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Searches for rare and forbidden kaon decays at the NA62 experiment at CERN

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The decay $K^+ \to \pi^+ \nu\bar{\nu}$ is highly suppressed in the Standard Model (SM), while its rate can be predicted with minimal theoretical uncertainty. The branching ratio (BR) for this decay is thus a sensitive probe of the flavor sector of the SM; its measurement, however, is a significant experimental challenge. The primary goal of the NA62 experiment is to measure BR($K^+ \to \pi^+ \nu\bar{\nu}$) with $\sim$10% precision. This will require the observation of 10^{13} K^+ decays in the experiment's fiducial volume, as well as the use of high-performance systems for precision tracking, particle identification, and photon vetoing. These aspects of the experiment will also allow NA62 to carry out a rich program of searches for lepton flavor and/or number violating K^+ decays. Part of the experimental apparatus was commissioned during a technical run in 2012; installation continues and data taking is expected to begin in late 2014. The physics prospects and the status of the NA62 experiment are reviewed.

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1 Introduction

The $K \to \pi\nu\bar{\nu}$ decays are flavor-changing neutral current (FCNC) processes that probe the $s \to d\nu\bar{\nu}$ transition via the Z-penguin and box diagrams shown in Figure 1. They are highly GIM suppressed and their Standard Model (SM) rates are very small. For several reasons, the SM calculation for their branching ratios (BRs) is particularly

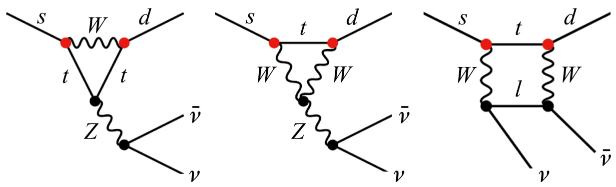

Figure 1: Diagrams contributing to the process $K \to \pi\nu\bar{\nu}$.

clean (see [1] for a recent review):

- The loop amplitudes are dominated by the top-quark contributions. The neutral decay violates CP; its amplitude involves the top-quark contribution only. Small corrections to the amplitudes from the lighter quarks come into play for the charged channel.
- The hadronic matrix element for these decays can be obtained from the precise experimental measurement of the K_{e3} rate.
- There are no long-distance contributions from processes with intermediate photons.

In the SM, $\text{BR}(K_L \to \pi^0\nu\bar{\nu}) = 2.43(0.39)(0.06) \times 10^{-11}$ and $\text{BR}(K^+ \to \pi^+\nu\bar{\nu}) = 7.81(0.75)(0.29) \times 10^{-11}$ [2]. The uncertainties listed first derive from the input parameters. The smaller uncertainties listed second demonstrate the size of the intrinsic theoretical uncertainties. Because of the corrections from lighter-quark contributions, these are slightly larger for the charged channel.

Because the SM rates are small and predicted very precisely, the BRs for these decays are sensitive probes for new physics. In evaluating the rates for the different FCNC kaon decays, the different terms of the operator product expansion are differently sensitive to modifications from a given new-physics scenario. If $\text{BR}(K_L \to \pi^0\nu\bar{\nu})$ and $\text{BR}(K^+ \to \pi^+\nu\bar{\nu})$ are ultimately both measured, and one or both BRs is found to differ from its SM value, it may be possible to characterize the physical mechanism responsible [3], e.g., a mechanism with minimal flavor violation [4], manifestations of supersymmetry [5], a fourth generation of fermions [6], Higgs compositeness as in the littlest Higgs model [7], or an extra-dimensional mechanism such as in the Randall-Sundrum model [8].

The decay BR($K_L \to \pi^0\nu\bar{\nu}$) has never been measured (the KOTO experiment at J-PARC [9] has a good chance of observing it). BR($K^+ \to \pi^+\nu\bar{\nu}$) was measured by Brookhaven experiment E787 and its successor, E949. The combined result from the two generations of the experiment, obtained with seven candidate events, is BR($K^+ \to \pi^+\nu\bar{\nu}$) $= 1.73^{+1.15}_{-1.05} \times 10^{-10}$ [10]. The purpose of the NA62 experiment at the CERN SPS is to measure BR($K^+ \to \pi^+\nu\bar{\nu}$) with a precision of about 10% in two-years' worth of data taking. Observation of $\sim$100 signal events will require a sample of 10^{13} K^+ decays within the geometrical acceptance of the experiment, for which the signal detection efficiency must be at least 10%. Then, for a measurement with 10% precision, the background level must be kept down to no more than about 10% of signal. This implies an overall background rejection factor of 10^{12}. The residual background level must also be determined to within about 10%.

