Physics Opportunities with High Intensity Accelerators

The Six Accelerator Capability areas:

– Energy Frontier Hadron Colliders
– Energy Frontier Lepton and Gamma Colliders
– High Intensity Secondary Beams Driven by Protons
– High Intensity Electron and Photon Beams
– Electron-ion Colliders
– Accelerator Technology Testbeds and Test Beams

Example Acc. Sources:
– Neutrino super-beams
– Project-X
– Beta-beams
– DAEδALUS & pion DAR
– IsoDAR (isotope DAR)
– Neutrino Factory

Example Physics:
– Neutrino 3-flavor mixing
– Sterile neutrino hints
– Other weakly interacting and dark sector particles
– Non-standard neutrino interactions
Neutrino 3-flavor Mixing ⇒ Precision Measurement Era

\[ U_{PMNS}^{2013} = \begin{pmatrix} 0.779 \text{ to } 0.848 & 0.510 \text{ to } 0.604 & 0.122 \text{ to } 0.190 \\ 0.183 \text{ to } 0.568 & 0.385 \text{ to } 0.728 & 0.613 \text{ to } 0.794 \\ 0.200 \text{ to } 0.576 & 0.408 \text{ to } 0.742 & 0.589 \text{ to } 0.775 \end{pmatrix} \]

Neutrino mixings now known with similar error to 1995 quark mixings.

Beyond neutrino mixings:

- Need to determine “Mass Hierarchy”
  - Use long baseline experiments through matter effects (i.e. LBNE)

- Need to determine and measure “CP Violation”
  - Key question for the physics of neutrino mixing (also maybe Leptogenesis)
  - Difficult: need precision oscillation measurements
Key Experimental Requirements

• Beam (neutrino/antineutrino source) intensity
  – Statistics at a premium (especially for $\bar{\nu}$ running)
  – Need good understanding of flux and flavor components

• Detector size and efficiency
  – Larger size can impact cost and detection efficiency

• Control of systematic uncertainties
  – Need to fit shape of event energy distribution
    • Energy dependence of flux, backgrounds, and efficiency
  – Need to compare $\nu$ versus $\bar{\nu}$ distribution
    • May be complicated by $\nu$ contamination in $\bar{\nu}$ running

Examples

LBNE: Fermilab to South Dakota
  – 35 kton Liquid Argon - 700kW to 1200kW beam power
  – Optimum 1300km distance for on-axis pion decay-in-flight
  – Significant matter effects

Hyper-K: J-PARC to Hyper-K
  – 560 kton water cherenkov - 750kW beam power
  – Off-axis 295km distance
  – Small matter effects
Improvements with Better Accelerator Sources

**Project-X:**
- x3 improved intensity for LBNE
- (0.7MW → 1.1MW → 2.3MW)

**Beta-Beams:**
- Pure $\nu_e$ and $\bar{\nu}_e$ beams generated by the $\beta$-decay of accelerated radio-nuclides stored in a high energy storage ring.
  - Measure $\nu_e \rightarrow \nu_\mu$ oscillations
**Improvements with Better Accelerator Sources (2)**

**DAEδALUS:**
- Pion decay-at-rest neutrino source produced by high-intensity cyclotron
  - Very high-intensity $\bar{\nu}_\mu$ source with known spectrum
- Neutrino sources at three different distances
  - Use inverse-beta-decay interaction to isolate a pure sample of $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations
- Can combine DAEδALUS antineutrino data set with long baseline neutrino-only data for much improved CP violation search
  - Example: combination with Hyper-K

![Diagram](image.png)
Collection of Data That Doesn’t Fit 3-neutrino Model ⇒ Sterile Neutrinos?

- MiniBooNE/LSND $\nu_e / \bar{\nu}_e$ appearance signals

Data sets indicate a high $\Delta m^2$

Can be fit by introducing a new $\nu$, ...but it must be non-interacting (sterile)!

- Reactor Anomaly: $\bar{\nu}_e$ disappearance signals?

