Neutrino Physics and Requirements to Accelerators

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IPAC’13, May 17, 2013
Neutrino industry
Neutrino physics: problems and methods

- Mass
- Dirac/Majorana
- Magnetic moments
- Oscillation/sterile neutrinos
- Astronomy
- Cosmology
- Geology
- Accelerator
- Reactor
- Atmospheric
- Solar
- Astro-objects
- Relic-neutrino
- Earth
- Radioactive sources
- Liquid scintillator
- Liquid Argon
- Sampling detector
- Emulsion
- Water Cerenkov
- Nuclear chemistry

- Semiconductor/crystals/gaseous/scintillator
Current & Future Neutrino Experiments (selected)

- **Basic properties of neutrinos**
  - Magnetic moments: Texono, GEMMA, ...
  - Absolute mass: Katrin, Mare, Project 8, ...

- **Neutrino oscillations & sterile neutrinos**
  - Atmospheric neutrinos($\theta_{23}$): SuperK, INO, HyperK, PINGU, ...
    - mass hierarchy...
  - Solar neutrinos($\theta_{12}$): SuperK, Borexino, LENA...
    - Solar & astrophysics
  - Reactor neutrinos($\theta_{13}$): Daya Bay, Double CHOOZ, Reno, DYBII...
    - mass hierarchy, sterile neutrinos,...
  - Accelerator neutrinos($\theta_{23}, \theta_{13}$): MINOS, T2K, NOVA, LBNE, HyperK, LBNO...
    - mass hierarchy, sterile neutrinos, $\delta$, ...

- **Neutrino astronomy & applications**
  - Supernova $\Rightarrow$ with solar/atmospheric/reactor neutrinos
  - Geo-neutrinos $\Rightarrow$ with solar/reactor neutrinos
  - High energy neutrino astronomy(Icecube, Antares, KM3,...)
**Neutrino Oscillation**

- If the neutrino mass eigenstate is different from that of the weak interaction, neutrinos can oscillate: from one type to another during the flight:

\[
\begin{align*}
\nu_e & \rightarrow \nu_\mu \\
\nu_\mu & \rightarrow \nu_e \\
\nu_e & \rightarrow \nu_\mu
\end{align*}
\]

**Oscillation probability:**

\[
P(\nu_e \rightarrow \nu_\mu) = \sin^2(2\theta) \sin^2(1.27\Delta m^2 L/E)
\]

**Oscillation matrix for 3 generations:**

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= \begin{pmatrix}
V_{e1} & V_{e2} & V_{e3} \\
V_{\mu1} & V_{\mu2} & V_{\mu3} \\
V_{\tau1} & V_{\tau2} & V_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

- Known parameters: \(\theta_{23}, \theta_{12}, |\Delta M^2_{23}|, \Delta M^2_{12}\)
- Recent progress: \(\theta_{13}\)
- Unknown parameters: mass hierarchy\((\Delta M^2_{23})\), CP phase \(\delta\)
\[ \theta_{12} \text{ and } \Delta M^2_{12} \]

- **First evidence in 60’s-80’s by Homestake**
  - Solar \( \nu_e \) disappearance

- **Well established by SNO using solar neutrinos in 2000:**
  - Disappeared solar \( \nu_e \) actually become \( \nu_\mu + \nu_\tau \)

- **Confirmed by KamLAND using reactor neutrinos in 2001**
  - Reactor \( \bar{\nu}_e \) disappearance & \( \theta_{12} \) and \( \Delta M^2_{12} \) well determined

- **Current measurements:**
  \[
  \tan^2 \theta_{12} = 0.436^{+0.029}_{-0.025}, \quad \Delta m^2_{21} = 7.53^{+0.18}_{-0.18} \times 10^{-5} \text{ eV}^2
  \]

- **Issues now:**
  - Mostly solar related

- **Future experiments**
  - DYBII(reactor)

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ArXiv: 1303.4667
θ_{23} and ΔM^2_{23}