2 The NA62 experiment

The experimental signature is a K^+ coming into the experiment and decaying to a π^+, with no other particles present. The first line of defense against abundant decays such as $K \to \mu\nu$ and $K \to \pi\pi^0$ (together representing about 84% of the total K^+ width) is to precisely reconstruct the missing mass of the primary and secondary tracks and reject events with $M^2_{\rm miss} \approx 0$ or $M^2_{\rm miss} \approx m^2_{\pi^0}$, assuming the secondary is a μ^+ or a π^+, respectively. However, the rejection power from kinematics alone is at best 10^4, and in any case, about 8% of K^+ decays (e.g., K_{e3}, $K_{\mu 3}$) do not have closed kinematics. The remainder of the experiment's rejection power must come from redundant particle identification systems and hermetic, highly-efficient photon veto detectors. The NA62 apparatus [11], schematically illustrated in Figure 2, was designed around these principles, which we now consider in turn.

Beamline and decay volume The experiment makes use of a 400-GeV primary proton beam from the SPS with 3×10^{12} protons per pulse and a duty factor of about 0.3. This is collided on a beryllium target at zero angle to produce the 75-GeV $\pm 1\%$ unseparated positive secondary beam used by the experiment. This beam consists of about 525 MHz of π^+, 170 MHz of p, and 45 MHz of K^+, for a total rate of 750 MHz. The beamline opens into the vacuum tank about 100 m downstream of the target. The vacuum tank is about 110 m long and fully encloses the four tracking stations of the magnetic spectrometer; the pressure inside is kept at a level of 10^{-6} mbar. The fiducial volume occupies the first 60 m of the vacuum tank (upstream of the spectrometer). About 10% of the K^+'s entering the experiment decay in the fiducial volume, corresponding to 4.5 MHz of K^+ decays.

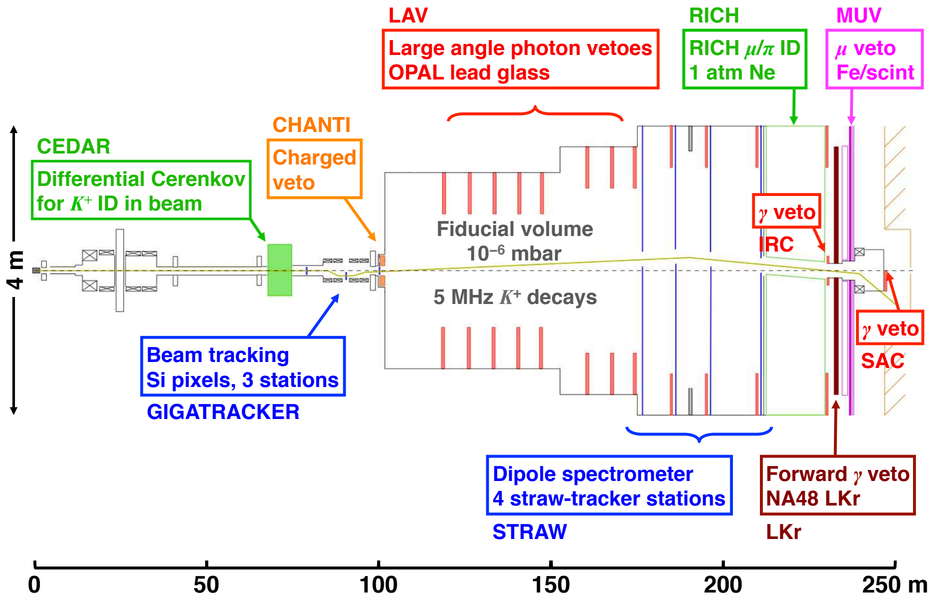

Figure 2: Schematic diagram of the NA62 experiment.

High-rate, precision tracking In order to obtain the full kinematic rejection factor of 10^4 for two-body decays, both the beam particle and the decay secondary must be accurately tracked.

The beam spectrometer [12] consists of three hybrid silicon pixel tracking detectors installed in an achromat in the beam line. Each detector consists of a 200-μm-thick monolithic sensor and 10 bump-bonded, 100-μm-thick readout ASICs. The pixel size is 300×300 μm^2, giving a momentum resolution $\sigma_p/p \sim 0.2\%$ and an angular resolution $\sigma_\theta = 16$ μrad. This beam-tracking system is referred to as the Gigatracker, because it will track the individual particles in the 750-MHz secondary beam.

