The Project X Kaon Physics Research Program

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August 31st, 2010

Abstract

Fermilab has been working with the international particle physics and nuclear physics communities to explore and develop research programs possible with a new high intensity proton source known as "Project-X". Project X will provide multi-megawatt proton beams from the Fermilab Main Injector over the energy range 60-120 GeV, simultaneous with multi-megawatt protons beams at 3 GeV with very flexible beam-timing characteristics. The Project-X research program includes world leading sensitivity in long-baseline neutrino experiments, neutrino scattering experiments, a rich program of ultra-rare muon and kaon decays, opportunities for next-generation electric dipole moment experiments and other nuclear/particle physics probes that reach far beyond the Standard Model of particle physics. Two high impact rare kaon decay experiments have been identified for the initial Project X program: precision measurements of the rare decays $K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$. These measurements will reach precision comparable to the small uncertainties of Standard Model predictions and will realize the ultimate potential for these processes to reveal new physics. Both experiments can be driven with 3 GeV Project X beam using a common production target. The motivation and prospects of these measurements are discussed in this white paper.

Introduction

The existence of flavor for quarks and leptons gives the Standard Model its structure of families or generations of elementary particles. Higher order effects related to the family structure has been instrumental in the development of the Standard Model (SM). For example, the absence of neutral currents in kaon decay led to the prediction of the charm quark. Kaon decays also led to the observation of matter anti-matter asymmetries (CP violation), and to the Cabibbo-Kobayashi-Maskawa model, which in turn predicted the existence of a third generation of particles. Mixing of neutral B mesons, in a role like that played by neutral kaon mixing in establishing the mass range for the charm quark, was the first experimental observation that correctly anticipated the large value of the top quark mass. The dramatic discovery of neutrino masses provided the first incontrovertible evidence that the original Standard Model was incomplete, and could provide a window to the unification of forces. Several of the great questions of particle physics have flavor at their core, and flavor physics can play a unique and crucial role in the progress of the field.

Numerous elements directly associate LHC physics with flavor. Without a Higgs or some other mechanism of electroweak symmetry breaking (EWSB), quark flavor effects would not even exist. All flavor phenomena in the Standard Model is encoded by a handful of input parameters that currently lack explanation. But beyond the Standard Model, flavor phenomena can cover a much wider landscape and are even more strongly entangled with the dynamics of symmetry breaking. New particles, such as charged Higgs particles or supersymmetric partners, can mediate flavor-changing processes. New flavors may appear, either in the form of new generations, or as exotic partners of standard quarks (such as composite quark states in "little Higgs" models). New sources of CP violation can arise from couplings of non-minimal Higgs sectors or of super-partners. All of these new sources of flavor effects put the natural suppression of most flavor-violating phenomena in the Standard Model in jeopardy, and physicists expect much larger effects from new Terascale physics at the LHC. In the context of Beyond Standard Model (BSM) theories, this is a fundamental issue called "the flavor problem."

Equally important is that in several BSM frameworks, the parameters of flavor are not just arbitrary inputs but instead are the result of dynamics or symmetries of the underlying theory. Unified theories predict relations between the couplings of quarks and leptons. In supersymmetric models with neutrino masses, a mix of symmetry relations and dynamics connects neutrino mixing and flavor transitions in the charged-lepton sector. In extra-dimensional theories, the family replicas can be understood as different branes on which fermions are bound to live, and mixings are tied to the relative positions of these branes in the extra dimensions. In super-symmetric theories, the large value of the top quark mass can dynamically generate electroweak symmetry breaking, making EWSB, in some sense, a flavor-driven phenomenon. Finally, the numerical coincidence of the top mass value with the scale of EWSB is yet another mysterious hint of a possible direct connection between EWSB and flavor.

These connections between symmetry breaking and flavor, as well as the flavor mysteries of neutrino masses and the matter-antimatter asymmetry of the universe, strongly suggest that flavor will play a key role in exploring the new physics landscapes unveiled by the LHC. Most conceivable new physics manifestations will provide new sources of flavor phenomena, underscoring our need to address the flavor problem. The optimal approach to understanding flavor will depend on the details of the discoveries. It is sensible to expect, on the basis of the history of particle physics and of the explicit models of new physics available today, that experiments at the Energy Frontier and flavor experiments at the Intensity Frontier will provide complementary advances in the coming phases of exploration of the laws of nature.

Advanced rare-decay kaon experiments have probed branching fractions in the 10^{-11} – 10^{-12} range including the rarest particle decay ever observed, $B(K_L \rightarrow e^+e^-) = 9 \times 10^{-12}$, and the discovery of the long sought after process $B(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$[1] . These measurements were achieved with 20-50 kW of "slow extracted" proton beam power from proton synchrotrons, the BNL AGS, Fermilab, and others. Next-generation experiments, aimed at 1000-event Standard Model sensitivity to the $K \rightarrow \pi\nu\bar{\nu}$ process, require branching fraction sensitivities at the 10^{-14} level, which require beam power in excess of 200 kW per experiment with high-duty-factor beams. High-duty-factor beams have historically been generated with slow-extracted-beam techniques, which do not scale to the required high power of these next generation experiments. Continuous-wave-linac technology presents an opportunity to break through this power barrier and provide high-power, high-duty-factor proton beams to drive next-generation experiments.

