Questions in Experimental Neutrino Physics
- part 2: The Known Unknowns

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“known” Questions in ν-physics
(answered or being answered)

- Experimental neutrino physics in the last decades was driven by the following questions:
  
  - why do we see less neutrinos from the sun?
  - where are the atmospheric νs?
  - could this be due to oscillations?
  - What are the parameters of Oscillation?
    - Especially, is $\theta_{13}$ non-zero?
    - Is the $\theta_{23}$ mixing maximal?
  - what is going on with neutrino interactions?!
Big Questions in $\nu$-physics

- Experimental neutrino physics in the next decade (and beyond) will be driven by the following questions:

  - How much do neutrinos weigh?
  - What is the nature of the $\nu$?
  - Which neutrino is the heaviest and which is the lightest (MH)?
  - Do neutrinos violate CP?
  - Is our picture correct?
  - Are there more than 3 kinds of neutrinos?

\[ \beta \text{ decay and } 0\nu\beta\beta \text{ decay} \]

- Long-baseline neutrinos
- Short-baseline neutrinos

$\nu_\mu \rightarrow \nu_e$

En. range (0.1-10)GeV
Neutrino masses

• **Known constraints:**
  – Non zero (at least one must be > 0.05eV)
  – Direct measurements put it < 2eV
  – If Inverted Hierarchy \( \Sigma m_\nu > 0.1 \text{eV} \)
  – Cosmological constraints (model dependent?) \( \Sigma m_\nu < 0.23 \text{ eV} \)

• **Why are they so light?**
β-decay to measure ν-mass

Tritium is a good candidate for mass measurements:
- endpoint energy of 18.6 keV
- Lifetime 12.3 yrs
- Simple structure minimizes systematics

KATRIN
KATRIN

Works using the MAC-E filter (effectively high pass filter)

\[ \mu = \frac{p}{B} = \text{const} \]

Start foreseen for 2016.

Cannot really scale up from here.
Other ideas: Holmium

Electron capture on Holmium (HOLMES, ECHO)

\[ ^{163}\text{Ho}^+ + e^- \rightarrow ^{163}\text{Dy}^* + \nu_e \rightarrow ^{163}\text{Dy} + E_i + \nu_e . \]

Low temperature Bolometric detectors – all energy contained.

Projected sensitivities could reach the 0.2 eV range in the next “several” years.
Other ideas: Frequency

\[ \omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e} \]

First tests with a $^{83}$Kr source

Projected sensitivities
In the 0.2 eV range (2018) and even
In 0.05 eV range (2018+)

B. Monreal and JAF, Phys. Rev D80:051301

https://lanl.arxiv.org/abs/1408.5362
Big Questions in $\nu$-physics

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\[ \beta \text{ decay and } 0\nu\beta\beta \text{ decay} \]

- Long-baseline neutrinos:
  - $\nu_\mu \rightarrow \nu_e$
  - (0.1-10)GeV
  - En. range

- Short-baseline neutrinos
Dirac vs Majorana

- Of the building blocks of matter (quarks, leptons), neutrinos are the only charge-less.
- Thus, they are allowed to have a Majorana mass term.
- In such case, the neutrino is its own anti-particle and we could observe $0\nu\beta\beta$ decay.

\[
(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e
\]

\[
(A,Z) \rightarrow (A,Z+2) + 2e^-
\]

\[
0\nu\beta\beta
\]
$\beta\beta$ decay

Standard process

two “simultaneous” beta decays

$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu} |M^{0\nu}|^2 |\langle m_\nu \rangle|^2 / m_e^2$

$\langle m_\nu \rangle^2 = |\sum_i U_{ei}^2 m_{\nu i}|^2$

never observed

$\tau > 10^{25}$ y
(except a now excluded claim)

$0\nu$-DBD

a virtual neutrino is exchanged between the two electroweak lepton vertices

Only possible for certain isotopes, where the single beta transition is forbidden
Approaches to measurement

- Large mass to increase statistics.
- Increase energy resolution.
- Reconstruct 2 electron kinematics to reduce background.
- Either way, to cover the IH region need sensitivity 0.1 - 1 counts / y ton
Recent Results

