The ORKA Detector Facility Research Program

ORKA Collaboration

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Abstract

The ORKA Experiment is designed to measure $K^+ \to \pi^+\nu\bar{\nu}$ to the few percent level, allowing the full potential of this short-distance dominated process for probing Beyond the Standard Model physics. Although the ORKA Experiment is highly optimized for $K^+ \to \pi^+\nu\bar{\nu}$, it will be capable of producing world-leading results on many other physics processes. In addition, the ORKA beamline, a facility of unprecedented capability, could be used to perform additional extremely worthwhile experiments.

Key words: Kaons
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1. Introduction

ORKA [1] is an experiment designed to achieve a sensitivity of $< 10^{-13}$ for $K^+ \to \pi^+\nu\bar{\nu}$, a process with nearly unique sensitivity to new physics beyond the Standard Model. The abundant motivation for making such a measurement is detailed in the proposal. $K^+ \to \pi^+\nu\bar{\nu}$ has a very challenging signature so that in order to achieve this demanding objective, an extremely capable beamline and detector needs to be designed and constructed.

ORKA is basically a detector for K^+ goes to π^+ plus missing energy. In the case of $K^+ \to \pi^+\nu\bar{\nu}$, the missing energy is in the form of a neutrino–anti-neutrino pair. Many other candidates for the missing energy have been proposed over the years, however. In general, evidence for other forms of missing energy can be sought in observation of the shape of the π^+ spectrum. This technique will make possible great sensitivity to many of modes of considerable interest, as discussed below.

2. $K^+ \to \pi^+\nu\bar{\nu}$ and $K^+ \to \pi^+\nu\bar{\nu}\gamma$

Although the primary subject of this note is the "other" physics of ORKA it is worth noting that there are two kinematic regions ("pnn1" and "pnn2") in which $K^+ \to \pi^+\nu\bar{\nu}$ will be measured with different backgrounds and acceptance issues. In the E787/949 series of experiments these were analyzed separately and typically these analyses served as the basis for different student theses. No doubt this will continue to be the case in ORKA. Note also that if the ratio of rates in these two regions differs from predicted by the Standard Model (SM), this could indicate the presence of a very exotic form of new physics such as the presence of "unparticles" [2].

Another mode that may be observable given the sensitivity of ORKA will be $K^+ \to \pi^+\nu\bar{\nu}\gamma$. Typically the low energy part of the γ spectrum yields events that are experimentally indistinguishable from $K^+ \to \pi^+\nu\bar{\nu}$, whereas the higher energy part of the gamma spectrum leads to events that would have been vetoed in previous experiments. But the improvements in the ORKA beam and detector could make it possible to get at least a crude measure of the rate of this process in the SM [3].

3. $K^+ \to \pi^+ X^0$

One of the most popular and easily probed source of missing energy is the case in which a single unseen particle recoils from the π^+. In this case the π^+ spectrum is a peak whose width is determined by the resolution of the apparatus. Typically the X^0 is a light or massless particle such as a familon [4], or various species of axion [5], light scalar pseudo-Nambu Goldstone bosons in models of meta-stable SUSY breaking [6], sgoldstinos [7], a gauge boson corresponding to a new U(1) gauge symmetry [8, 9], and various light-mass dark-matter candidates [10–12]. In general these models do not predict branching ratios; rather they use limits on $K^+ \to \pi^+ +$ "nothing" to constrain their parameters. The current limit from E787/949 is 0.73×10^{-10} [13] and at this level, $K^+ \to \pi^+ \nu\bar{\nu}$ starts becoming a background. Thus further progress in establishing a limit is likely to go as the square root of the sensitivity. However it is interesting to note that a single event was observed very near the end point of the spectrum which corresponds to a massless X^0. Combined with the fact that the measured $K^+ \to \pi^+ \nu\bar{\nu}$ branching ratio is rather higher than (although statistically consistent with), the SM prediction makes this a very interesting mode for future study.

4. $K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \pi^0 X^0$

A process with similar physics interest to $K^+ \to \pi^+ \nu\bar{\nu}$ is $K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$ [14]. This process bears approximately the same relation to $Ke4$ decay as $K^+ \to \pi^+ \nu\bar{\nu}$ does to $Ke3$. That is, given the very well-measured $Ke4$ branching ratios, one can make a firm prediction of $K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$ in the Standard Model. One can thus use this mode to search for new physics as in $K^+ \to \pi^+ \nu\bar{\nu}$. In this case the possible new physics contributions can be mediated by axial-vector as well as by the vector currents that can enter in $K^+ \to \pi^+ \nu\bar{\nu}$.