Through the process of the Project X workshops numerous world-class kaon physics experiments enabled by this game-changing accelerator technology were explored. This broad program is summarized in the *Physics Reach* section; here the two leading "Day-1" experimental opportunities are identified:

- Precision measurement of $B(K_L \rightarrow \pi^0 \nu\bar{\nu})$: New physics can induce substantial enhancements to the branching fraction $B(K_L \rightarrow \pi^0 \nu\bar{\nu})$. The Standard Model rate, $B(K_L \rightarrow \pi^0 \nu\bar{\nu}) = (2.7 \pm 0.40) \times 10^{-11}$, has been calculated with precision and is uniquely sensitive to matter-antimatter asymmetries of physics beyond the Standard Model. Measuring this highly suppressed process requires very intense kaon sources. The KOTO experiment at JPARC in Japan is pursuing discovery of this process with an initial sensitivity of a few events at the Standard Model level; a higher sensitivity experiment would be planned for the future. The beam power available with Project X allows consideration of experiments with much higher sensitivity, at the 1000-event level in the Standard Model. Pursuit of this challenging measurement is complicated by the fact that all particles in both the initial and final states are neutral and consequently hard to detect. The high-precision timing properties of proton linac technology provide experimental tools (time-of-flight techniques) to strengthen the experimental signature and reject background processes to the required level.

- **Precision measurement of** $B(K^+ \rightarrow \pi^+ \nu\bar{\nu})$: New physics can likewise induce substantial enhancements to the charged mode $B(K^+ \rightarrow \pi^+ \nu\bar{\nu})$ rate in the Standard Model, which can be calculated precisely. Measuring this highly suppressed process, predicted to be $B(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (8.5 \pm 0.07) \times 10^{-11}$ in the Standard Model, with high precision requires very bright kaon sources and consequently extremely intense proton drive beams. This process was discovered at Brookhaven's proton facility, the AGS, using the "stopped kaon" techniques fueled with a high-intensity, low-energy K^+ beam which produced seven candidate events. Today in Europe CERN experiment NA62 is pursuing the next step in sensitivity beyond discovery with a promising new technique driven by the SPS proton facility which aims for 100-event sensitivity. The proven techniques developed at the Brookhaven AGS can be further exploited to reach 1000-event sensitivity with Project X, which could deliver 200 times the rate of K^+ decays realized at the AGS.

Proton Beam and Beam Structure Needed

Previous kaon experiments driven with relatively high energy proton beams typically optimized kaon yields with high-Z thick targets where secondary interactions boosted kaon yields by up to 30%. Next generation experiments driven with high-power 3.0 GeV Project X beams are better served with low-Z targets, such as carbon which has high kaon transparency, low spallation neutron yield, and excellent thermal properties for high beam power management. The Fermilab Accelerator Physics Center has recently developed a new comprehensive simulation module in the LAQGSM/MARS (MARS15) framework [2,3,4] for particle production in the challenging T_p region of 1-4 GeV. Kaon production in this module is treated as a sum of well measured exclusive channels with little tuning. The simulations have been benchmarked against the high quality data sets from the COSY facility [5] and one such benchmark is shown in figure 1 is an absolute prediction of forward K^+ production yield on carbon in excellent agreement with COSY data.

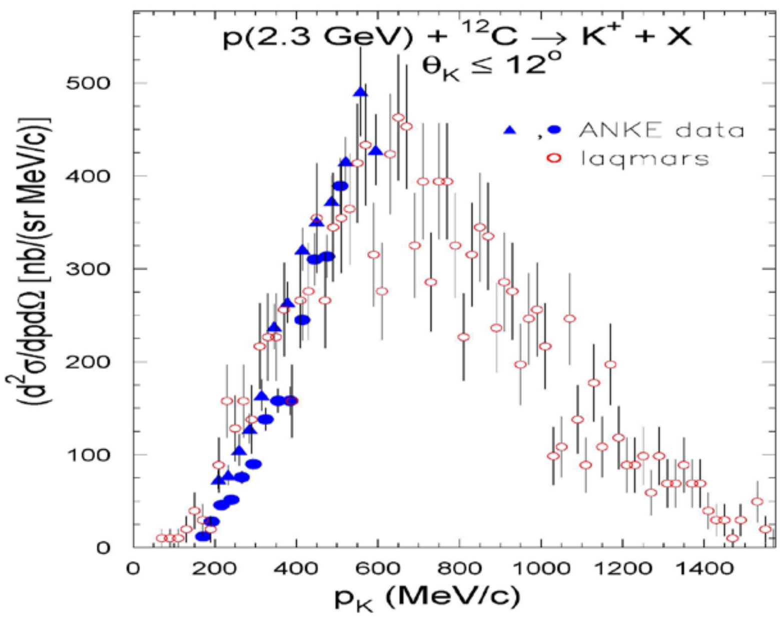

Figure 1: K^+ momentum spectrum from 2.3 GeV protons (kinetic) on a thin carbon target simulated with LAQGSM/MARS15 [2]. The simulated rate is absolutely normalized.

The estimated (LAQGSM/MARS15) kaon yield at constant beam power (yield/T_p) is shown if Figure 2. The yield on carbon saturates at about 5 GeV, and the T_p = 3.0 GeV yield is about a factor of about x2 less than the peak yield in the experimentally optimal angular region of 17-23 degrees which mitigates the high forward flux of pions and neutrons. The enormous beam power of Project X more than compensates for the unsaturated yield point as indicated in Tables 1 and 2.

