Consideration of an Experimental Kaon Physics Program at Fermilab in the post Run-II era.

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Abstract:

The Fermilab director has charged [1] a steering group to explore the physics reach of an experimental program based on the Fermilab accelerator complex in the post Run-II era. In addition to the approved and planned neutrino physics program it is natural to consider opportunities in quark and charged lepton flavor physics. To that end a "flavor-physics" working group has been formed to advise the steering group, and this note is a mid-term report of the evolving discussion regarding kaon physics within the flavor-physics group.

Goals and Time-Frame:

The flavor physics group is working to identify world-class experiments in the era of 2012 to 2022 where both the physics landscape and accelerator resources must be considered. The year 2012 is the earliest that new world-class experiments could be operational at Fermilab given the current roadmap of US investments. The possible evolution of the Fermilab accelerator complex in the near term is assumed to follow the plan described by Dave McGinnis in his presentation [2] to the steering group. The scientific case outlined here would be substantially enhanced by an intense proton driver replacing the Booster in the later years of the period considered.

Enabling Technologies:

The confluence of two technologies at the end of Run-II represent a potential break-through in high sensitivity kaon physics. Rare-decay experiments at the sensitivity frontier operate on a precipice of balancing sensitivity with the extreme conditions of a high-rate beam and detector environment. Employing the Tevatron as a stretcher ring outlined by McGinnis [2] simultaneously minimizes kaon detector rates ***and*** the proton tax on the coincident neutrino physics program fueled by the Main Injector. Even more significant is the expected maturation of 3.9 GHz SCRF deflecting mode (ILC crab) cavities and cryo-modules that could serve as core elements of a high purity kaon beam separator system [3]. Both the stretcher ring and kaon separators are enabled by superconducting accelerator technology.

The demonstrated sensitivity and rate environments of recently completed rare-decay kaon experiments is listed below in Table 1. The projected sensitivity and rate environments of proposed and possible experiments is listed in Table 2. For the purpose of discussion "KTeV-II" is a separated K^+ beamline based on ILC crab cavities driven by the Tevatron in continuous spill configuration operating at 120 GeV. The KTeV-II configuration would be a 10% tax on the NuMI timeline. "KTeV-III" is operation of the same beamline in the "SNuMI" era with twice the kaon flux at the same 10% tax on coincident neutrino program.

A "Figure of Merit" (FOM) is introduced in Table-2 to characterize sensitivity normalized to beam rate for planned and possible future experiments. Experiments of course optimize detector designs for their rate environment, and the tradeoffs are particularly complex in neutral beam experiments. Hence the FOM is not a strictly quantitative metric between experiments but it does illustrate the dramatic joint strength of a high duty-factor stretcher ring and charged beam separators.

Completed Experiments:	Total Kaon decay exposure (x10^{10})	Beam Intensity (MHz)	Beam Purity (kaons)
BNL E871	**5000**	**1000**	**12%**
BNL E777/865	**70**	**2000**	**3%**
FNAL KTeV-I	**70**	**50**	**20%**
BNL E949	**200**	**2** (stopped K^+)	**30%**
KEK 391a	**0.5**	**0.7** (E_n>1GeV)	**2%**
CERN NA48/2	**10**	**20**	**3%**

Table-1: Summary of the sensitivity and beam conditions of high sensitivity kaon experiments completed in the past decade. Detector acceptances vary between decay modes, but typically were in the range of 1-10%.

Proposed and possible future Experiments:	Projected Kaon decays per year (x10^{10})	Beam Intensity (MHz)	Beam Purity	FOM: Yield(x10^{10}) / Beam(MHz)
CERN NA48/3	**500**	**800**	**3%**	**0.6**
JPARC E14-I	**90**	**110** (E_n>1GeV)	**12%**	**0.8**
JPARC E14-II	**500**	**1800** (E_n>1GeV)	**5%**	**0.3**
FNAL KTeV-II	**3500**	**10**	**70%**	**350**
FNAL KTeV-III	**10000**	**30**	**70%**	**350**

Table-2: Summary of the estimated reach of future rare-decay experiments. CERN and JPARC parameters are from the respective proposals [4,5]. "KTeV-II" is a separated K+ beamline based on ILC crab cavities driven by the Tevatron in continuous spill configuration operating at 120 GeV. The KTeV-II facility would be a 10% tax on the NuMI timeline. "KTeV-III" in the SNuMI era would be a 10% tax on the NuMI timeline. The KTeV-II detector rates are based on the Fermilab CKM proposal [3].

Physics Drivers:

It is important to concentrate on flavor physics drivers that will stand the test of time and which can add significant value to energy frontier measurements expected from Run-II and the LHC. Kaon physics has enjoyed a distinguished history in this regard, and the potential reach outlined below holds the promise of continuing this legacy of interplay with the energy frontier. The experimental concepts considered will focus on measurements driven by charged beams given the breakthrough potential of the KTeV-II and KTeV-III configurations. The concepts (1) through (5) constitute a chronologically evolving program starting with the beam and detector design defined in the CKM proposal [3].

