Future charged kaon decay experiments

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Future experiments aiming to perform precise measurement of rare kaon decays are briefly reviewed; in particular those experimental programs designed to gain new insight on the Unitarity triangle and on the CKM mechanism by observing an hundred of events of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay are considered. This rare process, BR $\sim 10^{-10}$, is computed with very small theoretical errors, providing one of the cleanest tests of the Standard Model (SM) and, possibly, it could give some hints on the flavour structure of New Physics. A target accuracy of order 10% should be reached, thus making experiments in this field very challenging projects, expecially with respect to backgrounds suppression, particle identification capabilities and detector efficiency, while keeping costs and complexity at a reasonable level.

1. Introduction

The reason for the great interest for the rare decays $K \to \pi\nu\bar{\nu}$ is that these branching ratios can be predicted, in the various theoretical models, with very small errors since they are dominated by short-distance contributions. At the quark level the transition is $s \to d\nu\bar{\nu}$, that mainly proceeds through Z^0 penguin and box diagrams. The decay amplitude is completely dominated by the c and t quarks contributions [1], and the adronic matrix elements between the kaon and the pion can be precisely derived from the well measured $K^+ \to \pi^0 e^+ \nu$ decay by using the isospin symmetry [2].

The precise measurement of the two decay modes branching fractions gives a very interesting test of the SM, since it provides a determination of the lower right corner of the unitarity triangle from loop processes, completely independent from the B sector (Fig. 1). The theoretical error is currently at the level of a few percent and should improve by using NNLO calculations in the next years, so that the target accuracy for any experiment should be in the range of 10% or better. Finally, these decays can give important indications on the flavour structure of New Physics, since any modification to the SM would give some contribution, ranging from 10-20% in MSSM [3], up to 50% in Minimal Flavour Violation models [4].

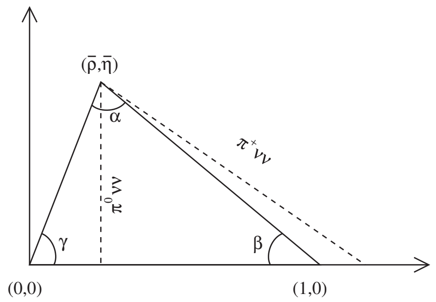

Figure 1. Unitarity triangle in the $[\bar{\rho}, \bar{\eta}]$ plane: the right corner can be completely determined by the BR($K^+ \to \pi^+ \nu\bar{\nu}$) and BR($K_L \to \pi^0 \nu\bar{\nu}$).

The only experimental observation of the K^+ mode by the BNL-E949 experiment [5], obtained with the stopped kaon technique and through the complete reconstruction of the decay chain, gives a value higher than the SM expectation, even though with a large error since only three signal events have been counted:

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (14.7^{+13.0}_{-8.3}) \times 10^{-11}.$$

For what illustrated above, any new experiment should observe $\mathcal{O}(100)$ events in order to obtain a real improvement.

2. Future experiments proposals

One very elegant possibility would be to repeat a **stopped kaon experiment** in which the full kinematics of the π^+ is measured (momentum, energy and range), the full $\pi \to \mu \to e$ chain is reconstructed and all additional photons are vetoed by dedicated detectors. In order to achieve a much larger statistics with respect to the BNL experiment, it has been proposed to use an improved version of the E949 apparatus at the J-PARC facility in Jaeri, Japan [6]. Unfortunately, a dedicated kaon beam-line is not currently foreseen in the first phase of the J-PARC complex, so that this project could not possibly start before an upgrade of the accelerator facility.

The other possibility is to observe the **kaon decays in-flight**; in this case one of the major experimental difficulties is that the pion is the only observable particle in the final state, so that the kaon momentum as well as the pion momentum should be measured by two separate spectrometers. Under the hypothesis that the observed charged particle in the final state is indeed a π^+ and that the decaying particle is a K^+, the missing mass squared m^2_{miss} can be built from the measured p_K, p_π and $\theta_{K\pi}$ and then the m^2_{miss} can be used as discriminant between the signal and the – largely dominant – background decays. The signal and the three main background decays m^2_{miss} distributions are shown in Fig. 2. However, additional rejection power from veto detectors is mandatory in order to reach a significant signal-to-noise ratio, both against not kinematically constrained background (that amounts to the 8% of the total) and against residual $K^+ \to \pi^+\pi^0$ and $K_{\mu 2}$ decays.