The magnetic spectrometer for the secondary particles consists of four straw chambers operated inside the vacuum tank [13]. Each chamber has 16 layers of straw tubes arranged in 4 views. The straws are made from metalized, 36-μm-thick mylar ultrasonically welded along the seam. They are just under 10 mm in diameter and are 2.1 m long. With a 70% Ar–30% CO_2 gas mixture, the point resolution on a single view is $\sigma_x \leq 130$ μm. Considering that each chamber is only $0.45\,X_0$ thick, with the spectometer magnet providing a $p_\perp$ kick of 270 MeV, the momentum resolution for tracks is $\sigma_p/p = 0.32\% \oplus 0.008\%\,p$.

Redundant particle identification The principal PID challenge for single tracks is to reject $K \to \mu\nu$ decays with an inefficiency of less than 10^{-7} after the application of kinematic cuts. The bulk of NA62's π/μ separation capability is provided by the downstream muon vetoes (MUV). There are three MUV systems. MUVs 1 and 2 are iron/scintillator hadron calorimeters. These are used mainly for offline μ identification and provide a rejection factor of 10^5. MUV 3 is highly segmented and provides fast μ identification for triggering. It can veto μ's online at a rate of 10 MHz with a time resolution $\sigma_t < 1$ ns.

An additional two orders of magnitude in π/μ separation are provided by a large (3.7-m-diameter by 18-m-long) ring-imaging Cerenkov counter (RICH) [14] filled with neon gas at 1 atm ($p_{\rm thresh} = 12$ GeV for π). In addition to providing good π/μ discrimination over the entire fiducial momentum interval ($15 < p < 35$ GeV), the RICH measures the π crossing time with a resolution of 100 ps and contributes to the level-0 trigger.

Beam timing and PID Considering that the rates of primary and secondary tracks in the experiment are respectively about 750 MHz and 10 MHz, accurately matching the correct secondary track to the correct primary is a basic challenge for the experiment. Due to the effectively incorrect reconstruction of the primary, for mismatched events the missing mass resolution is worsened by a factor of three. Precise timing of the secondary can be obtained from the RICH ($\sigma_t \sim 100$ ps), while for the primary, the Gigatracker provides $\sigma_t \sim 150$ ps. Cerenkov identification of the kaons in the beam both provides a precise, redundant measurement of the beam particle's timing and reduces the effective beam rate from 750 MHz to 45 MHz, hence reducing the mismatch probability.

Such identification is provided by the CEDAR/KTAG, a differential Cerenkov counter based on the CERN CEDAR-W design [15]. One of the CEDAR-W detectors has been refurbished to run with H_2 at 3.85 bar and outfitted with a new, high-segmentation readout (KTAG). The beam identification from the CEDAR/KTAG is fundamental to the suppression of background from beam-gas interactions—without it, the vacuum in the decay tank would have to be kept at the level of 10^{-8} mbar.

With the help from the CEDAR/KTAG, the probability of mismatching the primary and secondary tracks is held below 1%. Nevertheless, events with mismatched tracks still account for half of the events not rejected by kinematics.

Hermetic photon vetoes Rejection of photons from π^0's is important for the elimination of many background channels. The most demanding task is the rejection of $K^+ \to \pi^+\pi^0$ decays. For these decays, requiring the secondary π^+ to have $p <$ 35 GeV guarantees that the two photons from the π^0 have a total energy of 40 GeV. If the missing-mass cuts provide a rejection power of 10^4, the probability for the photon vetoes to miss both photons must be less than 10^{-8}. The photon veto system consists of four separate subdetector systems. The ring-shaped large-angle photon vetoes (LAVs) are placed at 12 stations along the vacuum volume and provide coverage for decay photons with 8.5 mrad $< \theta <$ 50 mrad. Downstream of the RICH, the NA48 liquid-krypton calorimeter (LKr) vetoes forward (1 mrad $< \theta <$ 8.5 mrad), high-energy photons. A ring-shaped shashlyk calorimeter (IRC) about the beamline provides coverage for photons with $\theta < 1$ mrad, while further downstream, a small-angle shashlyk calorimeter (SAC) around which the beam is deflected completes the coverage for very-small-angle photons that would otherwise escape via the beam pipe.