~17 kg of $^{76}$Ge

~88 kg of $^{136}$Xe

206 kg of $^{130}$Te
Merging the results

- First attempt to combine different measurements into a single limit.
- Thic combination requires normalizing the isotopes via nuclear matrix elements.
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- $\beta$ decay and $0\nu\beta\beta$ decay

- long-baseline neutrinos

$\nu_\mu \rightarrow \nu_e$ (0.1-10) GeV En. range

- short-baseline neutrinos
LSND

- LSND, a pion DAR (Decay At Rest) observed an excess of $\bar{\nu}_e$
- The $\Delta m^2$ of $\sim 1\text{eV}^2$ is incompatible with standard neutrino oscillations
- A new neutrino state?

We have very strong constraints from LEP restricting the number of light neutrino species. To circumvent new state would have to be **sterile.**
MiniBooNE

Set out to confirm/disprove LSND.
- Same L/E
- Different detector (Cherenkov)
- Different source (DIF)
- Different excess (somewhat)

Excess is present full data set both in neutrinos and anti-neutrinos.
Reactor Experiments + Gallium (disappearance)

- Recalculation of Reactor neutrino fluxes show a deficit (including Daya Bay)
- Calibration sources for Gallium experiments show a similar behaviour.

- HINTS: Very different experimental techniques are pointing to short baseline oscillations.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Type</th>
<th>Channel</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSND</td>
<td>DAR</td>
<td>$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ CC</td>
<td>3.8$\sigma$</td>
</tr>
<tr>
<td>MiniBooNE</td>
<td>SBL accelerator</td>
<td>$\nu_\mu \rightarrow \nu_e$ CC</td>
<td>3.4$\sigma$</td>
</tr>
<tr>
<td>MiniBooNE</td>
<td>SBL accelerator</td>
<td>$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ CC</td>
<td>2.8$\sigma$</td>
</tr>
<tr>
<td>GALLEX/SAGE</td>
<td>Source - e capture</td>
<td>$\nu_e$ disappearance</td>
<td>2.8$\sigma$</td>
</tr>
<tr>
<td>Reactors</td>
<td>Beta-decay</td>
<td>$\bar{\nu}_e$ disappearance</td>
<td>3.0$\sigma$</td>
</tr>
</tbody>
</table>

Has our three neutrino model become 4?

“Known” physics

- $\Delta m^2 \sim 1\text{eV}^2$

- incompatible with 3 neutrino model.
- New neutrino has to “sterile”.
- If confirmed – Physics Beyond the Standard Model

“Unknown” physics

How can we further understand this new neutrino?

By measuring oscillations!

Many existing experiments sensitive to the effects.
MINOS/ MINOS+

Far Detector (5.4 kton)

Near Detector (1 kton)

High $\Delta m_{43}^2$: Oscillations in Near Detector

Low $\Delta m_{43}^2$: Oscillations in Far Detector

No $\nu_\mu$ disappearance observed!
Many New Measurements

So far, disappearance experiments see no further signs of the sterile neutrino.

ICARUS

Daya-Bay
Global fits

- Appearance/disappearance – significant tension of the 3+1 model.
Global fits

- Appearance/disappearance – significant tension of the 3+1 model.
- The 3+2 model does a little better.

<table>
<thead>
<tr>
<th>Model</th>
<th>$\chi^2_{\text{min}}$/dof</th>
<th>GOF</th>
<th>$\chi^2_{\text{PG}}$/dof</th>
<th>PG</th>
</tr>
</thead>
<tbody>
<tr>
<td>3+1</td>
<td>712/(689 – 9)</td>
<td>19%</td>
<td>18.0/2</td>
<td>$1.2 \times 10^{-4}$</td>
</tr>
<tr>
<td>3+2</td>
<td>701/(689 – 14)</td>
<td>23%</td>
<td>25.8/4</td>
<td>$3.4 \times 10^{-5}$</td>
</tr>
<tr>
<td>1+3+1</td>
<td>694/(689 – 14)</td>
<td>30%</td>
<td>16.8/4</td>
<td>$2.1 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

J.Kopp, Win2015

Need definitive test: $\nu_e$ appearance?
How to measure $\nu_e$ appearance in a LArTPC

- $\nu_e$ appearance is even more challenging because EM showers can come from gammas (e.g. originating from $\pi^0$ decays).
- The LArTPC and its bubble chamber like-data gives us strong background rejection tools.
Differentiating photons from electrons

• An EM shower that starts after a gap from the vertex is always background (especially if you can see two of them).