Marquee Kaon Physics Drivers in the 2012+ era accessible by KTeV-II and KTeV-III:

1) **Beyond the Standard Model (BSM) decay amplitudes in $K \rightarrow \pi\nu\nu$**: The CKM matrix parameters will be very well established by 2012 leading to precise and robust Standard Model predictions [6] for both the neutral (1-2% theoretical error) and charged (3-4% theoretical error) branching ratios. These processes are highly suppressed and thus quite sensitive to BSM amplitudes. Many BSM models have been studied [7] with enhancements to the branching fraction ranging from 10% to 500% (charged mode), 1000%(neutral mode). The excellent control of theoretical errors permits 5σ discovery sensitivity for enhancements as small as 10% in the neutral decay and 20% in the charged decay branching ratios. By 2012 the CERN NA48/3 experiment expects to accumulate sensitivity to about ~100 $K^+ \rightarrow \pi^+\nu\nu$ Standard Model events and the JPARC experiment expects to have sensitivity to about ~5 $K_L \rightarrow \pi^0\nu\nu$ Standard Model events. Considering a $K^+ \rightarrow \pi^+\nu\nu$ experiment at Fermilab, KTeV-II could be sensitive to >100 events ***each year*** and KTeV-III >200 events each year which would match the theoretical error on the branching ratio in several years of running. The higher statistics $K^+ \rightarrow \pi^+\nu\nu$ samples will also have sensitivity to BSM physics through measurement of the decay form factor. Turning to $K_L \rightarrow \pi^0\nu\nu$, this process is uniquely sensitive to CP-violating physics beyond the Standard Model. The "Kaons at the Main Injector" (KAMI) proposal [8] argued that a high intensity neutral beam in the SNuMI era could collect about 40 Standard Model events/year with a 10% tax on the neutrino program. Proponents of the KOPIO experiment have likewise explored [9] using the Fermilab Booster to drive a $K_L \rightarrow \pi^0\nu\nu$ physics program. The Booster slow-spill scenario discussed by McGinnis [2] could yield about 20 events/year with a 10% tax on the neutrino program in the SNuMI era.

2) **Probing Lepton Universality:** Marciano and Sirlin have shown [10] that the ratio of $BR(\pi \rightarrow e\nu)/BR(\pi \rightarrow \mu\nu)$ is theoretically stable to

better than 1×10^{-4}. In fact the best limit on μ/e lepton universality to date comes from testing the measurement of $BR(\pi \rightarrow e\nu)/BR(\pi \rightarrow \mu\nu)$ against this robust calculation. A similar analysis [11] has been applied to $BR(K^+ \rightarrow e\nu)/BR(K^+ \rightarrow \mu\nu)$ which is theoretically stable to 0.04% . The $BR(K^+ \rightarrow e\nu)/BR(K^+ \rightarrow \mu\nu)$ ratio is currently measured now only to the 3% level due to the low $K^+ \rightarrow e\nu$ branching ratio of 1×10^{-5}. BSM (SUSY) effects on the ratio as high as 2% have recently been noted in the literature [12]. Both the proposed NA48/3 experiment and the KTeV-II concept can deliver the necessary statistical sensitivity to reach the theoretical floor of 0.04% on the $BR(K^+ \rightarrow e\nu)/BR(K^+ \rightarrow \mu\nu)$ ratio.

3) **Search for Lepton Flavor Violation (LFV):** Lepton Flavor Violation is present in many extensions of the Standard Model including SUSY, Horizontal gauge bosons, Extended Technicolor, Large extra dimensions, Lepto-quarks, etc [13]. The broad sweep of different LFV models lead to the following possible signatures:

   a) Pure leptonic LFV-processes. ($\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$, $\tau \rightarrow \mu\gamma$, $\tau \rightarrow e\gamma$, $\tau \rightarrow 3l$, etc).

   b) Quark-lepton LFV processes of the $d \rightarrow d\mu e$ type. (neutrinoless conversion: $\mu^- + (A, Z) \rightarrow e^- + (A, Z)$).

   c) Quark-lepton LFV processes of the $s \rightarrow d\mu e$ type. (kaon LFV decays $K_L \rightarrow \mu e$ (sensitive to axial/pseudo-scalar couplings) , $K^+ \rightarrow \pi\mu e$ (sensitive to vector/scalar/tensor couplings) , etc).

   d) Lepton-number-violating decays – L non-conservation (neutrinoless 2β-decays, $K^+ \rightarrow \pi^-\mu^+\mu^+$, $K^+ \rightarrow \pi^-\mu^+e^+$, etc).