- First evidence in 80’s by Kamiokande and IMB
  - Atmospheric neutrinos \( \nu_\mu \) disappearance
- Well established by SuperKamiokande in 1998
  - Atmospheric neutrinos \( \nu_e \) disappearance (as a function of L/E)
- Confirmed by accelerator experiments
  - Beam \( \nu_\mu \) disappearance (K2K, T2K, MINOS…)
  - \( \nu_\tau \) appeared in \( \nu_\mu \) beam (OPERA)
- Current measurements:
  
  \[
  |\Delta m^2| = (2.41^{+0.09}_{-0.10}) \times 10^{-3} \text{ eV}^2
  \]
  
  \[
  \sin^2(2\theta) = 0.950^{+0.035}_{-0.036}
  \]

- Issues now:
  - Sign of \( ΔM^2_{23} \)
  - Is \( θ_{23} \) maximal?
- Future experiments
  - NOVA, INO, HyperK…

ArXiv:1304.6335
\( \theta_{13} \) and \( \Delta M^2_{13} \)

- **First evidence of non-zero \( \theta_{13} \) in 2011 by T2K, MINOS and Double Chooz**
- **Well established non-zero \( \theta_{13} \) by Daya Bay using reactor neutrinos in 2012**
- **Confirmed afterwards by RENO, Double Chooz and T2K**
- **Precision:**
  - \( \Rightarrow 13\% \rightarrow 4\% \text{ in 5 years} \)
- **Future experiments**
  - \( \Rightarrow \text{None} \)

\( \Delta M^2_{13} \) not independent:

\[
\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}
\]

\[
\text{NH : } |\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|
\]

\[
\text{IH : } |\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|
\]
Daya Bay: $\theta_{13}$ is determined

$\sin^2 2\theta_{13} = 0.089 \pm 0.010 \pm 0.005$

7.7 $\sigma$ for non-zero $\theta_{13}$


RENO, Double Chooz & T2K confirmed the results at 3-5 $\sigma$
Neutrino physics in the Future

- **Mass hierarchy**
  - By reactor neutrinos: DBYII
  - By atmospheric neutrinos: INO, HyperK, PINGU
  - By Long baseline accelerator neutrinos: HyperK, LBNE, LBNO,…

- **CP phase**
  - By atmospheric neutrinos: HyperK
  - By Long/medium baseline accelerator neutrinos: HyperK, LBNE, LBNO,…

- **Sterile neutrinos**
  - Radioactive sources: CeLAND, SoX,…
  - By reactor neutrinos: Nucifer, Stereo, Solid …
  - By short baseline accelerator neutrinos: MicroBoone, IsoDAR, Icarus/Nessie, nuSTORM…

Thanks to the large $\theta_{13}$
## Mass Hierarchy by reactors: DYBII

<table>
<thead>
<tr>
<th>Location</th>
<th>Power/GW</th>
<th>Status</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daya Bay</td>
<td>17.4</td>
<td>running</td>
<td></td>
</tr>
<tr>
<td>Huizhou</td>
<td>17.4</td>
<td>planned</td>
<td></td>
</tr>
<tr>
<td>Lufeng</td>
<td>17.4</td>
<td>approved</td>
<td></td>
</tr>
<tr>
<td>Yangjiang</td>
<td>17.4</td>
<td>Construction</td>
<td></td>
</tr>
<tr>
<td>Taishan</td>
<td>18.4</td>
<td>construction</td>
<td></td>
</tr>
</tbody>
</table>

- **Overburden**: ~ 700 m

**Notes:**
- Mass Hierarchy
- Mixing parameters
- Supernova neutrinos
- Geoneutrinos
- Sterile neutrinos
Physics reach of DYBII

For 6 years, taking into account all uncertainties and with the help of $\Delta m^2_{\mu\mu}$ from T2K and Nova, sensitivity can reach $4\sigma$
HyperK for Mass Hierarchy & CP

- Atmospheric & accelerator neutrinos
- 1 Mt water Cerenkov detector
- Beam from J-PARC (0.75 MW, 295 km)
- Physics:
  - Mass hierarchy
  - CP phase $\delta$
  - $\theta_{23}$

