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Expression of Interest to Measure Rare Kaon Decays at the CERN SPS

NA48-Future Working Group

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1 Introduction

We are investigating the possibility to measure very rare kaon decays at the CERN SPS. The physics motivation is given in Section 2. We are reviewing opportunities to study rare decays of both charged and neutral kaons. We concentrate first on the charged kaon because we are not limited by the current proton intensity that can be delivered by the SPS on the T10 target. The aim of this document is to outline our ideas in view of the upcoming Villars meeting which will take place in September. We are performing a feasibility study for an experiment able to collect about 50 $K^+ \to \pi^+\nu\bar{\nu}$ events with a signal to background ratio of 10:1 in about two years of data taking (NA48/3). The two undetectable neutrinos in the final state require the design of an experiment with redundant measurement of the event kinematics and hermetic vetoes to achieve the necessary background rejection. Particular care has to be taken to suppress the two body decays $K^+ \to \pi^+\pi^0$ and $K^+ \to \mu^+\nu$ which have branching ratios up to 10^{10} times larger than the expected signal. The reconstruction of the two body kinematics may suffer from reconstruction tails and backgrounds can originate if photons from $K^+ \to \pi^+\pi^0$ are not detected or if muons from $K^+ \to \mu\nu$ are mis-identified as pions. To suppress backgrounds from the two body decays, kinematics and particle identification have to be used in conjunction.

We plan to use 400 GeV/c protons from the SPS to perform the experiment. The advantage of using a high energy proton machine such as the SPS is two-fold: on the one side, the cross sections to produce kaons increases as a function of proton energy so that to achieve the same kaon flux one needs less protons thus reducing the non-kaon-related accidental activity. In addition, the higher kaon energy leads to easier photon detection which simplifies the suppression of the backgrounds originating from $K^+ \to \pi^+\pi^0$: for example, employing a 75 GeV/c kaon beam and limiting the momentum of the reconstructed π^+ to 40 GeV/c, there are at least 35 GeV of electro-magnetic energy from the π^0 deposited into the photon vetoes. This reduces significantly the probability that both photons from the π^0 decay are left undetected because of photonuclear reactions. The disadvantage of employing high energy protons and, consequently, high energy secondary beams, is that the pions and the protons cannot be efficiently separated from kaons. The consequence is that the upstream detectors which measure the momentum and the direction of the kaons are exposed to a particle flux about 17 times larger than the useful (kaon) one. It is important to point out that the magnetic spectrometers placed downstream of the decay region do not suffer from the same limitation because:

1. The protons and the undecayed kaons and pions are kept in a vacuum beam-pipe that crosses the spectrometers.
2. The muons from pion decays stay in the beam-pipe without illuminating the drift chambers because of the small transverse momentum released by the pion decay.

In section 3 the kaon beam will be briefly described. As already mentioned, the experiment is not limited by the amount of protons that can be delivered by the SPS. We assume a duty cycle of the SPS similar to the one available during the 2003 data taking. There are several challenging aspects for this experiment. They include:

- Perform tracking at 1 GHz total rate, ~ 40 MHz/cm^2, within a minimal material budget, minimal detector dead-time, and excellent time resolution.

- Achieve positive kaon identification in a high rate environment by means of a differential Cherenkov counter insensitive to pions and protons with minimal accidental mis-tagging.
- Construct and operate hermetic photon vetoes to provide a π^0 rejection in excess of $\sim 10^7$.
- Achieve a muon rejection of at least 10^5.
- Perform redundant measurement of the momentum of the in-coming K^+ and out-coming π^+ for suppression of the tails in the reconstruction of the missing mass for two body decays.
- Veto the charged particles coming from kaon decays contained in the area covered by the beam.
- Minimise the accidental activity from non-kaon decays (e.g. muons from the proton dump and tracks coming from pion and kaon decays occurring upstream of the decay region).

We assume to use as much as possible of the NA48/2 detectors and infrastructure to keep the cost of the new experiment reasonable. However, significant upgrades are needed. To plan for these upgrades, we have started a quite detailed simulation of the new experiment and we need to validate it with experimental data that can be collected using the current K12 (NA48/2) beam with some dedicated data taking in 2004. In particular, the intensity of the current beam could be increased in 2004 by a significant factor to allow one to test a MICROMEGAS-type beam detector in the rate conditions foreseen for the new experiment. This intense beam will also allow us to evaluate whether it will be possible to employ the current NA48/2 magnetic spectrometer in the new experiment. Unfortunately most of these tests are incompatible with the normal data taking of NA48/2 and extra beam time has to be scheduled. An overview of the tests planned during 2004 is given in section 5 where we motivate the beam request in more detail.