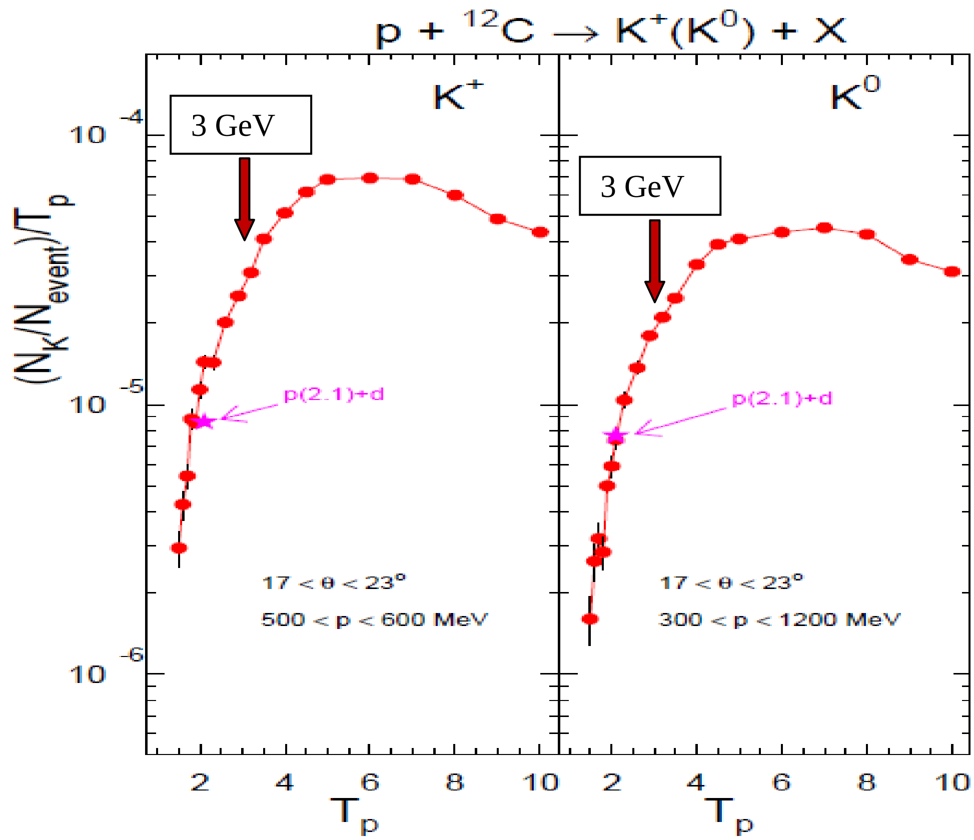

Figure 2: The estimated (LAQGSM/MARS15) kaon yield at constant beam power (yield/T_p) for experimentally optimal angular and energy regions as a function of T_p (GeV).

Beamline to Detector

Both the $K^+ \to \pi^+ \nu\bar{\nu}$ experiment (CKX) and the $K_L \to \pi^0 \nu\bar{\nu}$ experiment (NKX) can be served from the same production target, similar to the strategy employed in the JPARC hadron hall. Conceptual design of the common production target and beamlines has begun based on the BNL and JPARC experience. Initial design [6] of a short high acceptance separated K^+ beam line has been completed. The layout of the CKX and NKX Day-1 experiments in the Project-X rare decay campus is illustrated in Figures 3 through 6.