These signals are at the 2-4$\sigma$ level ⇒ Need new “definitive” experiments

Establishing the existence of sterile neutrinos would be a major result for particle physics
Probing $\Delta m^2 \sim 1 \text{ eV}^2$ Oscillations

Short and Very-short Baseline Oscillation Experiments

$\nu$ - Source

Radioactive Source
or
Isotope Source
or
Reactor Source
or
Proton into Dump Source

$\nu$ - Detector

• Need definitive experiments
  – Significance at the $> 5\sigma$ level
  – Smoking gun: Observation of oscillatory behavior within detector

• Several directions for next generation accelerator experiments
  – Multi-detector accelerator neutrino beam experiments
  – Very short baseline (VSBL) experiments with compact neutrino sources

• Many ideas and neutrino sources:
  – Reactor sources
  – Radioactive sources
  – Isotope sources
  – $\pi$ / K decay-at-rest sources
  – $\pi$ decay-in-flight sources
  – Low-energy $\nu$-Factory source

Light Sterile Neutrinos: A White Paper

Improvements with Better Accelerator Sources

• Short baseline pion decay-in-flight beams
  – Project-X could provide an enhanced replacement to the existing Booster-Neutrino Beam
  – Multi-detector (near-mid-far) provide definitive sterile osc searches
    • LAr1: 1 kton liquid argon
    • BooNE-X: 1-2 kton oil/scint

• Pion decay-at-rest beam
  Protons into dump
  \[ \rightarrow \pi^+ \rightarrow \nu_\mu \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \]
  – Spallation neutron facilities
    • OscSNS: at SNS facility
    • JPARC SN facility
  – Also, Project-X RCS option
  – Physics signals:
    \[ \bar{\nu}_e \text{ appearance} \]
    \[ \nu_\mu^{12}\text{C neutral current} \]
    \[ \nu_e \text{ disappearance} \]

Other Physics:
- \( \nu \) Coherent Scattering
- Supernova cross sections
Improvements with Better Accelerator Sources (2)

- **IsoDAR:** Isotope Decay-at-rest beam (high intensity $\nu_e$ source)
  - P ($60$ MeV@10 ma) into target $\rightarrow ^8\text{Li}$
  - $^8\text{Li} \rightarrow ^8\text{Be} + e^- + \bar{\nu}_e$
    - Known $\bar{\nu}_e$ energy spectrum (mean $6.5$ MeV)
    - Observe changes in the event rate as a function of $L/E$
      - $\sim 160,000$ IBD events / yr in Kamland
Possible Staging of Neutrino Factory

Neutrino factory has the advantages:

1. well collimated beam
2. known energy spectrum
3. easier detection of outgoing $\mu^\pm$ in $\nu_e \rightarrow \nu_\mu$
   but need magnetized detector

• $\nu$STORM: Short baseline neutrino factory enabling a definitive search for sterile neutrinos
• L3NF: An initial long baseline neutrino factory, optimized for a detector at Homestake that exceeds the capabilities of conventional superbeam technology.
• NF: A full intensity neutrino factory ultimate source to enable precision CP violation measurements

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<th>L3NF</th>
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Non-Standard Neutrino Interactions

- Non-standard neutrino interactions (NSI) would alter matter effects in long baseline neutrino oscillation measurements
  - LBNE with Project-X has good baseline and statistics

NC NSI discovery reach (3σ C.L.)

\[
sin^2 2\theta_{13} = 0.094
\]
only one \( \epsilon \neq 0 \) at a time
Left/right edges: Best/worst arg(\( \epsilon \))

- Precision neutrino-electron scattering can also probe NSI since it is a well-understood Standard Model process
  - An IsoDAR cyclotron experiment at Kamland would have good statistics for \( \overline{\nu}_e + e \rightarrow \overline{\nu}_e + e \)
Searching for Exotic Particles with Short-baseline Experiments

- Short baseline experiments are a good tool for exotic particle searches including axions, dark gauge bosons, and WIMPs
  - A “portal’ to the dark sector is dark photon mixing with normal photons and $\pi^0 / \eta^0$ decays to photons can produce “dark-sector” particles
  - Best to run in a “beam-dump” mode (no decay region) to suppress the conventional neutrino backgrounds from pion and muon decay.
    - Not compatible with regular neutrino running - so need dedicated running
  - Intensity and energy are key parameters that could be significantly improved with various stages of Project-X
    - Increase of x100 @ 8 GeV and x10 @ 100 GeV
End of Part 1
Physics Opportunities
Backup Slides