• Even if the gap is very small all is not lost.
  – We can reconstruct the charge at the start of the shower - “dE/dx discrimination”.

![Diagram showing EM showers, single electron, e⁻/e⁺ pair producing gamma, and reconstructed single shower MC.](image)
Data-Based dE/dx plot

Electron/single gamma separation

- Never measured for electron events coming from neutrinos in LAr.
MicroBooNE

Average Cryostat Temperature

Argon condenses at 87 K

Time (5/20/2015 to 6/10/2015)
MicroBooNE cooling down now.

Will reside on the same beam as MiniBooNE.

Using the LArTPCs Reconstruction capabilities should resolve the nature of the MiniBooNE excess.
MicroBooNE vs MiniBooNE

- MicroBooNE can resolve the nature of the MiniBooNE excess by performing a $\nu_e$ appearance search.

- As a single detector experiment it will not be able to observe the length dependence of an excess signal.

visible Neutrino Energy (GeV)

NC $\pi^0$ background!
SBN Program at Fermilab

SBND, near detector near the SciBooNE hall should be online in 2018.

ICARUS, far detector – being refurbished at CERN should be online in 2018.
SBND, or MicroBooNE with a Near Detector

- Due to its proximity to the target hall, it is sufficient for it to run for one year to amass higher statistics than MicroBooNE (~1M events).

- This will test the near-far strategy with liquid argon for the first time.
Source and Reactor experiments

**SOX**

- First phase: **Ce-source** (100 kCi)
  \[ ^{144}\text{Ce} \rightarrow ^{144}\text{Pr} + e^- + \overline{\nu}_e \]
  \[ ^{144}\text{Pr} \rightarrow ^{144}\text{Nd} + e^- + \overline{\nu}_e \]
- \( E_\nu < 3 \text{ MeV}, \) oscillation length \( \sim 1\text{m} \)

→ oscillation pattern within the scintillator volume

**PROSPECT**

- moveable near detector @ \( \sim 7\text{ m} \)
- far detector @ \( \sim 18\text{ m} \)
- Simulated PROSPECT data, binned in L/E; Stat err. only

- Mass Splitting: 1.78 eV\(^2\)
  - Osc. Amplitude: 0.09
  - Phase I, 1 Year Livetime
  - Phase II, 3 Year Livetime

- Mass Splitting: 0.10 eV\(^2\)
  - Osc. Amplitude: 0.09
  - Phase I, 1 Year Livetime
  - Phase II, 3 Year Livetime
Future Sensitivity

SOX
1.5 yrs data

FNAL SBN
~3yrs

PROSPECT
1-3 yrs data

A. M. Szelc, LV Krakow School of Theoretical Physics
Big Questions in ψ-physics

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- which neutrino is the heaviest and which is the lightest (MH)?
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- is our picture correct?
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β decay and 0νββ decay

long-baseline neutrinos

short-baseline neutrinos

νμ → νe

(0.1-10)GeV

En. range
Mass Hierarchy

• We still don't know what is the ordering of neutrino masses.

• Observing oscillations allows us to measure only mass splittings, i.e. $\Delta m^{2}_{23} = m^{2}_{2} - m^{2}_{3}$.

• The way nature has decided to make this ordering will inform GUT theories and determines options for $0\nu\beta\beta$ decays.

• This will affect the $\nu_{e}(\bar{\nu}_{e})$ appearance in a $\nu_{\mu}(\bar{\nu}_{\mu})$ beam due to matter effects.

Can be measured by NOvA and T2K.
Matter effects

- Electron neutrinos are preferred, in matter

Due to the abundance of electrons in matter electron neutrinos will behave slightly differently.