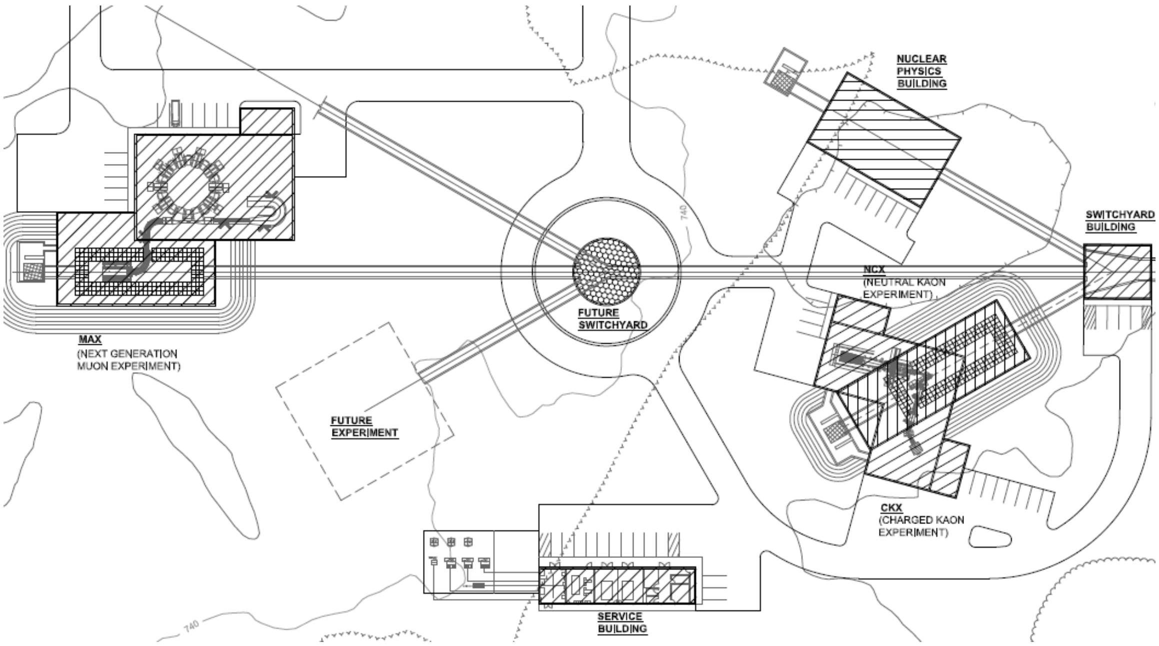

Figure 3: Conceptual design of the Project-X 3.0 GeV rare processes campus.

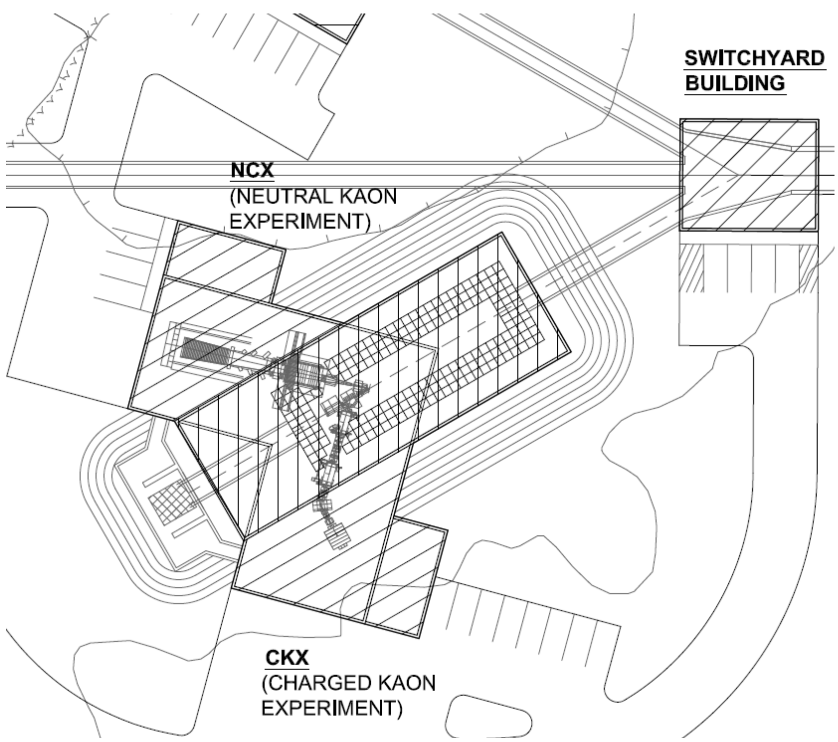

Figure 4: Conceptual study of the Project X kaon experimental hall with a common target station.

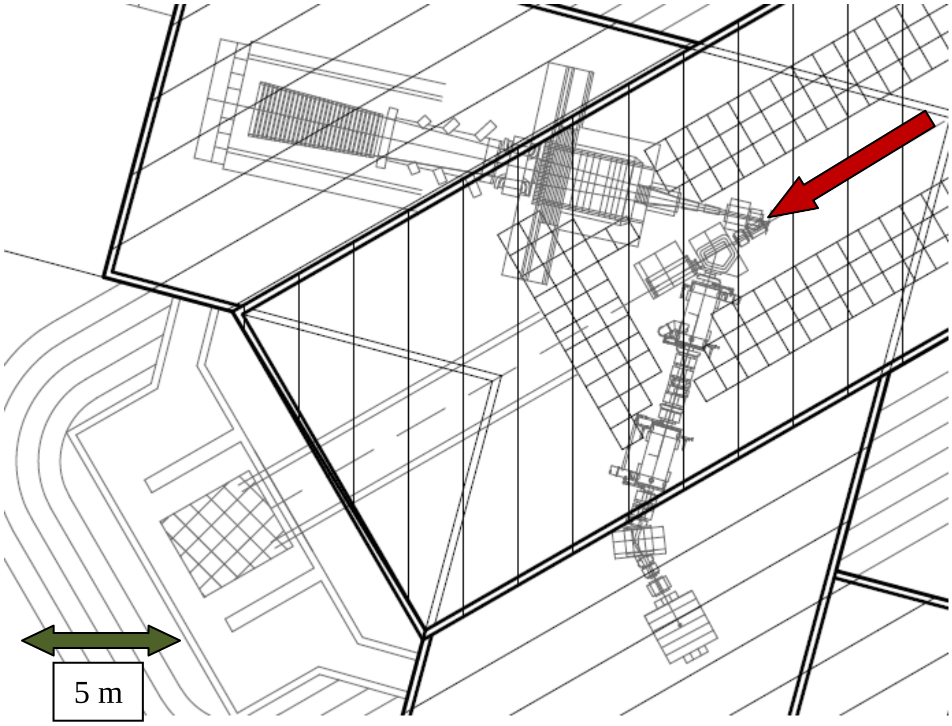

Figure 5: The NKX (above) and the CKX (below) concept beamlines and experiments served with a common production target (3 GeV proton beam indicated with red arrow).

