Neutrino Physics – a Survey

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NuFact 2019 – 21st International Workshop on Neutrinos from Accelerators
The Grand Hotel
Daegu, Korea
All theorists are liars

Neutrino physics has a rich history of anomalies:
It took 40 years for Ray Davis and John Bahcall to be taken seriously with the solar neutrino anomaly.
The atmospheric neutrino anomaly did not last quite that long, but still was labeled an anomaly till Super-K came around in 1998.
Much of the anomalous nature stemmed from theoretical prejudice: neutrinos are massless, neutrino mixing angles are small, astrophysics isn’t an exact science, chemistry is really scary asf.
Of course, I happen to be a theorist . . .
The big question

Things the Standard Model does NOT explain

• Neutrino mass
• Dark matter
• Baryon asymmetry
• Dark energy
• Gravity

50 years of ideas, most have been retired by LHC results, but NO hard experimental evidence to lead the way and no indication of what energy scale to look at.

Is there anything within our means we can find?
Neutrinos are massive – so what?

Neutrinos in the Standard Model (SM) are strictly massless, therefore the discovery of neutrino oscillation, which implies non-zero neutrino masses requires the addition of new degrees of freedom.

...yes, this is not SUSY, large extra dimensions or anyone’s favorite BSM model, but it IS the only laboratory-based evidence for the incompleteness of the SM.

Alas, it is indirect evidence: no energy scale, no symmetry, no new interaction, no new particles are seen in the laboratory.
Neutrino masses are different

The crucial difference between neutrinos and other fermions is the possibility of a Majorana mass term

\[ m_L \bar{\psi}_L \psi^C_R + m_R \bar{\psi}_R \psi^C_L \]

on top of the usual Dirac mass term

\[ m_D \bar{\psi}_L \psi_R \]

This could be the reason why neutrinos are so much lighter and have mixing angles so different from the quark sector.
Neutrino mass determination

Finding the scale $\Lambda$ of neutrino mass generation rests crucially on knowing

- Dirac vs Majorana mass
- Absolute size of mass

All direct experimental techniques for mass determination rely on $\nu_e$, which is mostly made up of $m_1$ and $m_2$. 
CP violation

There are only very few parameters in the νSM which can violate CP

- CKM phase – measured to be $\gamma \simeq 70^\circ$
- $\theta$ of the QCD vacuum – measured to be $< 10^{-10}$
- Dirac phase of neutrino mixing
- Possibly: 2 Majorana phases of neutrinos

At the same time we know that the CKM phase is not responsible for the Baryon Asymmetry of the Universe...
We currently have no way to directly measure any of sides containing $\nu_{\tau}$.
What did we learn from that?

Our expectations where to find BSM physics are driven by models – but we should not confuse the number of models with the likelihood for discovery.

- CKM describes all flavor effects
- SM baryogenesis difficult
- No New Physics at a TeV

and a vast number of parameter and model space excluded.
Non-standard interactions

NSI are the workhorse for BSM physics in the neutrino sector. They can be parameterized by terms like this

\[ \mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_f \epsilon^{fP}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\rho \nu_\beta) (\bar{f} \gamma^\rho P f), \]

where \( f \) can be any fermion and \( P \) is the projection onto right and left-handed components.

Wolfenstein, 1978

NB – for sizable effects in neutrino oscillation, these new interactions have to arise at energies well below the electroweak scale to avoid charged lepton flavor violation bounds. e.g Farzan, 2015
Impact on three flavors

Three flavor analysis are not safe from these effects!

PH, D. Vanegas, 2016

In this example, CP conserving new physics fakes CP violation in oscillation!
Flavor models

Simplest un-model – anarchy Murayama, Naba, DeGouvea

\[ dU = ds_{12}^2 dc_{13}^4 ds_{23}^2 d\delta_{CP} d\chi_1 d\chi_2 \]

predicts flat distribution in \( \delta_{CP} \)

Simplest model – Tri-bimaximal mixing Harrison, Perkins, Scott

\[
\begin{pmatrix}
\sqrt{\frac{1}{3}} & \frac{1}{\sqrt{3}} & 0 \\
\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\
\frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}}
\end{pmatrix}
\]

obviously corrections are needed – predictivity?
3 \sigma \text{ resolution of } 15^\circ \text{ distance requires } 5^\circ \text{ error. NB – smaller error on } \theta_{12} \text{ requires dedicated experiment like JUNO}
What can we learn from that?

– If we refute three flavor oscillation with significance, we have found new physics, but this requires great precision.

– If we confirm three flavor oscillation with great precision, we need the context of specific models to learn anything about BSM physics.

Corollary: Only if we do this precisely we really will learn something!

Note, that a lot of BSM physics can be looked for at near detectors and in neutrino astrophysics.