Sensitivity mostly from the beam

From T. NaKaya, talk at NeuTel 2013
### Future Accelerator Neutrino Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Beam Power (MW)</th>
<th>Baseline (km)</th>
<th>Detector</th>
<th>Start Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOVA</td>
<td>0.7</td>
<td>810</td>
<td>14 kt Iron calorimeter</td>
<td>2015</td>
</tr>
<tr>
<td>HyperK</td>
<td>0.75</td>
<td>295</td>
<td>560 kt Water Cerenkov</td>
<td>~ 2022</td>
</tr>
<tr>
<td>LBNE</td>
<td>0.7 → 2.3</td>
<td>1300</td>
<td>10 kt → 35kt Liquid Ar TPC</td>
<td>~ 2022 → ?</td>
</tr>
<tr>
<td>LBNO</td>
<td>0.75 → 2.0</td>
<td>2300</td>
<td>20 kt LAr TPC + 35 kt MIND</td>
<td>?</td>
</tr>
</tbody>
</table>
LBNE & project-X

- From Fermilab Main injector (& its upgrade) to Homestake (1300 km)
- Program in phases:
  - beam power: 0.7-2.3 MW
  - LAr TPC mass: 10-35 kt

From M. Diwan, talk at NeuTel 2013
LBNO

- From CERN SPS (& its upgrade) to Pyhäsalmi (Finland)
- Beam power: 0.7 MW $\rightarrow$ 2.0 MW
- Baseline of 2300 km: better MH sensitivity than that of LBNE
- Overburden is $\sim$1400m, good for many other physics

From A. Rubbia, talk at NeuTel 2013
The CN2PY beam

- Phase 1: use the proton beam extracted beam from SPS
  - 400 GeV, max $7.0 \times 10^{13}$ protons every 6 sec, 750 kW beam power
- Phase 2: use the proton beam from the new HP-PS

From A. Rubbia, talk at NeuTel 2013, ICARUS+NESSIE
First phase: ICARUS+NESSIE

• Beam from SPS: as an initial phase of the neutrino physics program at CERN
• Two types of detector for background rejection:
  – NESSIE: magnetized Iron calorimeter
  – ICARUS: Liquid Ar TPC
• Key parameters:
  – Near site @ 300m
    • NESSIE mass=840t
    • ICARUS mass= 119t
  – Far site @ 1600
    • NESSIE mass=1515t
    • ICARUS mass= 476t
• Physics: sterile neutrinos
Sterile neutrinos

- Sterile neutrinos as the partner of active neutrinos, may exist and oscillate with their active partners.
- Theoretical motivation: various extension of SM
- Experimental “hints”: LSND: $\nu_e$ in $\nu_\mu$ beam; MiniBooNE: $\nu_e$ in $\nu_\mu$ beam; Reactor: $\nu_e$ deficit; Gallex: $\nu_e$ deficit
- Global fit with severe tensions
- Not favored by cosmological bounds (PLANCK) but there are ways out

Solution: experiments
- Radioactive sources(or):
  - CeLAND ($^{144}\text{Ce}$ in KamLAND), SoX ($^{51}\text{Cr}$ in Borexino),...
- Reactors
  - Nucifer, Stereo, Solid,...
- Accelerator beams
  - IsoDAR, MicroBoone, Icarus/Nessie, nuSTORM...
IsoDAR

- A proton beam on $^9$Be $\rightarrow$ n $\rightarrow$ n + $^7$Li $\rightarrow$ $^8$Li $\rightarrow$ $\bar{\nu}_e$
- Site may be at KamLAND or SNO
- Phased program of DAEδALUS:

![Diagram of IsoDAR](image-url)
DAEδALUS

- Multiple superconducting Cyclotrons to produce muon neutrinos from $\pi$ decays at rest
- Look for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation with a L/E dependence to measure the CP phase $\delta$
nuSTORM

- A 3.8 GeV muon storage ring + Minos-like detector to solve sterile neutrino problem, proposed at Fermilab
- A phased program for neutrino factory

Existing technology
Existing proton beam
R&D for neutrino factory
LOI submitted
Neutrino Factory

- Neutrinos from muon decays for $\theta_{13}$, MH & CP
- Typical parameters:
  - $\sim 10$ GeV muon beam
  - $\sim 10^{21}$ $\nu$/year
  - $\sim 4$ MW power
  - $\sim 2000$ km baseline
  - 0.1 – 1.0 Mt detector
- Technology is far from mature. Global efforts:
  - Proton driver $\Rightarrow$ also needed by super-beams
  - Target $\Rightarrow$ MERIT
  - Cooling $\Rightarrow$ MICE
  - Muon acceleration $\Rightarrow$ EMMA
- Also a pre-stage for muon collider
Where are we heading for?

