SEARCH FOR $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ DECAYS AT NA62 EXPERIMENT AT CERN

PAOLO MASSAROTTI*

*University of studies of Naples "FEDERICO II" and INFN,
Via Cintia, Naples, 80100, Italy
massarotti@na.infn.it*

Published 18 December 2014

Rare kaon decays provide unique opportunity to test the Standard Model and probe its possible extensions. The primary goal of the NA62 experiment is the measurement of the $Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ decay with a precision of 10% in two years of data taking. The detector setup together with the analysis technique is described.

Keywords: Kaon; rare decay; forbidden decay.

PACS Numbers: 13.20.Eb, 11.30.Hv, 12.15.Hh

1. Introduction

Kaons, the lightest second generation hadrons, have represented a copious source of information on the nature of fundamental interactions since their discovery in 1947. They were essential in establishing the foundations of the Standard Model (SM) of particle physics. Modern kaon physics continues this physics-rich tradition, being

*Speaker, for the NA62 Collaboration: F. Ambrosino, A. Antonelli, G. Anzivino, R. Arcidiacono, W. Baldini, S. Balev, S. Bifani, C. Biino, A. Bizzeti, B. Bloch-Devaux, V. Bolotov, F. Bucci, A. Ceccucci, P. Cenci, C. Cerri, G. Collazuol, F. Costantini, A. Cotta Ramusino, D. Coward, G. D'Agostini, P. Dalpiaz, H. Danielsson, G. Dellacasa, D. Di Filippo, L. DiLella, N. Doble, V. Duk, J. Engelfried, K. Eppard, V. Falaleev, R. Fantechi, M. Fiorini, P.L. Frabetti, A. Fucci, S. Gallorini, L. Gatignon, E. Gersabeck, A. Gianoli, S. Giudici, E. Goudzovski, S. Goy Lopez, E. Gushchin, B. Hallgren, M. Hita-Hochgesand, E. Iacopini, E. Imbergamo, V. Kekelidze, K. Kleinknecht, V. Kozhuharov, V. Kurshtsov, G. Lamanna, C. Lazzeroni, M. Lenti, E. Leonardi, L. Litov, D. Madigozhin, A. Maier, I. Mannelli, F. Marchetto, P. Massarotti, M. Misheva, N. Molokanova, M. Moulson, S. Movchan, M. Napolitano, A. Norton, T. Numaov, V. Obraztsov, V. Palladino, M. Pepe, A. Peters, F. Petrucci, B. Peyaud, R. Piandani, M. Piccini, G. Pierazzini, I. Popov, Yu. Potrebenikov, M. Raggi, B. Renk, F. Retière, P. Riedler, A. Romano, P. Rubin, G. Ruggiero, A. Salamon, G. Saracino, M. Savrié, V. Semenov, A. Sergi, M. Serra, S. Shkarovskiy, M. Sozzi, T. Spadaro, P. Valente, M. Veltri, S. Venditti, H. Wahl, R. Wanke, A. Winhart, R. Winston, O. Yushchenko, A. Zinchenko.

This is an Open Access article published by World Scientific Publishing Company. It is distributed under the terms of the Creative Commons Attribution 3.0 (CC-BY) License. Further distribution of this work is permitted, provided the original work is properly cited.

focused on studies of rare decays. Rare processes are sensitive to contributions of new particles which contribute to decay amplitudes at leading order. Thus they have unique sensitivity to new physics and thereby provide stringent tests of new theories and are an important testing ground for the SM.

Among the many rare flavour changing neutral current K and B decays, the ultra rare decays $K \rightarrow \pi \nu \bar{\nu}$ play a key role in the search for new physics through underlying mechanisms of flavour mixing. The SM branching ratio can be computed to an exceptionally high degree of precision. The prediction for the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ channel is $(7.81 \pm 0.75 \pm 0.29) \times 10^{-11}$ (Ref.1). The first error comes from the uncertainty on the CKM matrix elements, the second one is the pure theoretical uncertainty. This decay is one of the best probe for new physics effects complementary to the LHC, especially within non Minimal Flavour Violation models.^{2,3} Since the extreme theoretical cleanness of these decays remains also in these scenarios, even deviations from the SM value at the level of 20% can be considered signals of new physics. Also, the decay can be used for a measurement of V_{td} free from hadronic uncertainties and independently from that obtained with B mesons decays.

The decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ has been observed by the experiments E787 and E949 at the Brookhaven National Laboratory and the measured branching ratio is $1.73^{+1.15}_{-1.05} \times 10^{-10}$ (Ref. 4). However only a measurement of the branching ratio with at least 10% accuracy can be a significant test of new physics. This is the main goal of the NA62 experiment at CERN-SPS⁵ (section 2.1)

2. NA62 Experiment

The continuation of the CERN long standing kaon physics program is the NA62 experiment. In 2009 the existing NA48/2 experimental apparatus was dismantled in order to allow the construction of the new setup⁵ devoted to the study of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay.

In 2012 two different test runs were performed: a dry run in the summer devoted to the setup of the readout electronics, trigger and data acquisition chain and a technical run in the autumn with beam to study the performance of part of the NA62 subdetectors.

2.1. Measurement of the $Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ with 10% precision

Among the rare kaon decays the transitions $K \rightarrow \pi \nu \bar{\nu}$ are extremely attractive. They proceed as FCNC and their branching fractions are theoretically very clean since the hadronic matrix element can be obtained by the isospin symmetry of the strong interactions from the leading decay $K^+ \rightarrow \pi e^+ \nu$.⁶ For the charged kaon mode the NNLO calculations give $Br(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (7.81 \pm 0.80) * 10^{-11}$ (Ref. 1). Presently seven $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ events have been observed by the E787 and E949 collaborations in a stopped kaon experiment⁴ leading to $Br(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$. This value is twice the SM prediction but still compatible with it due to high uncertainty.

Fig. 1. $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ Feynman diagrams.

The decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is very sensitive to New Physics models where the theoretical predictions vary over an order of magnitude. Thus measuring $Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ could help to distinguish between the different types of New Physics⁷ once it is discovered.

The NA62 experiment will use a kaon decay in flight technique. Three different tools will be exploited to identify signal events and suppress background: kinematic properties, particle identification and vetoing.

New beam and detectors have been optimized for the study of the extremely rare decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$. The SPS proton on target intensity will be increased by 30% compared to previous set up. The secondary K^+ beam momentum will be selected as $75 \text{ GeV}/c \pm 1\%$. Kaons will decay in a 60m long evacuated tank with a rate of 800 MHz. The final beam line was tested during the technical run in 2012. The major detector components are shown in Fig. 2 and are:

CEDAR (KTAG): Hydrogen filled threshold Cherenkov counter used for positive kaon identification in the beam. A time resolution of 100 ps was achieved during the technical run which is important for the suppression of accidental background.

Gigatracker: Three stations of thin silicon pixel detectors for the measurement of kaon momentum, flight direction and time. The expected resolutions on the measured quantities will be $\sigma(p_K)/p_K \sim 0.2\%$ on momentum, $16 \mu\text{rad}$ on direction and 200 ps per station on time resolution.

CHANTI: Plastic scintillator anticounters providing a veto against interactions of the beam particles.

LAV: Twelve rings of lead glass counters surrounding the decay region and acting as photon veto detectors (LAV) for photon angles larger than 15 mrad with

Fig. 2. NA62 experimental layout

respect to the kaon flight direction. Currently eight LAVs were built and two of them were successfully operated in 2012.

Straw spectrometer: Four chambers of straw tubes separated by the MNP33 dipole magnet operating in vacuum. The expected momentum resolution will be $\sigma(p)/p = (0.3 \oplus 0.007 \text{ p[GeV}/c])\%$. Half a chamber was tested during the technical run.

RICH: Ring imaging Cherenkov detector measuring the velocity of the charged particles and allowing to separate pions from muons. The expected time resolution is better than 100 ps.⁸

CHOD: The charged hodoscope, a fast plastic scintillator counter detector to be used in the trigger.

IRC and SAC: Shashlyk type photon veto detectors covering angles down to zero (SAC) and also serving to veto photons converted in the upstream material (IRC). SAC was operated successfully in 2012 with a stand alone gigahertz flash ADC readout.

LKr: The NA48 liquid krypton calorimeter with renewed readout electronics serving to veto photons, emitted at angles from 1 to 15 *mrad*. The measured inefficiency is less than 10^{-5} for photon with energies above 10 GeV.

