi^0\nu\bar{\nu}$) at the CERN SPS. It is expected that this proposed experiment, together with the BR($K^+ \to \pi^+\nu\bar{\nu}$) measurement currently in progress at NA62, will result in significant input determining the validity of several possible models for new physics. The experiment also has the potential to independently verify and validate measurements of the CKM triangle. To aid in the design of the experiment, a series of simulations has been carried out to optimize various experimental parameters; with particular focus on the beamline. A baseline design for the K12 beamline for KLEVER has been laid out, utilizing a four-collimator system being to obtain the required neutral beam. The field orientations for the magnets following the collimators have been investigated and an optimal configuration has been found, giving rise to a background rate of 2.5 / 4.9 MHz of muons with $P > 1$ GeV/c at the UV / MEC. An investigation has also been made of the target used to derive the neutral beam. The rate requirement of less than 40 MHz of high energy photons sets the thickness of the absorber placed in the TAX. Investigations are currently ongoing to validate the use of a high-Z material for the target. Such a material would inhibit beam photon production at the source by promoting pair conversion. An additional possibility is to make the photon absorber crystalline, which would promote pair conversion further through coherent effects in the crystal matrix if the axis is aligned with the incoming photons. To this end, test beam studies have been performed and further analysis is ongoing. The KLEVER experiment is to take place in the period following the completion of NA62 data taking, currently expected to end with the advent of LS3. In the interim, detector development will continue, with construction of KLEVER potentially starting when NA62 is complete. In this case, it would be possible to start collecting data during LHC Run 4, in 2026.

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