Project-X
Fermilab PAC, Nov 2010
R. Tschirhart

Fermilab

Photo: H. Hayano, KEK
The Project-X Research Program

- **Long baseline neutrino oscillation experiments:**

  Driven by a high-power proton source with proton energies between 50 and 120 GeV that would produce intense neutrino beams directed toward massive detectors at a distant deep underground laboratory.

- **Kaon, muon, nuclei & neutron precision experiments driven by high intensity proton beams running simultaneously with the neutrino program:**

  These could include world leading experiments searching for muon-to-electron conversion, nuclear and neutron electron dipole moments (edms), and world-leading precision measurements of ultra-rare kaon decays.

- **Platform for evolution to a Neutrino Factory and Muon Collider**

  Detailed Discussion: [Project X website](#)
Progress since Aspen 2009

- **October 2009**: Workshop on the Application of High Intensity Proton Accelerators (AHIPA) October 2009: Excellent cross-cut, exploration of common ground.

- **November 2009**: 4th Project-X workshop: Produced accelerator and comprehensive research white papers.

- **January – August 2010**:
  - Development of thrust specific white papers.
  - Accelerator configuration refined and defined in a Functional Requirements document.
  - Emergence of Nuclear Energy R&D as part of the Project-X portfolio.

- **November 2010**: 5th Project-X Physics Workshop, focused forums on refining white papers of research thrusts.

- **November 2010**: OHEP expresses interest in advancing case and basis for Critical Decision Zero (CD0): Research program briefing November 17th 2010 at Germantown.
Expansion of the Fermilab Accelerator Complex
New Neutrino Beam at Fermilab…
…Directed towards NSF’s proposed DUSEL Precision Near Detector on the Fermilab site
100 kT fiducial volume Water Cherenkov Far Detector
17 kT fiducial volume Liquid Argon TPC Far Detector
Kaon, Muon and EDM Experiments Deeply Attack the Flavor Problem

Why don't we see the *Terascale Physics we expect* affecting the flavor physics we study today??
Deepest Probe of the Flavor Problem: muon-to-electron Conversion Expt at Project-X

Supersymmetry Predictions at $10^{-15}$

Heavy Neutrinos

Leptoquarks

Compositeness

Second Higgs doublet

Heavy $Z'$, Anomalous $Z$ coupling

After W. Marciano
The Window of Ultra-rare Kaon Decays at Project X

Standard Model rate of 3 parts per 100 billion! Project will has sensitivity for 1000 SM events

BSM particles within loops can increase the rate by x10 with respect to SM.
The Quest for Electric Dipole Moments

A permanent EDM violates both time-reversal symmetry and parity

To understand the origin of the symmetry violations, you need many experiments!

Neutron

Diamagnetic Atoms (Hg, Xe, Ra, Rn)

Quark EDM

Quark Chromo-EDM

Paramagnetic Atoms (Tl, Fr)
Molecules (PbO)

Electron EDM

Physics beyond the Standard Model: SUSY, Strings ...

Guy Savard, ANL
This Science has attracted Competition: The Proton Source Landscape This Decade...

- Pulsed machines driving neutrino horns: SPS (0.5 MW), Main Injector (0.3 MW now, 0.7 MW for Nova), JPARC (plan for 1.7 MW)
- Cyclotrons and synchrotrons driving muon programs: PSI (1.3 MW, 600 MeV), JPARC RCS (0.1-0.3 MW)
- Synchrotrons driving kaon physics programs: SPS (0.015 MW), JPARC (goal of >0.1 MW), Tevatron (0.1 MW)
- Linear machines driving nuclear and neutron programs: SNS, LANL, FRIB…not providing CW light-nuclei beams.

*Project-X*

M Seidel, PSI
The High Duty Factor Proton Source Landscape This Decade...

* Beam power x Duty Factor

Project-X CW-Linac

- PSI
- TRIUMF

P = 1MW*
P = 100kW*
P = 10MW*

Stopped/Slow kaon yield/Watt

E_{beam} [GeV]

power

* Beam power x Duty Factor
“Continuous Wave” (CW) Linac for Rare Processes...

- Beam extraction challenge is finessed.

- Duty factor is very high.

- The high frequency bandwidth intrinsic to a Linac can be exploited to generate excellent time resolution ($\delta t \sim 20psec$), a very powerful tool to face a high intensity environment.

- JLAB has demonstrated that beam can be cleanly multiplexed between many targets with minimal losses. These “touchless” RF beam multiplexers are enabled by the high linac bandwidth.