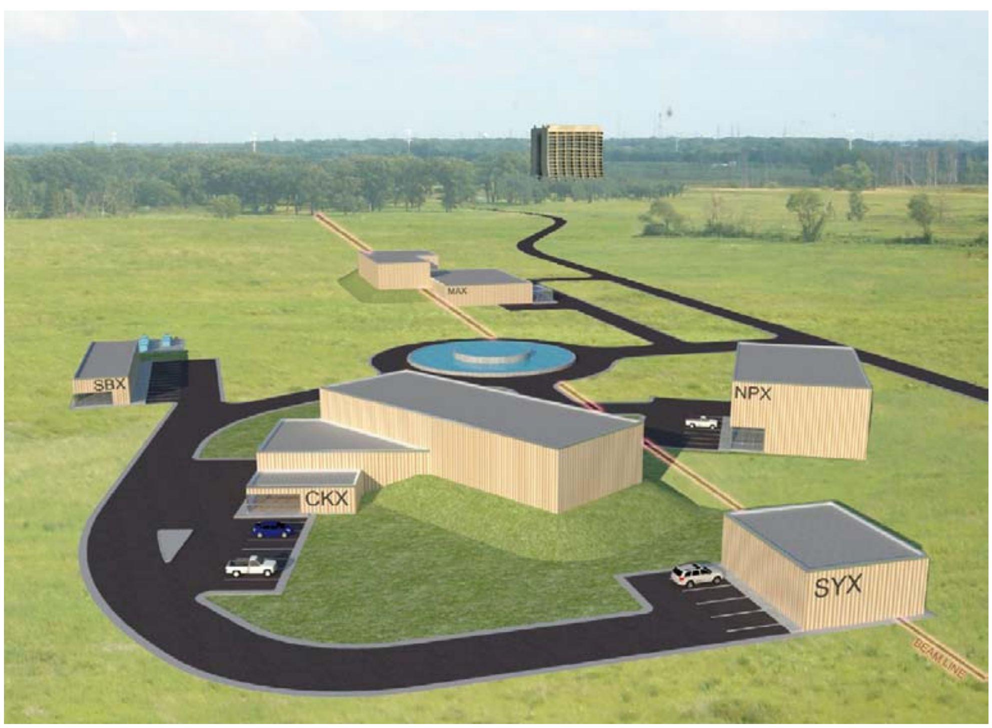

Figure 6: The CKX and NKX hadron hall concept viewed from the end of the linac.

Detectors

Considerations for a Project-X $K^+ \to \pi^+ \nu\bar{\nu}$ *detector:*

The BNL E787/E949 [7] program was the culmination of a long series of "stopping K^+ decays" experiments where high flux low-energy K^+ beams were transported to a target where the K^+ stop and subsequently decay with a lifetime of 12 nsec. The beam that impinges on the stopping target must be primarily kaons in order to control detector rates. Achieving this beam purity requires a separator system to remove the overwhelming pion component. Balancing the lifetime of K^+ ($\beta\gamma c\tau \sim 3.5$m) with the practical minimal length of a separator system (~14m) optimizes the separated beam momentum in the 400-600 MeV/c range which fortuitously is maximally produced on carbon at Project X energies as illustrated in figure 1.

The BNL E949 experiment's demonstrated performance serves as a good basis to extrapolate the reach of a high statistics experiment driven with Project X beam. Studies from the 2008 and 2009 Project-X workshops suggest that the rate capability and acceptance of stopped K^+ technique can be further improved with straightforward detector upgrades and by lowering the kaon momentum on the stopping target from 710 MeV/c used at BNL to about 500 MeV/c. A comparison of kaon stopping rates between Project X and the BNL AGS is shown in table 1.

Table 1 shows that the Project X kaon stopping target is more than x100 times brighter than the BNL E949 experiment, enabling a very high statistics (>1000 standard model events) Day-1 experiment which can precisely determine both the rate and form-factor of the $K^+ \to \pi^+ \nu\bar{\nu}$ process. Although the useful kaon rate is significantly greater than at BNL, the ideal timing and energy aspects of the Project X beam results in comparable instantaneous rate in the detector thereby maintaining a comfortable level accidentals. The Project X experiment requires a proton beam pulse train frequency of 30 MHz or greater which is comfortably within the bandwidth of the linac. The excellent timing of proton pulses (< 50 psec) within the pulse train may be exploited to improve the pion rejection from the beamline, which will be required to contend with the x4 higher pion flux per kaon from the production target.

	Beam Energy T_p	Protons/second (avg) on [target (λ_I)]	$p(K^+)$ (MeV/c)	Stopping K^+/second	K^+/π^+ Production Ratio
BNL AGS (E949)	21 GeV	12×10^{12} on [0.7 λ_I Pt.]	700-730	0.7 x 10^6 K^+/sec	1:24
Project-X/ K^+ expt	3.0 GeV	1/2 x 6000×10^{12} on [1.0 λ_I C]	450-570	98 x 10^6 K^+/sec	1:80

Table 1: Compares the measured rate of stopping K^+ in the BNL-E949 experiment with full LAQGSM/MARS thick-target simulations for Project-X charged kaon yield with ½ of the 1 ma 3.0 GeV proton beam.