E787 made the only previous measurement of this process, $B(K^+ \to \pi^+ \pi^0 \nu\bar{\nu}) < 4.3 \times 10^{-5}$ @ 90% CL [15]. Note that the sensitivity of this measurement was limited by the trigger bandwidth devoted to this signature and by the resolutions of the π^+ and γs, all of which will be very significantly improved in ORKA. We estimate that an improvement by at least three orders of magnitude will be possible.

E787 also put limits on $K^+ \to \pi^+ \pi^0 X^0$ as a function of m_X from 0 to 120 MeV, and presumably ORKA can do so as well. Once again certain processes are possible in this process that can't occur in $K^+ \to \pi^+ X^0$. For example a zero-mass vector X^0 is possible here.

5. $K^+ \to \pi^+ \gamma$

This mode violates angular momentum conservation and gauge invariance, but is allowed in non-commutative theories [16] [17] or those with other departures from point-particle quantum field theory and/or Lorentz invariance [18]. E949 put a 90% CL upper limit of 2.3×10^{-9} [19] on this mode. The estimated background was very low, and with the improvements to be incorporated in the ORKA detector, we expect the sensitivity to scale with the number of stopping kaons, a factor of ~ 360 with respect to the exposure of the previous measurement.

6. $K^+ \to \mu^+ +$ missing energy

There is a long history of searches for heavy neutrinos recoiling from muons or electrons in charged K [20] and π [21] decays. The motivation has evolved over time but remains compelling. For example a natural extension of the Standard Model incorporating neutrino mass and possibly explaining the origin of dark matter involves the inclusion of sterile neutrinos mixing with the ordinary neutrinos [22]. The weak eigenstates ν_{χ^k} of such neutrinos are related to the mass eigenstates ν_i by a unitary matrix, $\nu_l = \sum_{i=1}^{3+k} U_{li}\nu_i$ where $l = e, \mu, \tau, \chi_1, \chi_2 ... \chi_k$. An example of a sterile neutrino model is the Neutrino Minimal Standard Model that adds to the SM, three massive gauge-singlet sterile neutrinos [23]. In the context of this model, a search for peaks below the major, $m_\nu = 0$, one in the $K^+ \to \mu^+ X^0$ decay spectrum is sensitive to sterile neutrinos depending on the mass hierarchy structure and choice of parameters [24].

E949 is in the process of analyzing a data set sensitive to this process. It expects to reach a sensitivity of 2×10^{-8}–10^{-7} in the region $m_\nu = 150$–270 MeV. E949 did not have a suitable trigger for this mode (basically one looks at events that fooled the primary muon-rejecting trigger), so that the potential for many orders of magnitude larger exposure will be present in ORKA. However since any peak will be manifested over a background due to radiative $K\mu2$ decay, the sensitivity gain will go as $\frac{\eta_{\rm E949}}{\eta_{\rm ORKA}}\sqrt{\frac{N_{\rm ORKA}}{N_{\rm E949}}}$, where η is the photon veto inefficiency and N is the exposure. With a better photon veto, no trigger penalty and the much larger ORKA exposure compared to E949, sensitivities in the 10^{-10} range should be possible.

Another process with the $K^+ \to \mu^+ +$ "nothing" signature is $K^+ \to \mu^+\nu_\mu\nu\bar{\nu}$, a decay last searched for in 1973 (in an earlier generation of $K^+ \to \pi^+\nu\bar{\nu}$ experiment). A limit of 6×10^{-6} @ 90% CL was obtained [25]. This does not produce a peak in the μ^+ recoil spectrum, so is much more difficult to detect over the background due to $K^+ \to \mu^+\nu\gamma$ in which the photon is undetected. The measurement will be limited by knowledge of the photon inefficiency and of the branching ratio and spectrum of $K^+ \to \mu^+\nu\gamma$. At least an order of magnitude improvement in sensitivity is expected in ORKA.

There is a SM prediction for $K^+ \to \mu^+\nu_\mu\nu\bar{\nu}$ but it is many orders of magnitude below the reach of ORKA or any other current or proposed experiment. Thus, the main motivation for such a measurement is the search for BSM processes with the same $\mu^+ +$ "nothing" signature such as $K^+ \to \mu^+\nu_\mu X^0$ Over the years, the nature of the purported X^0 has changed from majorons [26] [27] in 1981, to a $U_{\mu R}(1)$ gauge boson [28] in 2011, but the signature has maintained its level of interest.