In more than 80% of $K^+ \to \pi^+\pi^0$ events, both photons from the π^0 arrive at the LKr. In most of the rest of the events, one photon is on the LKr and one is in the LAVs. For kinematic reasons, the energies of the two photons are anticorrelated: in events with a photon in the LAVs, the energy of the photon in the LKr tends to be quite high. Given these considerations, in order to achieve the required π^0 rejection performance, the LAVs must have a maximum inefficiency of 10^{-4} for photons with $E > 200$ MeV, while the LKr must have a maximum inefficiency of 10^{-3} for photons with $E > 1$ GeV and 10^{-5} for photons with $E > 10$ GeV. The LAV detectors consist of rings of lead-glass blocks salvaged from the OPAL electromagnetic calorimeter barrel [16]. The detection efficiency of these blocks for 200 MeV electrons was measured at the Frascati BTF and found to be about $(1 \pm 1) \times 10^{-4}$. The LKr is a quasi-homogeneous ionization calorimeter of depth $27\,X_0$ and with a transverse segmentation of 2×2 cm^2 [17]. In NA48, $K \to \pi\pi^0$ and e^- bremsstrahlung events were used to demonstrate that the inefficiency of the LKr for detection of photons with $E > 10$ GeV is less than 8×10^{-6}.

Trigger and data acquisition The experiment makes use of an integrated trigger and data acqusition system with three trigger levels. The lowest level, level 0, is implemented directly in the digital readout card for each detector subsystem. The detector hits are resolved into quantities such as the number of quadrants of the trigger hodoscope hit, the number of LKr clusters of energy greater than a given threshold, or the number of hits in MUV 3. These quantities can then be used in trigger logic to decide which events will be read out for level 1. Level 0 will process about 10 MHz of "primitive" detector hits; about 1 MHz of events will be read out for level 1. The level 1 trigger is implemented in software running on dedicated PCs for each detector. It is the first asynchronous trigger level and will reduce the rate of events seen by level 2 by an order of magnitude. The level 2 trigger is implemented in the event builder running on the acquisition PC farm; it is the first trigger level at which the configurations of entire events are used. The O(100 kHz) of events input to level 2 are reduced to a few kHz of events ultimately written to disk.

Expected performance Based on the above considerations, the event selection criteria can be listed:

- One track with $15 < p_\pi < 35$ GeV and π identification in the RICH.
- No γ's in the LAVs, LKr, IRC, or SAC.
- No μ hits in the MUVs.

- One beam particle in the Gigatracker with K identification by the CEDAR.
- $z_{\rm rec}$, the vertex between primary and secondary tracks, inside the 60-m fiducial volume.

Simulations then indicate that the acceptance for signal events is a little more than 10%, corresponding to about 45 signal events accepted per year of data taking. The $\pi^+\pi^0$ background is estimated to be about 10% while the $\mu\nu$ background is around 3%. Including backgrounds from all other channels, the total background is under 20%.

3 Other rare kaon and pion decays at NA62

The measurement of BR($K^+ \to \pi^+\nu\bar{\nu}$) will require a sample of 10^{13} K^+ decays in NA62's fiducial volume. These will be accompanied by 2×10^{12} π^0 decays from $K \to \pi\pi^0$ (BR = 21%). Studies of the prospects for searches for lepton-flavor (LF) or -number (LN) violating and other forbidden decays with NA62 are underway. Preliminary estimates of the single-event sensitivties (defined as the reciprocal of the product of the number of accepted decays) give results at the level of 10^{-12} for K^+ decays to states such as $\pi^+\mu^\pm e^\mp$ (LFV), $\pi^-\mu^+e^+$ (LFNV), and $\pi^-e^+e^+$ or $\pi^-\mu^+\mu^+$ (LNV); and at the level of 10^{-11} for π^0 decays to $\mu^\pm e^\mp$ [18].