- Excellent beam power scaling.
# Project-X Accelerator
## Functional Requirements

### CW Linac
- **Particle Type**: H\(^-\)
- **Beam Kinetic Energy**: 3.0 GeV
- **Average Beam Current**: 1 mA
- **Linac pulse rate**: CW
- **Beam Power**: 3000 kW
- **Beam Power to 3 GeV program**: 2870 kW

### RCS/Pulsed Linac
- **Particle Type**: protons/H\(^-\)
- **Beam Kinetic Energy**: 8.0 GeV
- **Pulse rate**: 10 Hz
- **Pulse Width**: 0.002/4.3 msec
- **Cycles to MI**: 6
- **Particles per cycle to Recycler**: \(2.6 \times 10^{13}\)
- **Beam Power to 8 GeV program**: 300 kW

### Main Injector/Recycler
- **Beam Kinetic Energy (maximum)**: 120 GeV
- **Cycle time**: 1.4 sec
- **Particles per cycle**: \(1.6 \times 10^{14}\)
- **Beam Power at 120 GeV**: 2200 kW
3 GeV Super-conducting CW Linac: High Power and High Duty Factor

1 μsec period at 3 GeV

- mu2e pulse (9e7) 162.5 MHz, 100 nsec 600 kW
- Kaon pulse (9e7) 27 MHz 1200 kW
- Nuclear pulse (9e7) 27 MHz 1200 kW

Separation scheme with traverse kicker ala JLAB.
## SC CW Linac Technology Map

### Sections

<table>
<thead>
<tr>
<th>Section</th>
<th>Freq</th>
<th>Energy (MeV)</th>
<th>Cav/mag/CM</th>
<th>Type</th>
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</thead>
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<tr>
<td>SSR0 ($\beta_G=0.11$)</td>
<td>325 MHz</td>
<td>2.5-10 MeV</td>
<td>26 /26/1</td>
<td>SSR, solenoid</td>
</tr>
<tr>
<td>SSR1 ($\beta_G=0.22$)</td>
<td>325 MHz</td>
<td>10-32 MeV</td>
<td>18 /18/2</td>
<td>SSR, solenoid</td>
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<tr>
<td>SSR2 ($\beta_G=0.4$)</td>
<td>325 MHz</td>
<td>32-160 MeV</td>
<td>44 /24/4</td>
<td>SSR, solenoid</td>
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<tr>
<td>LB 650 ($\beta_G=0.61$)</td>
<td>650 MHz</td>
<td>160-520 MeV</td>
<td>42 /21/7</td>
<td>5-cell elliptical, doublet</td>
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<tr>
<td>HB 650 ($\beta_G=0.9$)</td>
<td>650 MHz</td>
<td>520-2000 MeV</td>
<td>96 /12/12</td>
<td>5-cell elliptical, doublet</td>
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<tr>
<td>ILC 1.3 ($\beta_G=1.0$)</td>
<td>1300 MHz</td>
<td>2000-3000 MeV</td>
<td>64 / 8/8</td>
<td>9-cell elliptical, quad</td>
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</table>
An Incomplete Menu of World Class Research Targets Enabled by Project-X

Neutrino Physics:

- Mass Hierarchy
- CP violation
- Precision measurement of the $\theta_{23}$ (atmospheric mixing). Maximal??
- Anomalous interactions, e.g. $\nu_\mu \rightarrow \nu_\tau$ probed with target emulsions (Madrid Neutrino NSI Workshop, Dec 2009)
- Search for sterile neutrinos, CP & CPT violating effects in next generation $\nu_e, \bar{\nu}_e \rightarrow X$ experiments....x3 beam power @ 120 GeV, x10–x20 power @ 8 GeV.
- Next generation precision cross section measurements.
Pursuing next-generation neutrino parameters is beam-power hungry:

**Project-X Triples the Sensitivity**

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**Figure 3:** Plot showing 1 sigma error (in degrees) on $\delta_{CP}$ at an LBNE far detector complex composed of a 100–kT water Cherenkov detector and a 17–kT liquid argon detector. The exposure assumes a 700–kW proton beam. [Plot courtesy of Lisa Whitehead, Brookhaven National Laboratory]
Can we use “excess” 8 GeV pulsed power to drive LBNE as well??

A wide-band beam at 1300km
Muon Physics:

- Next generation muon-to-electron conversion experiment, new techniques for higher sensitivity and/or other nuclei.

- Next generation (g-2)\(\mu\) if motivated by next round, theory, LHC. New techniques proposed to JPARC that are beam-power hungry...