Kaon decay experiments have unique sensitivity to signatures in (c) and (d) and have probed mass scales in excess of 100 TeV/c^2 (assuming weak coupling). The last round of experiments were limited by extreme beam and detector rate environments which will not improve substantially in foreseeable $K_L \rightarrow \mu e$ searches. In contrast the relatively low rate environment of the KTeV-II and KTeV-III charged beams paired with modern detector technologies can plausibly improve the sensitivity of $K^+ \rightarrow \pi\mu e$ by x100 and the sensitivity of $K^+ \rightarrow \pi^-\mu^+\mu^+$ and $K^+ \rightarrow \pi^-\mu^+e^+$ by as much as x1000.

4) **Reaching toward Plank-scale Physics with a next Generation K_L-K_S Interferometer:** Precision measurements of K_L-K_S interference phenomena have severely constrained BSM physics and provides the most sensitive test of CPT symmetry to date through limits [14] on the K^0/K^0-bar mass difference (δm_K^0). CPT symmetry is at the foundation of quantum field theory which could begin to erode somewhere near the Plank scale, far beyond the reach of energy frontier machines. Due to the multiplier of the very fine K_L-K_S mass splitting, interferometer experiments have probed $\delta m_K^0/m_K^0$ to below $1\text{x}10^{-18}$ which is currently only a factor of x25 above m_K^0/M_{Plank}. It is however far from clear that m_K^0 is the relevant normalization scale. Nevertheless it is suggestive that pushing on the K_L-K_S interferometer is a well motivated probe of CPT symmetry. The interferometer sensitivity is maximized when the initial state is a pure mass eigenstate (K^0 or K^0-bar) as demonstrated by the CERN CPLEAR experiment [15] . The CPLEAR experiment exploited a large (50%) interference amplitude to make the world's best measurement of T-violation in the neutral kaon system as well as some the most sensitive probes of CPT symmetry. The intriguing possibility of generating a pure high intensity K^0 beam through charge exchange from a pure K^+ beam has been discussed previously [16]. Experiments with this K^0 beam in a KTeV-II configuration would have much higher statistical sensitivity than the now finished CPLEAR experiment. Measurements of this nature require excellent control of detector systematics which may be afforded by the low rate and high beam purity. Careful application of modern detector technology in this modest rate environment could plausibly improve CPT searches by an order of magnitude or more.

5) **High Intensity K_L-K_S Interferometer:** Evidence for BSM amplitudes from either high statistics $K^+ \rightarrow \pi^+\nu\nu$ experiments or low statistics $K_L \rightarrow \pi^0\nu\nu$ experiments in the next decade would motivate a high statistics measurement of $K_L \rightarrow \pi^0\nu\nu$. A novel and potentially powerful concept to precisely access CP-violating amplitudes is to measure coherent interference between $K_S \rightarrow \pi^0e^+e^-$ and $K_L \rightarrow \pi^0e^+e^-$ from a pure $\mathbf{K^0}$ source [17]. Direct access to CP-violation

amplitudes in $K_L \rightarrow \pi^0 e^+ e^-$ decays has been precluded by the relatively large background from $K_L \rightarrow e^+ e^- \gamma\gamma$ which has pushed experimenters reluctantly toward the more challenging $K_L \rightarrow \pi^0 \nu\nu$ mode where this background is not present. Recent measurement of $K_S \rightarrow \pi^0 e^+ e^-$ has established that the interference term between K_S and K_L decaying to $\pi^0 e^+ e^-$ could be large, much larger in fact than $K_L \rightarrow \pi^0 e^+ e^-$ and the troublesome $K_L \rightarrow e^+ e^- \gamma\gamma$ background! Initial studies [18] of this concept in the KTeV-III configuration suggest that good sensitivity to the interference amplitude and hence the CP-violating component may be realized with the Fermilab complex toward the end of the 2012-2022 period.

The KTeV-II and KTeV-III experiments would employ high performance open-geometry detectors that would have excellent efficiency for many rare decay and high precision measurements in addition to the Marquee physics program described above. Scaling from the similar experience of the KTeV and NA48 experiments, the KTeV-II and KTeV-III experiments could yield 50+ PhD theses and 100+ physics publications for the 10-year period considered.

Summary

The program outlined here addresses central issues in particle physics and the case [19] is not new. This physics potential motivated substantial investments in the last decade for both the KOPIO and CKM initiatives, and drives the leadership profile held today by the CERN and JPARC kaon physics efforts. What is new is the recognition that the Fermilab accelerator complex can be expeditiously configured in the post Run-II era to drive a kaon physics program of unprecedented sensitivity and with minimal operational impact on a coincident neutrino program. The large proton reserve in the complex and manageable detector rates supports an agile response to early evidence of new physics, and the eventual incorporation of a higher intensity proton driver would ensure leadership of the sensitivity frontier for decades to come.

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