MUV: Three muon veto stations based on iron and scintillator sandwich providing separation between pions and muons better than 10^{-5} .

Both KTAG and Gigatracker are exposed to the full 800 MHz hadron beam while the rate by the downstream detectors is at most 10 MHz.

The signature of the signal is one track in the final state matched to one K^+ track in the beam. Backgrounds come from all the kaon decays with one track left in the final state and from accidental tracks reconstructed downstream matched by chance to a track upstream. Let P_K and P_π be the measured four-momenta of the K^+ and π^+ , respectively.

The variable m_{miss}^2

$$m_{miss}^2 \simeq m_K^2 \left(1 - \frac{|P_\pi^2|}{|P_K^2|}\right) + m_\pi^2 \left(1 - \frac{|P_K^2|}{|P_\pi^2|}\right) - |P_K| |P_\pi| \theta_{\pi K}^2 \quad (1)$$

defines two regions (namely region I and region II) almost free of the backgrounds coming from the main K^+ decay modes (see Fig. 3). The residual sources of background contamination are: tails to the m_{miss}^2 of the main K^+ decay channels due to the detector resolution and to the corresponding radiative processes; semileptonic K^+ decays like $K^+ \rightarrow e^+ \pi^0 \nu_e$; rare decays like $K^+ \rightarrow \pi^+ \pi^- e^+ \nu_e$.

Different techniques have to be employed in combination to reach the required level of background rejection. Schematically they can be divided into: kinematic rejection, precise timing, high efficient photon vetoes, precise particle identification systems to distinguish π^+ , μ^+ and positrons. The kinematic rejection requires a minimal material budget for the kaon and pion tracking systems. The precise timing is required for a proper kaon-pion matching, given the different rate environments

Fig. 3. Shape of the squared missing mass for signal and background events under the hypothesis that the charged track is a pion.

upstream and downstream. The detector is almost hermetic for photons originating from π^0 in the decay region and the overall photon veto system composed of LAV, LKR, SAC, IRC provides an inefficiency less than 10^{-8} for a π^0 coming from $K^+ \rightarrow \pi^+ \pi^0$ decay. The conversions of low energy photons in the upstream material (RICH, beam tube) will be detected by the CHOD. Decays with muons in the final state (like $K^+ \rightarrow \mu^+ \nu$, $K^+ \rightarrow \pi^+ \pi^- \mu^+ \nu$) will be suppressed using the muon-pion identification based on RICH and MUV for which the total inefficiency should be less than 5×10^{-6} . The combined use of a RICH and a calorimetric technique allows a muon/pion separation suitable for the $K^+ \rightarrow \mu^+ \nu$ rejection.

Part of the subdetectors and the final beam line have been commissioned during a technical run at the end of 2012. The overall installation is on schedule for the first physics run in autumn 2014.

3. Conclusions

The ultra-rare $K \rightarrow \pi \nu \bar{\nu}$ decay is a unique environment where to search for new physics. The NA62 experiment at CERN-SPS will follow this road by collecting $O(100)$ events of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay. The first physics run is scheduled for autumn 2014.

References

1. J. Brod, M. Gorbahn and E. Stamou, Phys. Rev. D **83** (2011) 034030 [arXiv:1009.0947 [hep-ph]].
2. G. Isidori, F. Mescia, P. Paradisi, C. Smith and S. Trine, JHEP **0608** (2006) 064 [arXiv:hep-ph/0604074].
3. M. Blanke, A. J. Buras, B. Duling, S. Recksiegel and C. Tarantino, Acta Phys. Polon. B **41** (2010) 657 [arXiv:0906.5454 [hep-ph]].

4. A. V. Artamonov *et al.* [BNL-E949 Collaboration], Phys. Rev. D **79** (2009) 092004 [arXiv:0903.0030 [hep-ex]].
5. NA62 Technical Design Document, NA62-10-07;
<https://cdsweb.cern.ch/record/14049857>.
6. F. Mescia and C. Smith, Phys. Rev. D **76** (2007) 034017.
7. D. Straub, arXiv:1012.3893 [hep-ph]
8. B. Angelucci *et al.* Nucl. Instrum. Meth. A **621** (2010) 205.