- \(\mu\) edm

- \(\mu \rightarrow 3e\)

- \(\mu^+e^- \rightarrow \mu^-e^+\)

- \(\mu^-A \rightarrow \mu^+A'; \mu^-A \rightarrow e^+A'; \mu^-e^- (A) \rightarrow e^- e^- (A)\)

- Systematic study of radiative muon capture on nuclei.
Pursuing the Holy Grail of Stopped Muon Experiments: A High Acceptance Mono-energetic muon source
Kaon Physics:

- $K^+ \rightarrow \pi^+\nu\bar{\nu}$: >1000 events, Precision rate and form factor.
- $K_L \rightarrow \pi^0\nu\bar{\nu}$: 1000 events, enabled by high flux & precision TOF.
- $K^+ \rightarrow \pi^0\mu^+\nu$: Measurement of T-violating muon polarization.
- $K^+ \rightarrow (\pi,\mu)^+\nu_X$: Search for anomalous heavy neutrinos.
- $K_L \rightarrow \pi^0e^+e^-$: <10% measurement of CP violating amplitude.
- $K_L \rightarrow \pi^0\mu^+\mu^-$: <10% measurement of CP violating amplitude.
- $K^0 \rightarrow X$: Precision study of a pure $K^0$ interferometer: Reaching out to the Plank scale ($\Delta m_K/m_K \sim 1/m_P$)
- $K^0, K^+ \rightarrow$ LFV: Next generation Lepton Flavor Violation experiments...and more
JPARC Play Book

Hadron Hall Experimental Programs

Hypernuclei

ΔΔ, Σ Hypernuclei

Δ, Σ Hypernuclei

K meson Implantation of Kaon and the nuclear shrinkage

J/Ψ implantation?

Courtesy Nagamiya-san
Taking a page from the JPARC hadron hall playbook: One target can serve multiple kaon experiments.
Taking a page from the JPARC hadron hall playbook: One target can serve multiple kaon experiments.
An Incomplete Menu of World Class Research Targets Enabled by Project-X. continued...

**Nuclear Enabled Particle Physics:**
- Production of Ra, Rd, Fr isotopes for nuclear edm experiments that are uniquely sensitive to Quark-Chromo and electron EDM's.

**Baryon Physics:**
- \( pp \rightarrow \Sigma^+ K^0 p^+ \); \( \Sigma^+ \rightarrow p^+ \mu^+ \mu^- \) (HyperCP anomaly, and other rare \( \Sigma^+ \) decays)
- \( pp \rightarrow K^+ \Lambda^0 p^+ \); \( \Lambda^0 \) ultra rare decays
- \( \Lambda^0 \leftrightarrow \bar{\Lambda}^0 \) oscillations (Project-X operates below anti-baryon threshold)
- Neutron EDMs
Road to Future Progress:
Neutrino Research Program

• Strong international community. US community is healthy and growing.

• Value of higher beam power from the Main Injector is clear in principle. However, there is a need to develop and promote the research program strategy that addresses $\theta_{13}$, opportunities of near-term measurements, etc. Progress on Project-X need not be contingent on the magnitude of $\theta_{13}$.

• Explicitly engage the Neutrino Factory community to explore and develop the low-energy conceptual design from Project-X to DUSEL.

• Investigate opportunities that may exist with an 8 GeV neutrino program, including long-baseline beam to DUSEL.
Road to Future Progress: Muon Research Program

• International community active, US community is small, but growing with Mu2e and $(g-2)_\mu$.

• $(g-2)_\mu$. Let’s do it!

• No conceptual accelerator & beam design yet for driving next-generation $\mu \rightarrow e$ conversion experiment. A PRISM (FFAG) based solution needs further accelerator design work. Interesting synergies with Muon Collider cooling concepts are being explored that would clearly exploit Project-X. This work should be encouraged to answer the question:

  PSI has a 1-2 MW source for muon physics now...why & how is Project-X better??

• Good opportunity for Intensity Frontier fellows.
Road to Future Progress: Kaon Research Program

- International community active, Fermilab community essentially dormant now. Buoyed to some extent now by the US quark flavor physics community—but this community is currently under stress regarding futures.

- Excellent basis for 1000 event $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ experiment now.

- P996 Fermilab proposal stalled, raises questions in community.

- A plan for bridging to the Project-X era is needed.
  - Push for kaon experiment CDO @ Project-X ASAP.
  - Meaningful collaboration with JPARC and CERN initiatives in the near term?
Road to Future Progress: Nuclear-Particle Physics

• Strong international community. US community is healthy and growing.