Arguelles et al. 2019.
The way forward

Exps. Running 50% in neutrino mode

- T2K
- T2K II
- NOvA
- T2K(II)+NOvA
- DUNE

\[
\begin{align*}
\sin^2 \theta_{12} &= 0.304 \\
\sin^2 (2\theta_{13}) &= 0.085 \\
\sin^2 \theta_{23} &= 0.452 \\
\delta_{CP} &= -\pi/2 \\
\Delta m_{21}^2 &= 7.5 \times 10^{-5} \text{ eV}^2 \\
\Delta m_{31}^2 &= 2.457 \times 10^{-3} \text{ eV}^2
\end{align*}
\]
Neutrino cross sections

Using current cross section uncertainties and a perfect near detector.

Differences between $\nu_e$ and $\nu_\mu$ are significant below 1 GeV, see e.g. Day, McFarland, 2012

PH, Mezzetto, Schwetz, 2007
Nuclear effects – example

In elastic scattering a certain number of neutrons is made
Neutrons will be largely invisible even in a liquid argon TPC
\Rightarrow missing energy

Ankowski et al., 2015
Theory and cross sections

Theory is cheap, but multi-nucleon systems and their dynamic response are a hard problem and there is not a huge number of people working on this...

Without being anchored by data, any result will be based on assumptions and uncontrolled approximations.

This is a multi-scale problem, from low-energy chiral EFT to perturbative QCD, requiring a broad range of techniques and skills – requires a new subfield Electroweak Nuclear Theory named by E. Lisi.
Sterile neutrinos

We have measured in neutrino oscillation:

- $\Delta m_{21}^2 \sim 8 \cdot 10^{-5} \text{ eV}^2$ and $\theta_{12} \sim 1/2$
- $\Delta m_{31}^2 \sim 2 \cdot 10^{-3} \text{ eV}^2$ and $\theta_{23} \sim \pi/4$
- $\theta_{13} \sim 0.16$

Any $\Delta m^2 \gg \Delta m_{21}^2, \Delta m_{31}^2$ requires a 4th neutrino, BUT only three neutrinos with $m_\nu \leq m_Z$ couple to the Z $\Rightarrow$ “sterile” neutrino.
Evidence in favor

Or at least at odds with a simple 3-flavor framework

- LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ and $\nu_\mu \rightarrow \nu_e$
- Reactors $\nu_e \rightarrow \nu_e$
- Gallium $\nu_e \rightarrow \nu_e$
LSND and MiniBooNE

LSND 1995

MiniBooNE 2018

\[ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \simeq 0.003 \]

Statistically significant: 4 – 6\( \sigma \)
Figure courtesy D. Schmitz and C. Adams

Signal to noise not so different from LSND... will a near detector of completely different design help?
Pion decay at rest at JSNS, Gd-doped scintillator.

Direct test of the LSND result → should have been done 20 years ago!
The reactor anomaly

Daya Bay, 2014

Mueller et al., 2011, 2012 – where are all the neutrinos gone?
Neutrinos from fission

\begin{align*}
\text{stable} & \\
235\text{U} & \\
239\text{Pu} & \\
\end{align*}

\text{fission yield}

8E-5 \quad 0.004 \quad 0.008
\( \beta \)-branches

\[
\begin{array}{c}
\text{0} - \quad 9.9 \quad 5.34 \text{ s} \quad 5 \\
\text{49} \text{Zr}^57 \\
Q(g.s) = 7896 \text{ keV} \quad 23 \\
\end{array}
\]

\( \beta \) - 100%
\( \beta \)-spectrum from fission

\(^{235}\)U foil inside the High Flux Reactor at ILL

Electron spectroscopy with a magnetic spectrometer

Same method used for \(^{239}\)Pu and \(^{241}\)Pu

For \(^{238}\)U recent measurement by Haag et al., 2013

A priori calculations

Updated $\beta$-feeding functions from total absorption $\gamma$ spectroscopy (safe from pandemonium) for key isotopes.

For $^{238}$Pu, $^{239}$Pu and $^{241}$Pu better than 5% agreement with beta decay data.

$^{235}$U, the odd-one-out?

Estienne et al., 2019
Forbidden decays

e,ν final state can form a singlet or triplet spin state J=0 or J=1

Allowed:
s-wave emission (l = 0)

Forbidden:
p-wave emission (l = 1) or l > 1

Significant nuclear structure dependence in forbidden decays→ large unquantifiable uncertainties!
Latest result of Daya Bay

Only an issue if the prediction of Pu239 in the Huber+Mueller model is correct. 

Hayes et al., 2017

Daya Bay, 2017 and Diaz et al., 2019
The 5 MeV bump

Double Chooz 2019
Seen by all three reactor experiments
Tracks reactor power
NEOS Preliminary

Events/day/100 keV

Data signal (ON-OFF)
Data background (OFF)
H-M (flux uncertainty)
H-M + excess fit (1σ err)
Full uncertainty

Prompt Energy [MeV]

Ratio to Prediction

2 3 4 5 6 7

0.9 1.0 1.1

NEOS, 2016

24m from a large core (power reactor), confirms bump
NEOS vs Daya Bay

Huber, 2017
There is more U235 in NEOS, since core is fresh ⇒ 3 − 4 σ evidence against Pu as sole source of bump, but equal bump size is still allowed at better than 2 σ.
RENO and the bump

RENO, 2018

Slight correlation of bump amplitude with $^{235}$U fission fraction disfavors the ’all fissiles contribute equally’ hypothesis.
Latest data vs bump

**PROSPECT 2018**
Disfavors $^{235}\text{U}$ as sole culprit at $2.1\,\sigma$

Daya Bay 2019
Requires a bump in $^{235}\text{U}$ at $4\,\sigma$

P. Huber – VT-CNP – p. 35
Explanations?

• Specific high yield beta emitters Dywer, Langford 2015 and many others, very sensitive to quality of nuclear input data Hayes et al. 2015, Sonzogni et al. 2016, difficult to reconcile with Schreckenbach data.