It is important to place this initiative in the world contest. So far the study of the decay $K^+ \to \pi^+\nu\bar{\nu}$ has been performed with kaon decays at rest. BNL-AGS-E787 has collected data from 1995 until 1998 and has published [1] a measurement of the branching ratio $\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = 1.57^{+1.75}_{-0.82} \times 10^{-10}$ based on two events interpreted as signal. The follow-up experiment BNL-AGS-E949 [2] has collected data in 2002 and plans to collect more data in the future to possibly reach 10 signal events. Plans to further pursue the decay-at-rest technique at the J-PARC have been expressed [3]. As far as decay-in-flights are concerned, the CKM [4] Collaboration has proposed an experiment to measure 100 $K^+ \to \pi^+\nu\bar{\nu}$ at the Fermilab Main Injector. The design emphasises the separation of the pions and of the protons from the kaons in the beam. The experiment was not ratified by the HEPAP P5 sub-panel because of cost reasons. The proponents are trying to reduce the cost of the experiment preserving as much physics potential as possible. For such important measurements, to have independent experiments is quite important as we learned, for example, from the ϵ'/ϵ experience.

2 The $K \to \pi\nu\bar{\nu}$ decays

The rare decays $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ are extremely attractive: they offer unique opportunities for testing the Standard Model and deepening our knowledge of the CKM matrix. For a recent review with extensive references of these decays and of the CKM matrix in general, see [5].

At the quark level the two processes arise from the $s \to d\nu\bar{\nu}$ process, which originates from a combination of the "Z" penguin — the first two graphs in fig. 1 — and a double W exchange, the third graph.

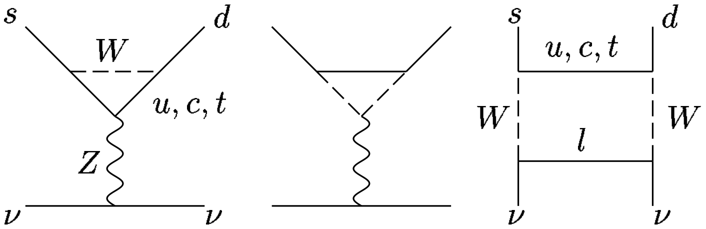

Figure 1: Graphs for $s \to d\nu\bar{\nu}$

In these graphs the *u,c,t* quarks appear as internal lines, but the top quark contribution dominates, with a smaller contribution, in the case of the $K^+ \to \pi^+\nu\bar{\nu}$ decay, from the charm quark. The up-quark contribution is in both cases negligible, so that $s \to d\nu\bar{\nu}$ is essentially a short distance process, well described by a Fermi-like coupling:

$$\mathcal{H}_{eff} = \sum_{l=e,\mu,\tau} \frac{G_l}{\sqrt{2}} (\bar{s}d)_{V-A} (\bar{\nu}_l \nu_l)_{V-A} \ , \tag{1}$$

where G_l is the effective coupling constant*. Given G_l, the branching ratios are directly related by isospin to that of the K^+_{e3} decay,

$$B(K^+ \to \pi^+ \bar{\nu}\nu) = 6 r_{K^+} B(K^+ \to \pi^0 e^+ \nu) \frac{|G_l|^2}{G_F^2 |V_{us}|^2} \tag{2}$$

$$B(K^0 \to \pi^0 \bar{\nu}\nu) = 6 \frac{\tau_{K_L}}{\tau_{K^+}} r_{K_L} B(K^+ \to \pi^0 e^+ \nu) \frac{(\mathrm{Im}\, G_l)^2}{G_F^2 |V_{us}|^2} \tag{3}$$

$r_{K^+} = 0.901$ and $r_{K_L} = 0.944$ are isospin breaking corrections [6] that include phase space and QED effects. The effective coupling constant G_l can be expressed as the sum of two contributions, the first arising from an internal top-quark line, the second from a charm quark,

$$G_l = \frac{\alpha\, G_F}{2\pi \sin^2 \Theta_W} \left[V^*_{ts} V_{td} X(x_t) + V^*_{cs} V_{cd} X^l_{NL} \right] \tag{4}$$

where $x_t = m_t^2 / M_W^2$. The X coefficients have been computed including the leading QCD corrections [7] [8]. The top quark contribution is precisely known, the main source of error arising from the uncertainty in the value of the t mass. The smaller contribution from the c-quark is affected by a larger error.