• No historical context for Fermilab. Some sensitivities with other labs and agencies.

• Working closely with Argonne National Lab is a great opportunity to bridge into this community.

• Should explore Intensity Frontier Fellows, Joint positions and Fellowships between ANL and FNAL, possibly University of Chicago.
Summary

Project-X is a next generation high intensity proton source that can deliver:

**Neutrinos:** An after-burner for LBNE that reduces the tyranny of (Detector-Mass $\times$ Running-time) by $\times3$, and a foundation for a Neutrino Factory.

**Rare Processes:** Game-changing beam power and timing flexibility that can support a broad range of particle physics experiments.

**Lepton Collider:** A platform for Muon Collider development.

**Prospects:** International collaboration formed, ongoing substantial US (DOE) investments in R&D (Project-X + SRF + ILC) on Super Conducting RF accelerator technology supporting Project-X.

Optimum Energy for ADS R&D
# Beam Requirements for a World Leading Rare Processes Program

<table>
<thead>
<tr>
<th>Rare Processes</th>
<th>Proton Energy (kinetic)</th>
<th>Beam Power</th>
<th>Beam Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rare Muon decays</td>
<td>2 - 3 GeV</td>
<td>&gt;500 kW</td>
<td>1 kHz - 160 MHz</td>
</tr>
<tr>
<td>(g-2) measurement</td>
<td>8 GeV</td>
<td>20 - 50 kW</td>
<td>30 - 100 Hz.</td>
</tr>
<tr>
<td>Rare Kaon decays</td>
<td>2.6 - 4 GeV</td>
<td>&gt;500 kW</td>
<td>20 - 160 MHz. (&lt;50 psec pings)</td>
</tr>
<tr>
<td>Precision K⁰ studies</td>
<td>2.6 - 3 GeV</td>
<td>&gt;200 kW (100μA internal target)</td>
<td>20 - 160 MHz. (&lt;50 psec pings)</td>
</tr>
<tr>
<td>Neutron and exotic nuclei EDMs</td>
<td>1.5 - 2.5 GeV</td>
<td>&gt;500 kW</td>
<td>&gt; 100 Hz</td>
</tr>
</tbody>
</table>
High Duty-Factor Proton Beams
Why is this important to Rare Processes?

• Experiments that reconstruct an “event” to a particular time from sub-detector elements are intrinsically vulnerable to making mistakes at high instantaneous intensity (I). The probability of making a mistake is proportional to $I^2 \times \delta t$, where $\delta t$ is the event resolving time.

• Searching for rare processes requires high intensity.

• Controlling backgrounds means minimizing the instantaneous rate and maximizing the time resolution performance of the experiment.

• This is a common problem for Run-II, LHC, Mu2e, High-School class reunions, etc.
What is the optimum energy for producing low-energy muons?

LAQGSM/MARS simulation validated with HARP data
# Sensitivity of Kaon Physics Today

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Sensitivity</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>CERN NA62</td>
<td>$100 \times 10^{-12}$</td>
<td>measurement sensitivity of $K^+ \rightarrow e^+\nu$</td>
</tr>
<tr>
<td>Fermilab KTeV</td>
<td>$20 \times 10^{-12}$</td>
<td>measurement sensitivity of $K_L \rightarrow \mu\mu e\bar{e}$</td>
</tr>
<tr>
<td>Fermilab KTeV</td>
<td>$20 \times 10^{-12}$</td>
<td>search sensitivity for $K_L \rightarrow \pi\mu e, \pi\pi\mu e$</td>
</tr>
<tr>
<td>BNL E949</td>
<td>$20 \times 10^{-12}$</td>
<td>measurement sensitivity of $K^+ \rightarrow \pi^+\nu\bar{\nu}$</td>
</tr>
<tr>
<td>BNL E871</td>
<td>$1 \times 10^{-12}$</td>
<td>measurement sensitivity of $K_L \rightarrow e^+e^-$</td>
</tr>
<tr>
<td>BNL E871</td>
<td>$1 \times 10^{-12}$</td>
<td>search sensitivity for $K_L \rightarrow \mu e$</td>
</tr>
</tbody>
</table>

Probing new physics above a 10 TeV scale with 20-50 kW of protons.

Next goal: 1000-event $\pi\nu\nu$ experiments... $10^{-14}$ sensitivity.
Validating Simulation Tools...

- Los Alamos + MARS simulation suite (LAQGSM + MARS15) is now a state of the art tool set to simulate the challenging region between 1-4 GeV/c proton beam momentum.

  [Gudima, Mokhov, Striganov]

- Validated against the high quality data sets from COSY.