7. $K^+ \to \pi^+\gamma\gamma$

Reactions of the form $K \to \pi\gamma\gamma$ present an interesting challenge to Chiral Perturbation Theory since there is no $O(p^2)$ contribution; the leading contributions start at $O(p^4)$ [29]. For $K^+ \to \pi^+\gamma\gamma$, both the branching ratio and the π^+ spectral shape are sensitive to the undetermined coupling-constant $\hat{c}$. There is no complete calculation at the next-to-leading order $O(p^6)$. The dominant effects are one-loop unitarity corrections, deduced from an empirical fit to the decay amplitude of $K^+ \to \pi^+\pi^+\pi^-$ and containing the same constant $\hat{c}$, and vector-meson exchange [30]. In $K^+ \to \pi^+\gamma\gamma$ vector-meson exchange is expected to be negligible compared to unitarity corrections. E787/949 probed this reaction at both the region of the cusp at the $\pi^+\pi^-$ threshold [31] and the very interesting region near the end point [19]. They collected a total of 31 events (including 5 background) and obtained a value of 1.1×10^{-6} for the branching ratio and 1.8 ± 0.6 for $\hat{c}$. More recently NA48 and NA62 have given talks about their data sets totaling 293 events. They obtain branching ratio and $\hat{c}$ results compatible with those published by E787/949. However they don't report any results in the important low $\gamma\gamma$ mass region, that is most useful in breaking ambiguities among different theoretical approaches to this process. Since the full ORKA exposure is almost four orders of magnitude larger than that used by E787/949 to extract ~ 25 signal events, we expect a sample size around $200,000$ in the new experiment.

8. High precision measurement of $Ke2/K\mu2$

A fundamental measurement in the kaon system is the ratio of $Kl2$ rates, $R_K \equiv \Gamma(K^+ \to {\rm e}^+\nu)/\Gamma(K^+ \to \mu^+\nu)$. The electronic mode is highly helicity suppressed, leading to a SM prediction of $(2.477 \pm 0.001) \times 10^{-5}$ [32]. The 0.04% precision is possible because the hadronic form factors cancel out in the ratio. This suppression makes this ratio very sensitive to new physics effects which don't share the $V - A$ structure of the SM contribution. In the last few years the interest in this ratio has been piqued by the realization that percent-level deviations are possible in the MSSM [33]. This stimulated recent measurements of R_K from NA62 [34] ($(2.487 \pm 0.013) \times 10^{-5}$) and KLOE [35] ($(2.493 \pm 0.025 \pm 0.019) \times 10^{-5}$)). So there are now measurements at the 0.5% level, but the theoretical precision calls for further progress. Preliminary work on what ORKA could do in this area indicate that a 0.1% result is possible. The statistics would be 0.02%

and most systematics could be held well below 0.1%. The leading one, external bremstrahlung, approaches the 0.1% level.

9. Pion decays

The copious $K\pi 2$ decays, $K^+ \to \pi^+\pi^0$ can be used as a source for tagged π^0s, once the π^+ has been measured. The direction and energy of the π^0 is known. Moreover, if one of the π^0's decay photons is detected, the energy and direction of the other is also known. These facts were exploited in E787/949 to obtain limits on the branching ratios of $\pi^0 \to \nu\bar{\nu}$ [36] and $\pi^0 \to \gamma X^0$ [37]. The former process is predicted to go as $m_\nu^2/m_{\pi^0}^2$ in the SM, so would be unmeasurably small, given current estimates of neutrino masses, but such a search is sensitive to any decays of the form $\pi^0 \to$ "nothing". The $\pi^0 \to$ "nothing" decay can arise from several different physics processes beyond the SM, including $\pi^0 \to \nu\bar{\nu}$ decay induced by helicity-flipping (chirality-changing) pseudoscalar interactions [38] [39], $\pi^0 \to \nu_1\nu_2$ decay where ν_1 and ν_2 are neutrinos of different lepton flavor, and π^0 decays to other weakly interacting neutral states. E949 set a 90% CL upper limit of 2.7×10^{-7} on this process. This analysis assumed that all events remaining after photon veto cuts were signal, so that future progress would go as the square of the photon vetoing inefficiency. The improvement with statistics is very small. Thus one might expect an improvement of around a factor 5 in ORKA using this technique. However if an independent method of measuring the photon vetoing inefficiency is developed, one can subtract a background, and the gain goes as $\sqrt{N}$. The ratio of K-stops of ORKA to that of the E949 sample is roughly a factor 200. Thus an additional factor of ~ 14 could be realized if this technique can be made to work.