Averaging over the three neutrino species, the authors of ref. [5] quote the result

$$P_0(X) = \frac{1}{\lambda^4} \left[\frac{2}{3} X^e_{NL} + \frac{1}{3} X^\tau_{NL} \right] = 0.42 \pm 0.06\ . \tag{5}$$

which is reflected in a theoretical error of $\sim 5 \div 7\%$ on the determination of V_{td}. This makes the $K^+ \to \pi^+ \nu\bar{\nu}$ one of the most attractive tools for the exploration of the unitarity triangle, a member of a very short list of theoretically clean processes.

To evaluate the importance of eqs. (2), (3) and (4), we recall the composition of the CKM matrix in the popular Wolfenstein parametrization [9], whose accuracy is fully sufficient for the present discussion†. The parameters A, λ can be defined to be positive.

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\varrho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \varrho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4) \tag{6}$$

Comparing with eq. (4), we see that the charm quark contribution to G_l depends from the well determined elements V_{cd}, V_{cs}, and that this term is (in this approximation) a real

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*There is a small difference between the couplings for ν_τ and $\nu_{e,\mu}$ Taking for G_l the average of the three implies a negligible (0.2%) error on the rates.

†As discussed in ref. [5], the final analysis would use a more exact parametrization and the modified Wolfenstein parameters $\bar{\rho} = \rho(1 - \lambda^2/2)$ and $\bar{\eta} = \eta(1 - \lambda^2/2)$.

number, so that it will not contribute to the $K_L \to \pi^0\nu\bar{\nu}$ decay. The theoretical prediction for this process is thus inherently cleaner than that for $K^+ \to \pi^+\nu\bar{\nu}$.

Since in our approximation $V_{ts} = -V_{cb}$, and the latter is accurately determined from semi-leptonic B decays, $|V_{cb}| = (41.5 \pm 0.8)10^{-3}$, a measurement of the branching ratios for the two decays leads to a determination of V_{td}, i.e of the Wolfenstein parameters ρ, η that define the "unitarity triangle", which is central to the analysis of the CKM matrix.

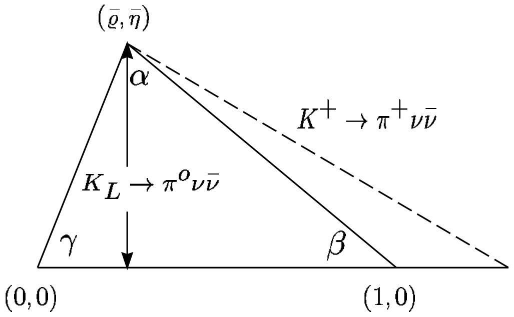

Figure 2: The unitarity triangle; the dashed line represents the measurement of $K^+ \to \pi^+\nu\bar{\nu}$.

At present the β angle (Fig. 2, from ref. [10]) has been accurately determined in B-factory experiments through the CP violation in $B \to \psi K^0$ decays, a process which allows for a very clean theoretical analysis. The length of the right-hand side of the triangle is determined by the analysis of $B^0\bar{B}^0$ oscillations, whose theoretical interpretation requires lattice QCD.

The rate of $K^+ \to \pi^+\nu\bar{\nu}$ determines the absolute value of G_l, which is represented by the dashed segment in fig. 2. The displacement from 1 of the lower extremity of this segment is due to charmed quark contributions. A measurement of this rate would offer a valid alternative to the measurement of $B^0\bar{B}^0$ oscillations, but with different, possibly smaller, theoretical uncertainties. Combining the measurement of $K^+ \to \pi^+\nu\bar{\nu}$ with the existing data on β and $B^0\bar{B}^0$ oscillations offers (ref. [11]) a significant test of the Standard Model.

The rate of $K_L \to \pi^0\nu\bar{\nu}$ offers a direct measurement of η, the height of the unitarity triangle. Its detection and measurement would establish the second example of direct CP violation after the measurement of ϵ'/ϵ in the K^0 system, but with the advantage of a very clean theoretical analysis [12].