Kaon Yields at Constant Beam Power

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).
KOPIO-AGS and Project-X kaon momentum spectra comparison

Figure 13: $K^0_L$ spectrum incident on KOPIO decay volume.
Rates sensitive to other BSMs: Warped Extra Dimensions as a Theory of Flavor??

The Randall-Sundrum (RS) idea

According to string theory, our universe might consist of a three-dimensional "brane," embedded in higher dimensions. In the model developed by Lisa Randall and Raman Sundrum, gravity is much weaker on our brane than on another brane, separated from us by a fifth dimension. (Time is the unseen fourth dimension.)

*Island Universes in Warped Space-Time*

(Wikipedia)

- **Fifth dimension**
  - Space is warped by energy throughout five-dimensional space-time. As a result, gravity is much weaker on our brane.

- **Gravity Brane**
  - Where gravity is concentrated

- **Gravitons**
  - Which transmit gravity, are closed strings, which are not confined to either brane.

- **Warped space-time**
  - Because space-time is warped, things are exponentially bigger and lighter closer to our brane.

The ends of open strings, whose oscillations are particles and forces other than gravity, are stuck to our brane.
Effect of Warped Extra Dimension Models on Branching Fractions

Buras et al. SM accuracy of <5%, motivates 1000-event experiments
$K_L \rightarrow \pi^0 \nu \nu$ Experimental Challenge: “Nothing-in nothing out”

- KEK/JPARC approach emphasizes high acceptance for the two decay photons while vetoing everything else: A hermetic “bottle” approach.

- The original KOPIO concept measures the kaon momentum and photon direction...Good! But costs detector acceptance and requires a large beam to compensate. Project-X Flux can get back to small kaon beam!

Another $K_L^0 \rightarrow \pi^0 \nu \nu$ Experiment Concept

- Use TOF to work in the $K_L^0$ c.m. system
- Identify main 2-body background $K_L^0 \rightarrow \pi^0 \pi^0$
- Reconstruct $\pi^0 \rightarrow \gamma \gamma$ decays with pointing calorimeter
- $4\pi$ solid angle photon and charged particle vetos
KOPIO inspired: Micro-bunch the beam, TOF determines $K_L$ momentum.

Fully reconstruct the neutral Kaon in $K_L \rightarrow \pi^0 \nu \bar{\nu}$ measuring the Kaon momentum by time-of-flight.

Start when proton beam hits the target. End at the decay time and decay point reconstructed from the two photons.

Timing uncertainty due to microbunch width should not dominate the measurement of the kaon momentum; requires RMS width < 200ps. CW linac pulse timing of less than 50ps is intrinsic.
EDM measurements: BSM slayers

Experimental Limit on d (e cm)


neutron: electron:

$\phi \sim 1$

Left-Right

$10^{-20}$

$10^{-32}$

$10^{-22}$

$10^{-34}$

$10^{-24}$

$10^{-36}$

$10^{-26}$

$10^{-38}$

$10^{-28}$

$10^{-30}$

$10^{-30}$

$10^{-32}$

$10^{-34}$

$10^{-36}$

$10^{-38}$

Electromagnetic

Multi Higgs

SUSY $\phi \sim 1$

Left-Right $\phi \sim \alpha/\pi$

Standard Model


Guy Savard, ANL
Enhanced EDM of $^{225}$Ra

**Enhancement mechanisms:**
- Large intrinsic Schiff moment due to octupole deformation;
- Closely spaced parity doublet;
- Relativistic atomic structure.

Enhancement Factor: $\text{EDM} (^{225}\text{Ra}) / \text{EDM} (^{199}\text{Hg})$

<table>
<thead>
<tr>
<th>Skyrme Model</th>
<th>Isoscalar</th>
<th>Isovector</th>
<th>Isotensor</th>
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<tbody>
<tr>
<td>$\text{SkM}^*$</td>
<td>1500</td>
<td>900</td>
<td>1500</td>
</tr>
<tr>
<td>$\text{SkO}'$</td>
<td>450</td>
<td>240</td>
<td>600</td>
</tr>
</tbody>
</table>

Schiff moment of $^{199}\text{Hg}$, de Jesus & Engel, PRC (2005)
Schiff moment of $^{225}\text{Ra}$, Dobaczewski & Engel, PRL (2005)

Guy Savard, ANL
Why DUSEL?

- 1300 km distance is a good compromise of mass-hierarchy and CP violation sensitivities
- Deep underground site allows rich physics program in addition to LB neutrinos

Bob Svoboda, 4th PXP Workshop