We've seen hints already:

\[ \text{SNO } ES \text{Rate} \propto \Phi(\nu_e) + 0.154 \Phi(\nu_\mu + \nu_\tau) \]

Borexino Mixing angle in Sun changes due to matter effects.
Matter effects

\[ P(\nu_e \rightarrow \nu_\mu) = P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_M \sin^2(\Delta m^2_M L/4E) \]

Passage through matter changes the effective \( \Delta m^2 \) and mixing angles:

\[ \Delta m^2_M = \Delta m^2 \sqrt{\sin^2 2\theta + (\cos 2\theta - x_\nu)^2} \]

\[ \sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x_\nu)^2} \]

Effects are Energy and density dependent.

Example: 1000km baseline, through the mantle, \( \Delta m^2_{31} \sim 2.4 \times 10^{-3} \text{eV}^2 \)

\[ |x_\nu| \simeq E/12 \text{GeV} \]

Sign inverted
For anti-nu

After B. Kayser
Matter Effects

NH, neutrino

IH, neutrino

IH, anti-neutrino

A. Smirnov

06/27/15
The NOvA detector

Detectors located 0.8° of NuMI beam axis

Narrowly peaked $\nu$ flux centered at 2 GeV

$$E_\nu = \frac{|\Delta m_{32}^2| L}{2\pi} \approx 2 \text{ GeV}$$

Achieves maximum oscillation

Suppresses high energy tail
What can NOVA tell us

Need 3+3 years of beam.
Full detector just recently assembled.
T2K is starting to probe

\[ \Delta m^2_{32} > 0 \]

\[ \Delta m^2_{32} < 0 \]

NH (slightly preferred)

IH
PINGU a very alternative approach

ICECUBE – Ice Cherenkov to look for HE neutrinos.

PINGU: Add strings to center of IceCube to measure MH

Can also do LE nus: $\theta_{23}$
PINGU and Mass Hierarchy

The world is your baseline.

Create oscillograms and the difference will point to the answer.
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- β decay
- and 0νββ decay

- long-baseline neutrinos
- short-baseline neutrinos

νμ → νe
(0.1-10)GeV
En. range
CP violation

- The Universe is surprisingly asymmetric – we see “matter” and almost no “anti-matter”.
- For this difference to originate in the Big Bang, we need a much less drastic value $1 \text{ in } 10^{10}$ difference.
- This can happen if CP is violated “enough”.
- Neutrinos could provide the needed quantities via leptogenesis - need non-zero $\delta$ phase.
- Need to measure $\nu_e$ vs $\bar{\nu}_e$ appearance asymmetry (watch out for MH!).

\[ U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

\[ \begin{align*}
\mu &\Rightarrow \tau \\
\mu &\Leftrightarrow e \\
e &\Leftrightarrow \mu
\end{align*} \]
Hyper-K

1 Megaton
(~20x larger than SuperK!)
295 km baseline

Needs MH to be determined.
DUNE : $\nu_e$ appearance at SURF (Homestake)

Deep Underground Neutrino Experiment (DUNE)
DUNE = LBNE + LBNO

- The merger of two big Long Baseline Neutrino proposals.
- Largest neutrino collaboration (750 people).
- First module planned ~2024
DUNE $\delta$CP measurement

- Need to see subtle differences between neutrinos and anti-neutrinos.
Summary

- There are many exciting experimental measurements in progress.
- And even more coming online in the next couple of years.
- Neutrino Physics is a data-driven (and vibrant) experimental field.
Things I did not talk about

- UHE neutrinos in IceCube
- Cross-section measurements.
- SuperNova Neutrinos.
- Many other cool things.
Thank you for your attention!
Coherent Pion Production

\[ \nu_\mu + A_{g.s.} \rightarrow \mu^- + \pi^+ + A_{g.s.} \]

\[ \bar{\nu}_\mu + A_{g.s.} \rightarrow \mu^+ + \pi^- + A_{g.s.} \]

Most pions are not contained so not possible to use \( Q^2 \) or \( t \) as discrimination.

MC used to build a binned background and signal expectation for a BDT response (based on kinematic variables).

This is then fit to the data.

Also, recent results from Minerva and T2K.