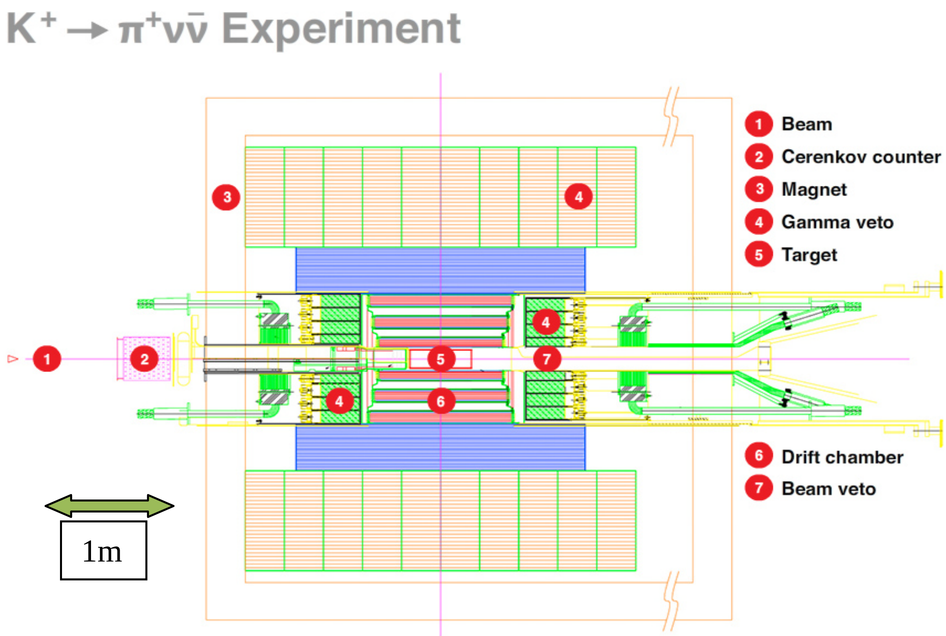

Figure 7: Conceptual design of a Project X $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ experiment based on evolution of BNL E949.

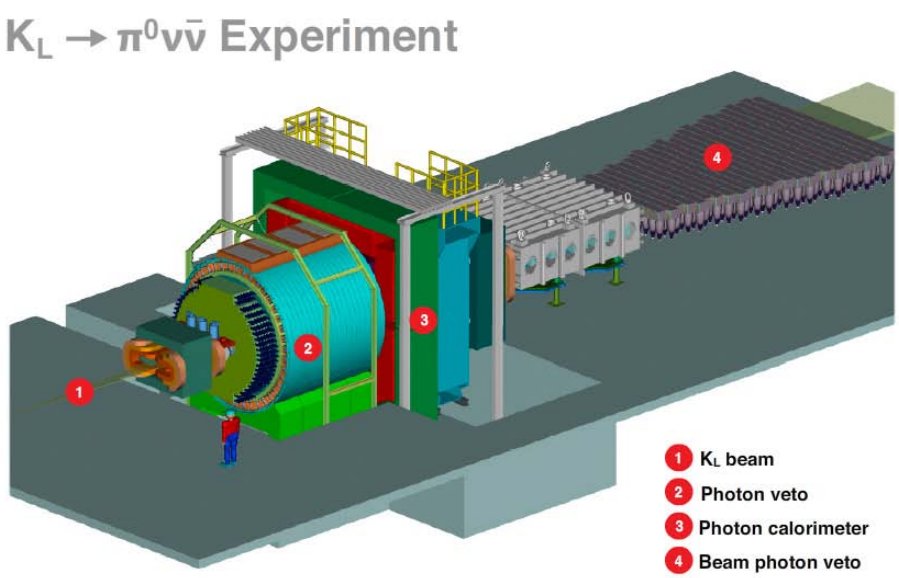

Figure 8: Conceptual design of the Project X $K_L \rightarrow \pi^0 \nu\bar{\nu}$ experiment based on KOPIO.

Considerations for a Project X $K_L \rightarrow \pi^0 \nu\bar{\nu}$ detector.

The KOPIO initiative [8] proposed to measure the $K_L \rightarrow \pi^0 \nu\bar{\nu}$ process with a Standard Model sensitivity of 100 events. The experimental technique and sensitivity was well developed and extensively reviewed. A sensitivity of 100 events required about 10,000 hours of upgraded BNL AGS proton beam ($100\text{x}10^{12}$ 24 GeV protons every 5 seconds on target). The neutral beam incident on the KOPIO detector was designed with a large targeting angle ($\theta = 42^0$) from the production target in order to produce the low momentum neutral kaons critical to the Time-Of-Flight (TOF) strategy of the experiment. An illustration of the experimental technique is shown in figure 7. The KOPIO design K_L beam had an average kaon momentum of 800 MeV/c with ~1000 neutrons (E_n>10 MeV) for every K_L in the beam acceptance which requires that the beam propagate through an excellent vacuum.

The KOPIO design measures the kaon momentum with TOF techniques in the 300-1200 MeV/c momentum range, which is well matched to the Project X kaon momentum spectrum shown in figure 1. The projected TOF performance of KOPIO at the AGS was limited by achievable proton beam bunching of the AGS. Low intensity AGS beam-bunching test runs achieved a proton bunching of $\sigma_t \sim 270$ psec, with a design goal of $\sigma_t = 200$ psec. The Project X beam pulse timing, including target time slewing, is expected to be less than 50 psec which would substantially improve the momentum resolution and background rejection capability of a $K_L \rightarrow \pi^0 \nu\bar{\nu}$ experiment driven with Project X beam. The comparative K_L production yields from thick targets fully simulated with LAQGSM/MARS15 are shown in Table 2.