Obviously, an important point is that the initial kaon is either separated from the primary hadron beam or positively identified. This has an important impact on the overall project, since on one side the cost of a **separated beam** would be a large fraction of the total budget, while on the other side, an **unseparated beam** implies a much more intense primary hadron flux and the presence of a $p/K^+/\pi^+$ separation detector. In the latter case, an high-momentum for the kaon is also desirable, since the separation of different

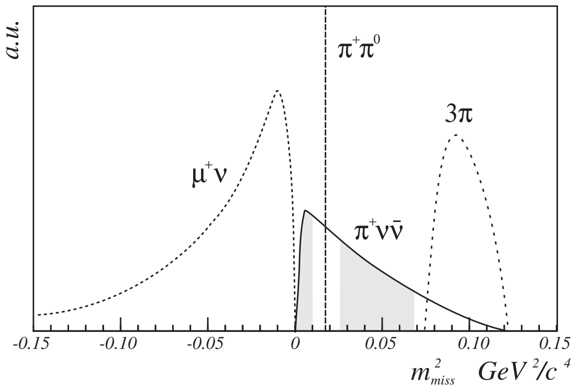

Figure 2. Distribution of m^2_{miss} for the signal decay $K^+ \to \pi^+\nu\bar{\nu}$, and the main background decays $K^+ \to \mu^+\nu$, $K^+ \to \pi^+\pi^0$ and $K^+ \to \pi^+\pi^+\pi^-$.

species generally improves at high momenta. A number of proposals using the in-flight technique has been put forward in the last years.

The CKM proposal [7] is a very ambitious experimental program for measuring at least 100 SM events, using part of the KTeV apparatus (in particular the CsI crystal calorimeter) in a new separated 30 GeV/c kaon beam at Fermilab.

Even if this project has been canceled by US funding agencies, it has seeded a number of important R&D studies, in particular on the possibility of realizing photon veto detectors excellent detection inefficiency at high energies (above about 1 GeV) [9]. A revised proposal for using a downgraded detector and an unseparated hadron beam, in order to reduce the overall costs, (Kplus) [8], has also been rejected.

A proposal of using part of the NA48 apparatus and an high-intensity kaon beam produced by the CERN SPS 400 GeV/c protons, aiming to measure $\sim$ 80 SM events per year with a 10% background, has been recently put forward (P326) [10]. The proposal is to produce a 75 GeV/c not separated kaon beam: limiting the pion momentum to 35 GeV/c, so that at least 40 GeV of electromagnetic energy is deposited in the photon vetoes, the $\pi^+\pi^0$ background decay is greatly reduced. Measuring the kaon and pion momenta, a kinematical selection identifying – mainly – signal events can be performed using the missing mass distribution (as shown in Fig. 2). In particular, excluding the region around the $\pi^+\pi^0$ peak, the signal can be selected by:

$$0 < m^2_{miss} < m^2_{\pi 0} - (\Delta m)^2,$$

$$m^2_{\pi 0} + (\Delta m)^2 < m^2_{miss} < \min m^2_{miss}(3\pi) - (\Delta m)^2,$$

and the overall acceptance is determined by the missing mass resolution $(\Delta m)^2$. Assuming a 0.3% momentum accuracy for the K spectrometer, at least of 1% for the π spectrometer at high momenta, and an angular resolution of order 50 μrad, a missing mass resolution of about $(\Delta m)^2 = 8 \times 10^{-3}$ GeV$^2/c^4$ can be achieved, leading to an acceptance at the level of 16%. In addition, in order to correctly match the mother and daughter tracks in the two spectrometers, very stringent requirements on the time resolution are needed. A good time response is also mandatory for the K spectrometer, due to the very high rate, in order to reduce dead time and pile-up effects.

Primary kaons should also be positively identified, by means of a Cherenkov differential counter, since the useful fraction of the primary unseparated hadron beam is only ≈1/17. Both the Cherenkov and the beam spectrometer should then be capable of efficient operation in a huge particle flux (0.8 GHz total rate, 60 MHz/cm^2 in the core area). The main requirements for the downstream spectrometer, tracking the pion in the final state, are the minimum material budget and the redundancy in order to reduce the non-Gaussian tails in the reconstruction resolution.