The interest in $\pi^0 \to \gamma X^0$ stems from the fact that owing to angular momentum conservation, observation of such a signal would indicate the unambiguous existence of a new vector particle. The possibilities for X^0 include a new light gauge boson [41] [42] [40] that appears in some extensions of the SM with an additional $U(1)$ interaction or an "axigluon" [43]. E787 set a 90% CL upper limit of 5×10^{-4} for this process. This was the very first stage of the E787 beamline and detector and the data was taken with a calibration trigger. Thus one can expect quite an improvement in ORKA. Once again the technique used assumed that all events remaining after the photon veto was applied were signal. Unfortunately it would probably be necessary to do the same kind of analysis in ORKA, so the anticipated improvement would probably be around a factor 25, in spite of the enormous increase in statistics. Still even the present limit is " ... is one of the most restrictive bounds we get on vectorial quark coupling" [44] so that a 25-fold improvement would clearly be quite valuable.

10. Concluding remarks

The above discussion does not include all the possible interesting measurements to be made with the ORKA detector and beamline. Some others, such as a new determination of the K^+ lifetime and the ratio of the $K^+ \to \pi^+\pi^0$ to $K^+ \to \mu^+\nu$ rates, are fundamental measurements. Improvement of the K^+ lifetime measurement could resolve discrepancies in the measurements used by the PDG [45]. Refinement of K^+ branching fractions, in concert with improved lattice QCD calculations, would improve the evaluation of $|V_{us}/V_{ud}|$ and test CKM unitarity [46]. Others, such as $K^+ \to \pi^+\gamma_{\rm dark}$; $\gamma_{\rm dark} \to e^+e^-$, where $\gamma_{\rm dark}$ is a "dark photon", are very interesting indeed. Not enough work has been done yet to determine how competitive ORKA will be with the other measurements in this area, for example at JLab and Mainz. Following completion of the ORKA research program the high intensity stopped kaon source could be employed to pursue a high precision search for anomalous T-odd transverse muon polarization in $K\mu 3$ decays that is now being pursued by the "TREK" initiative at JPARC [47]. The TREK experiment will be beam power limited, and the experience gained in delivering high quality high power beam to the ORKA experiment can be leveraged to drive the ultimate sensitivity achievable with the TREK technique

11. Summary

Table 1 gives the current sensitivity to processes that can be probed by ORKA, and the anticipated reach of ORKA.

Table 1
Processes that can be probed by ORKA.

Process	Current	ORKA	Comment
$K^+ \to \pi^+ \nu\bar{\nu}$	7 events	1000 events	
$K^+ \to \pi^+ X^0$	$< 0.73 \times 10^{-10}$ @ 90% CL	$< 2 \times 10^{-12}$	$K^+ \to \pi^+ \nu\bar{\nu}$ is a background
$K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$	$< 4.3 \times 10^{-5}$	$< 4 \times 10^{-8}$	
$K^+ \to \pi^+ \pi^0 X^0$	$<\sim 4 \times 10^{-5}$	$< 4 \times 10^{-8}$	
$K^+ \to \pi^+ \gamma$	$< 2.3 \times 10^{-9}$	$< 6.4 \times 10^{-12}$	
$K^+ \to \mu^+ \nu_{heavy}$	$< 2 \times 10^{-8} - 1 \times 10^{-7}$	$< 1 \times 10^{-10}$	150 MeV $< m_\nu <$ 270 MeV
$K^+ \to \mu^+ \nu_\mu \nu\bar{\nu}$	$< 6 \times 10^{-6}$	$< 6 \times 10^{-7}$	
$K^+ \to \pi^+ \gamma\gamma$	293 events	200,000 events	
$\Gamma(Ke2)/\Gamma(K\mu2)$	$\pm 0.5\%$	$\pm 0.1\%$	
$\pi^0 \to \nu\bar{\nu}$	$< 2.7 \times 10^{-7}$	$< 5 \times 10^{-8}$ to $< 4 \times 10^{-9}$	depending on tech nique
$\pi^0 \to \gamma X^0$	$< 5 \times 10^{-4}$	$< 2 \times 10^{-5}$	

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