The rates of $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ offer an accurate determination of the unitarity triangle, which is completely independent from that executed within the B system. As an added enticement, $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ are second order weak interaction processes, which probe the short distance behavior of the Standard Model, and could be sensitive to new physics. An analysis of possible post-Standard Model scenarios is given in ref [11].

3 Beam design

A tentative layout of a high-acceptance, small momentum-bite (75.0 ± 0.7 GeV/c) K^+ beam for a possible future $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ experiment (NA48/3) has been studied. The beam is derived from the existing target station T10 along the present K12 beam line of length 102.0 m to the exit of the final collimator. It features large-acceptance, radiation-resistant quadrupoles, a front-end achromat for momentum definition, a beam cleaning stage and a parallel section. The parallel session incorporates a CEDAR differential Cerenkov counter to tag the K^+, and a second achromat accommodating 3 KABES tracking stations. For the measurement of the decay π^+, the last 12 m section of the NA48 decay-vacuum tank (blue tube) has been replaced by an additional magnetic spectrometer comprising 3 Wire Chambers (WC1, WC2, and WC4) before and after of a (new) MNP33-1 magnet, followed by a second spectrometer comprising WC3, WC5, and WC6 and the present MNP33-2 magnet. The magnets give P_T-kicks of ±210MeV/c (deflecting the beam by ±2.8mrad.), respectively, resulting in a $\sim$ 35 mm parallel displacement inside the beam tube. Small Angle PHoton Veto counters with radial coverage of, respectively, $40 < r < 90mm$ (SAPHV1 and $r < 90mm$ (SAPHV2) are shown in front of the Kevlar window and at the end of the hall. A beam deflecting (≈10 mrad) magnet (MBPL101245) is installed in place of the NA48 hadronic calorimeter. A comparison between the current NA48/2 beam and the future one is given in table 3.

4 Detector

The detector elements are listed here together with a very brief description of their specifications.

- CEDAR

  A Differential Cherenkov counter (CEDAR) placed on the incoming beam and sensitive only to kaons. The purpose of the CEDAR is to positively identify a kaon. This is important because only a small fraction of the incoming beam particles are kaons. A pion undergoing a scattering in the residual gas contained in the decay tank may be mistaken as signal if no other visible particles are produced in the process. CEDAR

Beam	Present K12 (NA48/2)	New High Intensity K^+ (NA48/3) > 2006	Factor w.r.t. 2004
SPS protons per pulse	1×10^{12}	3×10^{12}	3.0
Duty cycle (s / s)	4.8 / 16.8	same	1.0
Beam Acceptance H,V (mrad)	± 0.36	± 2.4, ± 2.0	
Solid Angle (μsterad)	$\simeq 0.40$	$\simeq 16$	40
Average K^+ Momentum	60	75	$K^+ : 1.50$
$< P_K >$ (GeV/c)			$\pi^+ : 1.35$
			Total: 1.35
Momentum band ΔP_K GeV/c	63-57 = 6	76.1-73.9=2.25	$\simeq 0.375$
Eff.:$\Delta P/P$ (%)	± 5	± 1.5	$\simeq 0.3$
RMS:$\Delta P/P$ (%)	$\simeq 4$	$\simeq 0.95$	$\simeq 0.25$
Beam size (cm)	± 1.5	± 2.5	
Area at KABES (cm^2)	$\simeq 7$	$\simeq 20$	$\simeq 2.8$
Divergence: RMS (mrad)	$\simeq 0.05$	$\simeq 0.1$	$\simeq 2$
Decay fid. length (m)	50	50	
(τ_{K^+})	0.11	0.09	0.8
Beam flux/pulse: p ($\times 10^7$)	0.86	49	
K^+	0.31	15	50 ($\simeq 30$)
π^+	3.32	150	45 ($\simeq 27$)
e^+	0.95	35	
Total per pulse ($\times 10^7$)	5.5	250	$\simeq 45$ ($\simeq 27$)
Rate (3s eff. spill length) (MHz)	18	800	$\simeq 45$ ($\simeq 27$)
Rate @KABES (MHz/cm^2)	2.5	40	$\simeq 16$ ($\simeq 10$)
Effective running time/yr (days)	1/2 × 120	2/3 × 90	
(pulses)	3.1×10^5	3.1×10^5	1.0
K^+ decays per year	1.0×10^{11}	$\mathbf{4} \times 10^{12}$	$\simeq 40$
Events/year		20	
(BR= 10^{-10} accept. = 5%)			

Table 1: A comparison between the current NA48/2 beam and the future one. The figures in brackets in the last column refer to increase in rate with respect to the sum of the positive and negative NA48/2 beams.

