International Workshop: Neutrino Research and Thermal Evolution of the Earth

27 October 2016

The Importance of Neutrinos
and
Some New Experiments to Measure Them

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With Many thanks to UH Neutrino Group, KamLAND, mTC, and NuLat Collaboration Colleagues
So, what IS a Neutrino?

This is a Neutrino

This was a Neutrino

Stable Elementary Particle - 3 of 6 constituents of matter
No electric charge - cannot see it
Very little interaction with matter - goes through the earth unscathed
Has very little mass - less than 1 millionth of electron
Lots of them though - 100 million in your body any time!
Subatomic Structure

Atom

Proton

Electrons

Nucleus

Quarks

Neutron
Where do Neutrinos come from?

- Nuclear Reactors (power stations, ships)
- Particle Accelerator
- Earth's Atmosphere (Cosmic Rays)
- Earth's Crust (Natural Radioactivity)
- Sun
- Supernovae (star collapse) – SN 1987A
- Astrophysical Accelerators – IceCube
- Big Bang (here $330 \text{ cm}^3$)
- Indirect Evidence
So why are neutrinos important?

Anthropic view: Keep physicists busy figuring out why and how....

Very unusual properties... shape shifters, totally unpredicted

Daily use? None! (Yet, but history of electron and many others)

Produced in abundance in Big Bang (associated with excess of matter?)

Supernovae explosions produce nu’s in horrendous numbers, and are associated with the production of elements heavier than iron

Learning about the interior of sun and earth.

Monitoring nuclear reactors unintrusively and remotely

Communication? Expensive on earth (but crazy fast traders...) Maybe ultimately with ET?

Neutrinos are Fundamental to our existence... and useful too.
How were Neutrinos discovered?

Radioactive Beta Decay

Spectrum

Beta (Electron) Energy

N(E)

“Neutrino” (E. Fermi)

“Neutron” (1930)

Wolfgang Pauli (1900-1958)
Nobel Prize 1945

Neutron

Proton

Niels Bohr: Energy not strictly conserved in the microscopic domain?

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First Detection! (1954 - 1956)

Anti-Electron Neutrinos from Hanford Nuclear Reactor

\[ \bar{\nu}_e \rightarrow p \rightarrow n \rightarrow Cd \rightarrow \gamma \rightarrow \gamma \rightarrow \gamma \rightarrow 3 \text{ gamma quanta in coincidence} \]
First Observation of Solar Neutrinos

Inverse Beta-Decay ("Neutrino Capture")

\[ ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^- + v_e \]

Homestake Solar-Neutrino Observatory (since ca. 1967)

600 Tons Cleaning Fluid

John Learned at Tohoku Forum for Creativity
27 October 2016
The Original Solar Neutrino Deficit

Calculation the expected fraction of solar neutrinos from various reactions

Homestake

Chlorine

\[ ^7\text{Be} \]

\[ ^8\text{B} \]

\[ ^{12}\text{C} + ^{16}\text{O} \] (CNO)

Uncertainty


John Bahcall

Raymond Davis Jr. Nobel ’02
Neutrinos are Shape Shifters!

They change from one type (e, mu, tau) to another (and back again) as they fly along.
Neutrino oscillation is a wave phenomenon (Wave-Particle Duality).
Neutrino Oscillations

Mass $m_1$

Mass $m_2 > m_1$

Oscillation Length

$$\frac{4\pi E}{m_2^2 - m_1^2}$$
Neutrino Oscillations

Oscillation Length \( \frac{4\pi E}{m_2^2 - m_1^2} \)
The Solar Neutrino Deficit Resolved

Homestake

Chlorine

Gallex/GNO

SAGE

Gallium

Super-

Kamiokande

Water

SNO (Deuterium)

8B

CNO

7Be

pp

νe+d→p+p+e−

ν+d→p+n+ν

 Electron-Neutrinos

All Neutrino Types
KamLAND Reactor Neutrino Experiment (Japan)

Japanese nuclear reactors 60 GW (20% world total)

- ~1 neutrino capture per day
- Taking data since Jan. '02
- Conclusive Results Fall '02.

detect $\nu_e$ from $>100$km and observe deficit due to oscillations
KamLAND Settles the Solar Problem

- Reactor neutrinos
- Geo neutrinos
- Accidental events

Events per 0.425 MeV bin

- KamLAND data
- No oscillation
- Best-fit oscillation

$sin^2(\theta) = 1.0$

$\Delta m^2 = 6.9 \times 10^{-5} \text{eV}^2$

Distance to Reactor (m) vs. $N_{\text{obs}}/N_{\text{exp}}$

- ILL
- Savannah River
- Bugey
- Rovno
- Goesgen
- Krasnyark
- Palo Verde
- Chooz
- KamLAND
Atmospheric Neutrino Flux

Primary Cosmic Ray

Nucleus (air)

Pions

Muons

Muon Neutrino

Muon Anti-Neutrino

Electron

Super-K Detector

Super-Kamiokande
Atmospheric Neutrino Anomaly

from above

Super-Kamiokande

from below

only half of the muon neutrinos from the far side of earth
SuperK neutrino oscillations paper now most cited paper in history of experimental particle physics


Nobel Prize 2015
Neutrino Mass and Composition

- **Atmospheric Neutrinos:**
  \[ m_3^2 - m_2^2 = 2 \cdot 10^{-3} \text{ eV}^2 \]

- **Solar Neutrinos:**
  \[ m_2^2 - m_1^2 = 7 \times 10^{-5} \text{ eV}^2 \]

Mixings peculiarly large,
No theoretical model

Differences of neutrino masses deduced from oscillation experiments.
Neutrinos may play crucial role in the genesis of excess matter over anti-matter in the universe... Hence we are here!
Matter Inventory of the Universe

Dark Energy
(Cosmological Constant)

Normal Matter
(of which ca. 10% luminous)

Dark Matter

Neutrinos
min. 0.1%
max. 6%
Neutrino Signal from Supernova 1987A

IMB event 33160, 39 MeV
Neutrinos Involved in Making the Heavy Elements

Neutrinos condition the neutron bath in which the atoms accrete mass.