- Neutrino factory is a dream machine for $\theta_{13}$, MH & CP
  - Long Baseline, high energy & high power $\Rightarrow$ expensive
- Previously discussed beta-beams are similar
- Since $\theta_{13}$ is known, and MH will likely be determined by DYBII/HyperK/LBNE/LBNO, we need only a machine to determine CP
- What is the best machine if HyperK/LBNE/LBNO did not find CP?

![Graphs showing Neutrino Fact and FoM vs E(GeV)]

Low energy $\Rightarrow$ cheaper
How low is the best for CP?

- Below in-elastic threshold: \( \sim 300 \text{ MeV} \) \( \rightarrow \) baseline = 150 km
- Such a threshold is similar for CC/NC & \( \nu/\bar{\nu} \)
- Although we lose statistics due to the lower cross section, but we have less systematics by being \( \pi^0 \) free

J. Formaggio and G. Zeller, Rev. Mod. Phys. 84.3(2012)1307
Europe efforts: Super-beams(π)

- **CERN HP-SPL**
  - 4.5 GeV proton driver, 4 MW power
  - Baseline: 130 km to Frejus

- **European Neutron Spallation Source at Lund (ESS)**
  - 2.5 GeV, 5 MW Superconduction Linac
  - Baseline: 260 km up; 540 km Garpenberg Mine?

- **Possible detector:** 440 kt fiducial mass MEMPHYS

- Neutrinos from $\pi$ decays suffer from backgrounds

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ESS $E_\nu$ spectrum: peaked at 300 MeV

*From T. Ekelof, talk at NeuTel 2013*
Efforts in IHEP: DYBIII

- A proton LINAC for ADS is now under development in China
- If R&D is successful, a CW Linac based ~15 MW proton driver can be used for neutrino beams
- Shoot towards the Daya Bay II detector? (150 km from CSNS site to DYBII)

**Phase I** (2011-2015)
- Injector 1
- 10 MeV
- 2013 ~5 MeV

**Phase II** (2016-201X)
- Injector 1
- 5-10 MW
- 2015 25-50 MeV

**Phase III** (201X-2022)
- Injector 2
- 100 MW
- 201X ~250 MeV

**Phase IV** (2023-2032)
- ≥1 GW
- ~2022 0.6~1 GeV
- ~2032 1.2~1.5 GeV

Key tech. R&D
- Phase I: Acc. & target & reactor prototype
- Phase II: Research Facility
- Phase III: Exp. Facility
- Phase IV: Demo Facility
Neutrinos from the muon decay

High-power proton linac (15MW, 1.5GeV)

Detector:
- Flavor sensitive
- Charge sensitive
- NC/CC sensitive

Neutrinos after the target/collection/decay: ~ $10^{21}$ ν/year
Issues (common to many proposals)

• **Proton accelerators**
  – High power CW machine, easier?
  – Challenges in RFQ and low-β superconducting cavities
  – Extremely low beam loss

• **Target**
  – Thermal load & radiation damage

• **Superconducting solenoids**
  – Some experience in low power case, but...
  – High heat load from radiation (kW level)
  – Radiation damage

• **Muon beam transport and decay channel**
  – Very large acceptance (>15000 mm-mrad)
  – Bunch rotation by superconducting cavities (100 MV)

• **Detector**
  – Flavor sensitive; Charge sensitive; NC/CC sensitive ➔
  MIND or water w/ Gd?
Summary

• Neutrinos are important in our universe
• Significant progress in the past
• Great prospects in the future
• (Accelerator + target + magnet) play a vital role: but a lot of technical challenges in front of us
• We need your help and let’s work together to discover the neutrino CP phase $\delta$
Thanks
谢谢