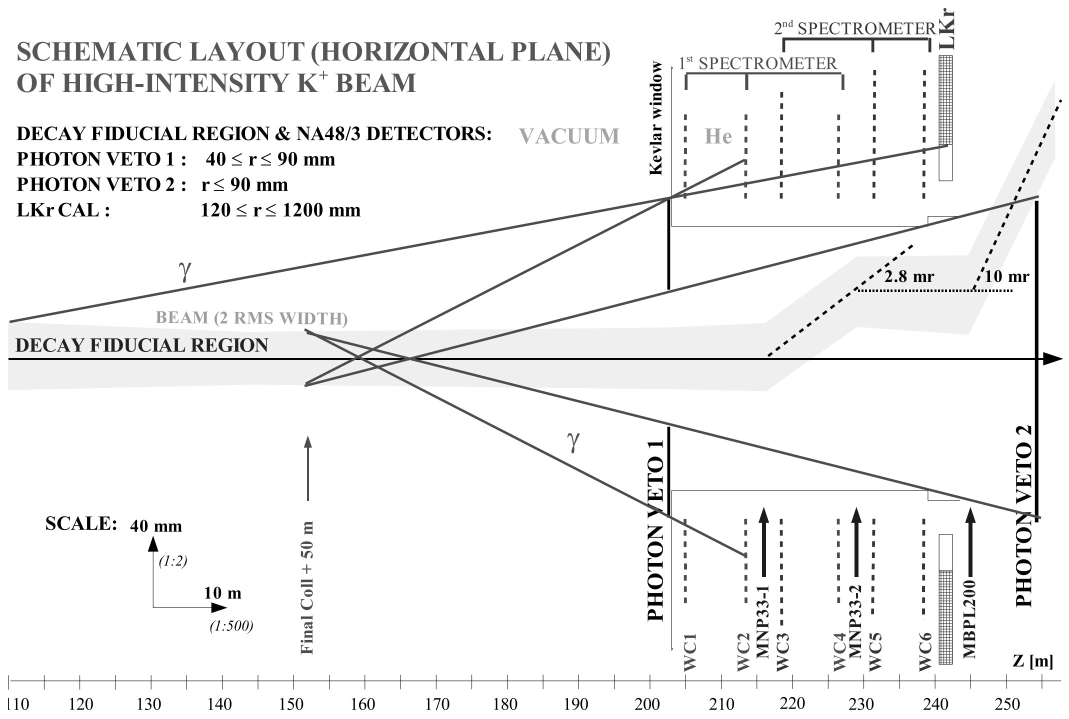

Figure 3: Beam layout incorporating Small Angle PHoton Vetoes

counters were built for use at the SPS. The counter is crossed by a rate of particles up to 1 GHz. However, exploiting the dependence of the Cherenkov angle as a function of particle speed, Cherenkov photons originating from pions can be blocked by a diaphragm and do not reach the photo-detectors. Cherenkov photons originating from protons miss the photo-detectors as well. The amount of kaons is about 6% of the beam intensity, so for a 1 GHZ unseparated rate, the counter should run at about 60 MHz. The divergence of the beam cannot exceed 0.1 mrad. Details concerning the CEDAR can be found in [13]. We understand that a CEDAR detector is being prepared for a possible test in the M2 (COMPASS) beam-line later this year. If the test takes place, we are certainly interested to participate in order to gather as much experience as possible and to evaluate the modifications to the front-end that may be needed to run at the NA48/3 beam intensities.

- KABES

  A KAon BEam Spectrometer (KABES) to reconstruct the momentum of the kaon and its direction. The design comes from the NA48/2 experience where MICROMEGAS-type chambers read-out in TPC mode have achieved excellent performance [14]. This can be combined with a Si pixel detector with sub-nanosecond time resolution. In NA48/3 KABES has to be able to perform the tracking of a 1 GHz hadron beam (about 10 times more intense -per unit area- than the combined positive and negative beams of NA48/2), providing an angular resolution of about 15 μrad and a momentum resolution of about 1% or better. Any effort has to be made to:

  - Shorten the detector signal employing a micro-mesh with thinner amplification gap.
  - Significantly improve the time resolution which is currently 650 ps.
  - Reduce the double pulse resolution sampling each strip continuously by means of 1 GHz FADC.
  - Consider a smaller micro-strip pitch.