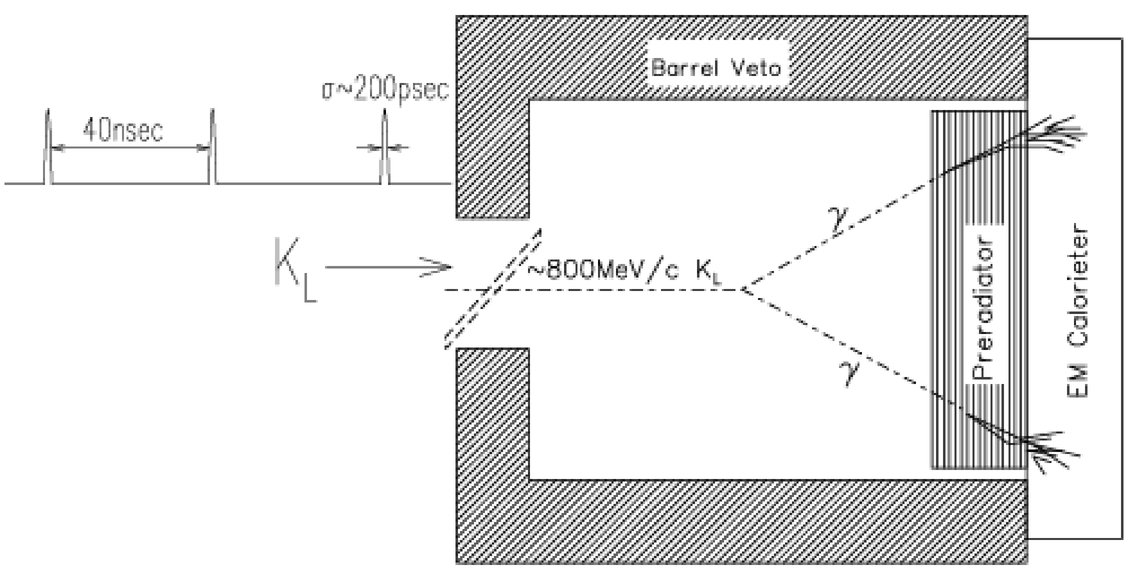

Figure 9: Illustration of the key elements of the KOPIO technique: TOF measurement of the K_L momentum, measurement of ($\pi^0 \rightarrow \gamma\gamma$) and veto of all other background process particles.

	Beam Energy	Target (λ_I)	p(K^+) (MeV/c)	K_L/second (into 500 μsr)	K_L/n Ratio (E_n>10 MeV)
BNL AGS	24 GeV	1.1 Platinum	300-1200	60×10^6 K_L/sec	~1:1000
Project X	3.0 GeV	1.0 Carbon	300-1200	450×10^6 K_L/sec	~1:2700

Table 2: Comparison the Project-X K_L production yield from a thick target fully simulated with LAQGSM/MAR15 into the KOPIO beam solid angle and momentum acceptance. The BNL AGS kaon and neutron yields are from RSVP reviews in 2004 (Bryman) and Jaffe (2005).

The AGS K_L/p yield from 24 GeV protons is 20x the Project X K_L/p yield for 3.0 GeV protons. Table 2 illustrates that Project X compensates this relative yield with a proton flux for kaons (1/2 of 1 mA) that is 150x the AGS RSVP goal of 100×10^{12} protons every 5 seconds. Hence the Project X neutral kaon flux into the KOPIO beam acceptance is 8x the AGS flux goal into the same beam acceptance as evident in table 2. A nominal five-year Project X run is 2.5x the duration of the KOPIO AGS initiative and hence the reach of a Project X $K_L \rightarrow \pi^0 \nu\bar{\nu}$ experiment is 20x times the reach of the RSVP goals

A TOF-based $K_L \rightarrow \pi^0 \nu\bar{\nu}$ experiment driven by Project X would need to be re-optimized for the Project X K_L momentum spectrum, TOF resolution, and corresponding background rejection. It is probable that this optimization would be based on a much smaller neutral beam solid angle which greatly simplifies the detector design, increases the acceptance, and relaxes the requirement to tag photons in the fierce rate environment of the neutral beam. Optimizing the TOF performance will likely require a proton pulse train frequency of 20-50 MHz and an individual proton pulse timing < 50 psec. The very high K_L beam flux, the potential of break-through TOF performance, and improvements in calorimeter detector technology support the plausibility of a Day-1 $K_L \rightarrow \pi^0 \nu\bar{\nu}$ experiment with ~1000 Standard Model event sensitivity.

Physics Reach

Through the process of the Project X workshops numerous world-class kaon physics experiments enabled by this game-changing accelerator technology were explored:

- $K_L \rightarrow \pi^0 \nu\bar{\nu}$ **:** 1000 events, precision measurement of the rate is particularly sensitive to new CP violating phenomena.
- $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ **:** >1000 events, precision measurement of the rate and form factor, both sensitive to new physics beyond the Standard Model.
- $K^+ \rightarrow \pi^0 \mu^+ \nu$: Search for new T-violating phenomena that can affect the transverse muon polarization.
- $K^+ \rightarrow (\pi,\mu)^+ \nu_x$: Search for anomalous heavy neutrinos with masses in the 50-250 MeV/c^2 range.