• Hayes et al. proposed neutron spectrum, disfavored by Littlejohn et al., 2018.

• BSM physics: new NC-like interaction between sterile neutrino and $^{13}$C in scintillator. Ruled out by COHERENT and reactor D$_2$O data Brdar, Berryman, PH, 2018

The bump remains unexplained at this point.
NEOS and sterile neutrinos

NEOS reports a limit, but their best fit occurs at $\sin^2 2\theta = 0.05$ and $\Delta m^2 = 1.73 \, \text{eV}^2$ with a $\chi^2$ value 6.5 below the no-oscillation hypothesis.

adapted from NEOS, 2016
DANSS has a similar result.
DANSS and NEOS

Dentler et al. 2018

This is a spectral effect independent of rate and shape predictions!

P. Huber – VT-CNP – p. 38
Reactor fit

More than $3\sigma$ evidence for oscillation even without using a flux prediction!

Dentler et al. 2018
Gallium anomaly

<table>
<thead>
<tr>
<th>Source</th>
<th>GALLEX</th>
<th>SAGE</th>
<th>SAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R^e_H$</td>
<td>$0.953 \pm 0.11$</td>
<td>$0.812^{+0.10}_{-0.11}$</td>
<td>$0.95 \pm 0.12$</td>
</tr>
<tr>
<td>$R^e_B$</td>
<td>$0.84^{+0.13}_{-0.12}$</td>
<td>$0.71^{+0.12}_{-0.11}$</td>
<td>$0.84^{+0.14}_{-0.13}$</td>
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<tr>
<td>Radius [m]</td>
<td>1.9</td>
<td>1.9</td>
<td>0.7</td>
</tr>
<tr>
<td>Height [m]</td>
<td>5.0</td>
<td>5.0</td>
<td>0.7</td>
</tr>
<tr>
<td>Source height [m]</td>
<td>2.7</td>
<td>2.38</td>
<td>0.72</td>
</tr>
</tbody>
</table>

25% deficit of $\nu_e$ from radioactive sources at short distances

- Effect depends on nuclear matrix element
- $R$ is a calibration constant
Nuclear matrix element update

Kostensalo et al. 2019
Significance decreases from $3.0 \sigma$ to $2.3 \sigma$, but all results in the $\nu_e/\bar{\nu}_e$ sector are fully consistent!
Disappearance and appearance

$\nu_\mu \rightarrow \nu_e$ requires that the sterile neutrino mixes with both $\nu_e$ and $\nu_\mu$

$\Rightarrow$ there must be effects in both $\nu_e \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\mu$

Up to factors of 2, the energy averaged probabilities obey

$$P_{\mu e} \lesssim (1 - P_{\mu \mu})(1 - P_{ee})$$
Disappearance data

\[ \sin^2 2\theta_{e\mu} = 4|U_{e4}U_{\mu4}|^2 \]

with

\[ 1 - P_{ee} \propto |U_{e4}|^2 \]

and

\[ 1 - P_{\mu\mu} \propto |U_{\mu4}|^2 \]

There is (and has been for decades) a strong tension between global appearance data and disappearance data.

Dentler, \textit{et al.}, 2018
Finding a sterile neutrino

All pieces of evidence have in common that they are less than $5 \sigma$ effects and they may be all due to the extraordinary difficulty of performing neutrino experiments, if not:

- N sterile neutrinos are the simplest explanation
- Tension with null results in disappearance remains

Due to their special nature as SM gauge singlets sterile neutrinos are strong candidates for being a portal to a hidden sector – significant experimental activity.
Current $\nu_e/\bar{\nu}_e$ data points to a region at the edge of the sensitivity current reactor experiments.

Shown are the allowed regions from a fit to reactor data after the year 2010 separated into rate and spectrum. The reactor flux model uses the latest $ab\ initio$ results from Estienne et al. for the central value and the Huber-Mueller results for the error bars. The gallium region is from Kostensalo et al.
Summary

Neutrino oscillation is solid evidence for new physics, we just have no idea what the new physics might be.

- Current data allows large corrections to three flavor framework.
- Precision measurements have the best potential to uncover even “newer” physics – either by finding discrepancies or correlations among results.
- Sterile neutrinos are, one of the best evidence we currently have for New Physics, anywhere!
Ceterum censeo

That we need better neutrino sources to address both the cross section issue and sterile neutrinos.

- Reactor have been used for 70 years and are a mess
- Horn-focused pion beams have been used for 50 years and are a mess

Accelerator-based ideas exist:

nuSTORM, ENUBET, isoDAR...