  Another aspect that has to be taken into account is the space charge effect due to ion build-up. The design of the experiment relies on the KABES detector to function at the specified rate. This has to be validated as soon as possible. Fortunately many of these aspects, and notably the FADC read-out and the micro-mesh with thinner amplification gap, can already be tested this year (2004) using the NA48/2 setup.

- ANTI

  A set of ring-shaped anti-counters surrounding the vacuum tank and providing full acceptance for photons originating from the decay region with angles larger than 10 mrad. NA48/2 is equipped with photon vetoes with the appropriate coverage. It remains to be seen whether the photon detection efficiency of these counters based on a sandwich of thick iron and plastic scintillator plates is enough for the new experiment.

- DCH

  A double magnetic spectrometer to measure the direction of the out-coming pion and its momentum and to provide a redundant measurement of the latter. A Chinese copy of the MNP33 dipole magnet which is currently employed by NA48/2 will be required. The NA48 spectrometer is formed by 4 large drift chambers. Their behavior at the aon decay intensity proposed for the new experiment ($\simeq$ 10 MHz) has to be tested. Two new chambers need to be built. The possibility to build a tracking station and to install and operate it in vacuum upstream of the kevlar window in order to reduce the effect of the multiple scattering and improve the angular resolution is being evaluated.

- CHOD

  A plastic scintillator hodoscope for triggering and precise timing of the charged track.

- LKr

  A high-performance electromagnetic calorimeter acting as photon veto between in the angular region between 1.0 and 10.0 mrad. The baseline option is to re-use the NA48 Liquid Krypton Calorimeter (LKr) with properly updated electronics.

- HAC

  An hadronic calorimeter to strengthen the particle identification capability. As pointed out in the beam section, the space currently occupied by the NA48 Hadron Calorimeter is reserved, in the current layout of NA48/3, for a beam deflecting magnet. Solutions to incorporate hadron calorimetry in the limited longitudinal space have to be studied.

- MUV

  A muon veto system capable of identify muons with inefficiencies smaller than 10^5. The design of the muon veto detector is complicated by the presence of the beam deflecting magnet and it is still under discussion.

- SAPHV1 and SAPHV2

  Two small angle photon vetoes covering the region of the beam-pipe which is crossing the magnetic spectrometer.

- CHV

  A charged veto to provide hermetic coverage for charged particles coming from kaon decays and occupying the beam region.

5 Beam Request for 2004

It is of the uttermost importance to test already in 2004 the capability of KABES, the performance of the NA48 detectors at intensities comparable to the NA48/3 ones, and to validate our (Monte-Carlo) knowledge of the photon vetoes with beam data. The point is that the availability of a charged kaon beam of NA48/2 with characteristics that can be made quite similar to the final one, represents a unique opportunity to quantify the necessary effort (technical and financial) to transform NA48/2 into a rare decay experiment capable to measure $K^+ \to \pi^+ \nu \bar{\nu}$. The tests that we want to perform are:

1. Drift Chambers

   We need to test the performance of the current drift chambers when exposed to a high rate of kaon decays. The K12 (NA48/2) beam rate of kaon decays can be increased by a factor of four opening the momentum bite. Another factor of three can be achieved increasing the number of protons on T10.

2. KABES

   The performance of the upstream tracker is essential for the new experiment. Our baseline choice is to pursue the MICROMEGAS-based detectors and we plan to test this year:

   - A new micro-mesh with 25 μm thick amplification gap. The purpose is to shorten the pulses from the chambers in order to reduce the occupancy of the TPC.
   - The read-out of about 20 KABES micro-strips by means of 1 GHz FADCs to improve the time resolution and the double pulse resolution. The FADCs are available because they are those used to read-out the NA48 proton tagger during the ϵ'/ϵ measurement.

3. Photon Hermeticity

   We plan to complement the NA48/2 setup with a small angle photon veto and to collect a large sample of $K^+ \to \pi^+\pi^0$ decays with a minimum bias trigger to measure the π^0 rejection power of the current setup and to be able to extrapolate the requirements for NA48/3.

To perform the tests mentioned above, we request one week of protons in the K12 beam-line in addition to the time scheduled for NA48/2 during 2004. We point out that the conditions to perform these tests are incompatible with the NA48/2 data taking because of magnetic settings, triggering, beam and detector conditions. These data will be very important to proceed in due time towards a possible Letter of Intent and Proposal.

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