- $K_L \to \pi^0 e^+ e^-$: <10% measurement of a direct CP violating amplitude, complementary sensitivity to new CP violating physics.

- $K_L \to \pi^0 \mu^+ \mu^-$: <10% measurement of direct CP violating amplitude, complementary sensitivity to new CP violating physics.

- $K^0 \to X$: Precision study of a pure K^0 interferometer, which can be sensitive to new physics out to the Plank scale ($\Delta m_K/m_K \sim 1/M_{Plank}$)

- $K^0, K^+ \to$ LFV: Most incisive next-generation search for Lepton Flavor Violating physics in the quark sector.

- $K^+ \to e^+ \nu$: Precision measurement of the branching ratio is a highly sensitive probe of lepton universality and of many BSM effects including LFV.

Each of the experimental opportunities are unique and incisive probes of physics beyond the Standard model. Precision measurement of the $K \to \pi\nu\bar{\nu}$ modes is particularly incisive, and are on the short list of golden modes in flavor physics. One example of many studies of $K \to \pi\nu\bar{\nu}$ sensitivity to new physics is illustrated in figure 10

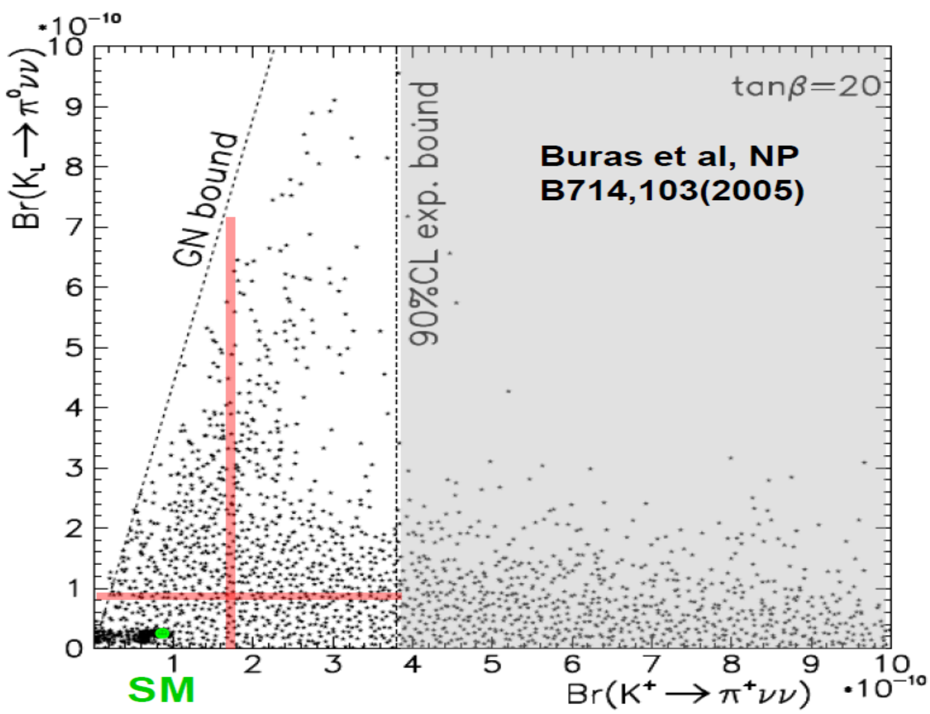

Figure 10: One of many BSM sensitivity studies for $K \to \pi\nu\bar{\nu}$. The green dot in the lower left corner spans the theoretical uncertainty of $K \to \pi\nu\bar{\nu}$ in the Standard Model. The vertical and horizontal stripes indicate the Project X measurement sensitivity, centered at the current central measured value of $K^+ \to \pi^+ \nu\bar{\nu}$ and x3 the SM expectation of $K_L \to \pi^0 \nu\bar{\nu}$ for illustration. The black dots are the result of a scan over the experimentally allow space of Minimal Super Symmetry (MSSM). The "Grossman-Nir (GN) Bound" is a robust limit on $K_L \to \pi^0 \nu\bar{\nu}$ based on the measurement of $K^+ \to \pi^+ \nu\bar{\nu}$

Conclusion

Next-generation experiments, aimed at 1000-event Standard Model sensitivity for the charged and neutral $K \rightarrow \pi\nu\bar{\nu}$ decays have been shown to be possible using the high-duty-factor, high intensity beams planned for Project X. The continuous-wave-linac technology proposed for Project X presents ideal conditions for these experiments. The measurements of $K^+ \rightarrow \pi^+\nu\bar{\nu}$ and $K_L^0 \rightarrow \pi^0\nu\bar{\nu}$ can be conducted using a common production target and would form flagship elements of the initial suite of Project X experiments. Both experiments would reach precisions of a few % comparable to the expected level of SM predictions and therefore offer the ultimate reach possible for uncovering deviations due to hypothetical non-SM physics. Many other incisive kaon decay measurements have been identified which would provide a suite of results to help to reveal the nature of new physics effects.

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