In order to suppress the kinematically irreducible background and to futher suppress events surviving the kinematical selection, efficient and hermetic photon vetoes and muon identification capabilities are needed. In particular a large RICH counter is foreseen in the P326 project in order to achieve a good π/μ separation in a wide momentum range. In addition, the dead time of all veto detectors should be kept under control in order to reduce the probability of fake events with a pion and missing energy.

All these detector elements are shown in the proposed layout, in Fig. 3.

A very intense kaon beam can be obtained with minor modifications to the beam-line used by NA48, while the requirements on the detector elements listed above are much more challenging and have stimulated an intense R&D activity on new detectors, in particular in order to establish a number of critical issues:

- track a $\sim$ 1 GHz rate of primary hadrons with a low-mass, fast and high-resolution detector, in particular realized with Silicon pixel technology with integrated fast readout (Gigatracker);

- track the charged decay products with a low-mass, high-efficiency spectrometer with good momentum resolution, in particular using straw tubes chambers operated in a high vacuum, i.e. a very innovative technique, never employed in large-scale experiments;

- identify photons in the final state with excellent efficiency, in order to reject the abundant $\pi^+\pi^0$ background at the level of 10^{-8}, by making use of several detector elements for maximizing the angular acceptance: the NA48 liquid Kripton quasi-homogenous calorimeter, a set of new photon veto detectors all along the decay region at larger angles, up to 50 mrad, and small angle calorimeters capable of closing the acceptance gap around the axis, realized using lead/scintillator sandwich detectors and wave-lenght shifting fibers readout;

- separate muons from pions, in order to reject the huge $K_{\mu 2}$ background, with excellent time resolution, good purity/efficiency and in a wide kinematical range, in particular employing a large volume, gas RICH detector.

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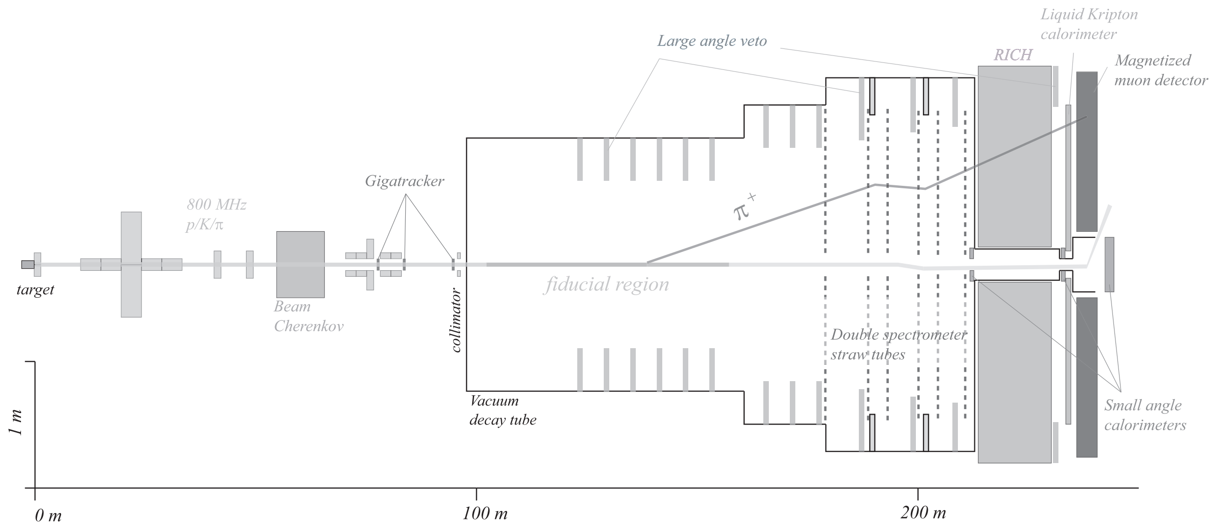

Figure 3. Layout of the P326 proposal at the CERN SPS for the measurement of BR($K^+ \to \pi^+\nu\bar{\nu}$). The various detector elements of the experiment are shown (see text). Notice the very compressed horizontal scale.

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