As a case in point, consider the decay $K^+ \to \pi^-\mu^+\mu^+$. This decay violates the conservation of lepton number. In analogy to the case of neutrinoless nuclear double beta decay, its observation would imply that the virtual neutrino exchanged between the μ^+'s annhilates itself—the neutrino must have a Majorana component. The most stringent limit on BR($K^+ \to \pi^-\mu^+\mu^+$) is from NA48/2 [19], and NA62's prospects for improving on this limit can be extrapolated from the NA48/2 experience. In a sample of 2×10^{11} $K^\pm$ decays, NA48/2 had 52 candidate events selected as $\pi^\mp\mu^\pm\mu^\pm$ for which $M(\pi\mu\mu) \sim m_K$. This was in excellent agreement with the Monte Carlo background estimate and gave the published result, BR($K^\pm \to \pi^\mp\mu^\pm\mu^\pm$) $< 1.1 \times 10^{-9}$ (90% CL). However, subsequent studies showed that the background consisted entirely of $K^\pm \to \pi^\mp\pi^\pm\pi^\pm$ events with two $\pi \to \mu$ decays, of which at least one was downstream of the spectrometer magnet and therefore poorly reconstructed. As it turns out, the increased $p_\perp$ kick of the NA62 magnet, together with the better invariant mass resolution of the straw-tube spectrometer, can eliminate this background altogether. It is then quite possible for NA62 to push the limit on this BR all the way down to its single-event sensitivity of order 10^{-12}.

Besides the LFV π^0 decays, there are a number of rare or forbidden π^0 decays to which NA62 has potential sensitivity, including $\pi^0 \to 3\gamma$, $\pi^0 \to 4\gamma$, and $\pi^0 \to e^+e^-e^+e^-$ [18].

One interesting prospect is to examine $e^+e^-\gamma$ final states of π^0 decays for evidence for a new, light vector gauge boson with weak couplings to charged SM fermions, a so-called U boson, or "dark photon". A hypothetical U boson could mediate the interactions of dark-matter constituents, as such providing explanations for various unexpected astrophysical observations and the results of certain dark-matter searches, and could also explain the $> 3\sigma$ discrepancy between the measured and predicted values for the muon anomaly, a_μ (see e.g. [20, 21]). A U boson with a mass of less than $m_{\pi^0}/2$ might be directly observable in $\pi^0 \to U\gamma$ decays with $U \to e^+e^-$. Using an appropriate trigger, NA62 may collect $\sim 10^8$ $\pi^0 \to e^+e^-\gamma$ decays per year. Moreover, NA62 has good invariant-mass resolution for the ee pair—about 1 MeV even before any attempt at kinematic fitting. Thus, NA62 should be quite competitive in this search.

Another possibility is to search for the invisible decay of the π^0. The least exotic decay to an invisible final state is $\pi^0 \to \nu\bar{\nu}$. This is forbidden by angular-momentum conservation if neutrinos are massless; for a massive neutrino ν of a given flavor and mass $m_\nu < m_{\pi^0}/2$ with standard coupling to the Z, the calculation of the decay rate is straightforward. The experimental signature $\pi^0 \to$ invisible could also arise from π^0 decays to other weakly interacting neutral states. Experimentally, the process $K^+ \to \pi^+\pi^0$ with $\pi^0 \to$ invisible is very similar to $K^+ \to \pi^+\nu\bar{\nu}$, with the important difference that in the former case, the π^+ is monochromatic in the rest frame of the K^+. This means that there is no help from kinematics in identifying $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma\gamma$ with two lost photons—the limit on BR($\pi^0 \to$ invisible) essentially depends on the performance of the photon vetoes. With stringent track-quality cuts for the π^+ and additional cuts in the $(p_{\pi^+}, \theta_{\pi^+})$ plane to deselect events with low-energy, large-angle photons, the π^0 rejection can be increased by perhaps a factor of ten with respect to the NA62 baseline rejection of 10^{-8}. Then, NA62 would have the potential to set a limit on BR($\pi^0 \to$ invisible) of $\sim 10^{-9}$, which is about 100 times better than present limits.

4 Outlook

As of October 2013, the CEDAR/KTAG, almost all of the LAV system, the new LKr readout, and the SAC are installed or under installation. The remainder of the detectors are under construction. The experiment will be ready to take data in the fall of 2014. A first period of data taking during the months of November and December is expected to net the first 10% of the NA62 data set. The remainder of the data will be collected in long runs in 2015 and 2016. Collection of the full data set will permit the measurement of BR($K^+ \to \pi^+\nu\bar{\nu}$) to within about 10%, which should help to shed light on the flavor structure of any new physics discovered at the LHC, or which may provide evidence for new physics even in the absence of such discoveries. NA62 is also well adapted to search for other rare decays of the K^+ and π^0, with single-event BR sensitivity at the level of 10^{-12} for lepton-flavor or -number violating decays and competitive prospects in related searches.

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