The r-process in supernovae is thought to be the main source of heavy elements.

And, the Fluorine in your toothpaste, for example.
KamLAND sees neutrinos from Japan (and Korea)

86% of ν events from ~180 km
KamLAND Observes Neutrino Oscillations

FIG. 4: Allowed regions projected in the ($\tan^2 \theta_{12}$, $\Delta m^2_{21}$) plane, for solar and KamLAND data from the three-flavor oscillation analysis for (a) $\theta_{13}$ free and (b) $\theta_{13}$ constrained by accelerator and short baseline reactor neutrino experiments. The shaded regions are from the combined analysis of the solar and KamLAND data. The side panels show the $\Delta \chi^2$-profiles projected onto the $\tan^2 \theta_{12}$ and $\Delta m^2_{21}$ axes.

FIG. 5: Ratio of the observed $\bar{\nu}_e$ spectrum to the expectation for no-oscillation versus $L_0/E$ for the KamLAND data. $L_0 = 180$ km is the flux-weighted average reactor baseline. The 3-$\nu$ histogram is the expected distributions based on the best-fit parameter values from three-flavor unbinned maximum-likelihood analysis of the KamLAND data.
FIG. 6: Prompt energy spectrum of the $\bar{\nu}_e$ events in the low-energy region. Bottom panel, data together with the fitted background and geo $\bar{\nu}_e$ contributions. The shaded background and geo $\bar{\nu}_e$ histograms are cumulative. Middle panel, background and reactor $\bar{\nu}_e$ subtracted data together with the geo $\bar{\nu}_e$’s for the decay chains of U (dashed) and Th (dotted) calculated from a geological reference model [12]. Top panel, the energy-dependent selection efficiency.

FIG. 8: Geo $\bar{\nu}_e$ flux versus the radiogenic heat production rate from the decay chains of $^{238}$U and $^{232}$Th. The measured geo $\bar{\nu}_e$ flux (gray band) is compared with the expectations for the different mantle models from cosmochemical [32], geochemical [5], and geodynamical [33] estimates (color band). The slope starting at 7 TW indicates the response to the mantle $\bar{\nu}_e$ flux, which varies between the homogeneous and sunken-layer hypotheses (solid lines), discussed in the text. The upper and lower slopes (dashed lines) include the uncertainties in the crustal contributions.
Moving on to the Big Picture and the Future needs
The Next Challenges in Big Neutrino Detectors: 50 KT LS - 600 KT WC Detectors?

Motivations (~in energy order):

- Geoneutrinos
- Neutrinoless $bb$ decay
- Solar Neutrinos (HeP, CNO...)
- RAA and Reactor Spectrum Problems
- Search for Sterile Neutrinos
- Relic SN Neutrinos
- Supernova Neutrinos
- Indirect DM Searches
- Other anomalies (LSND, MBOONE)
- Nuclear Counter-Proliferation
- Proton Decay Search
- Long-Baseline Oscillations
- Hierarchy
- CP violation
- Atmospheric Neutrinos
- Earth Tomography
- Cosmic Neutrinos (>100 TeV, >1PeV)

Under Construction

- SNO+
- JUNO

Rejuvenated Soon?

- KamLAND
- SuperK
- Borexino

Probable (my view)

- HyperK, HKK
- DUNE (10KT)
- Jinping
- INO

Also discussed

- USA (“Theia Project”)
- Europe LAGUNA (LENA)
New Physics Challenges, and New Detectors

Several Areas Needing Improvements
- Lower thresholds... big detectors reaching \( \sim 1-2 \) MeV
  More Pixelation (\( \sim 1 \text{m} \to \text{few cm} \))
  Timing (<100 ps)
- Better Scintillator or WBLS (more light, long atten)
- Great Cleanliness (Borexino or better)
- Lower CR backgrounds by going deeper than 2KMwe

- Directionality (even a little is good at few MeV)

- Better particle ID in LB experiments (back reconstruction)

Not all are possible in one type of detector

World Nu Community cannot afford Many >$500M Detectors

We must join together to move forwards.
Theia? SuperKamLAND?
What is missing in the world mix?

Assuming extended IceCube and KM3 at high energy + HyperK + SNO+ and JUNO and Jinping...

We need a detector with

\[ M > 20\text{kt with} \]
\[ \text{Threshold} \sim 1\text{ MeV} \]
\[ \text{Depth} \gg 2\text{ kmw} \]
\[ \text{An accelerator beam pointed at it} \]

JGL’s current favorite prospect:

50 KT LS Theia in Homestake

Now discuss some issues related to such development.

Photodetectors are prominent need, not discussed here.
2009 Realization that Liquid Scint Detector Can Reconstruct Events

First light yields topology.

Snapshot of the Fermat Surface for a Single Muon-like Track

Incoherent sum coincident with Cherenkov surface: Not polarized!
Fast and Simple Start to Reconstruction

- **Center of charge** fits middle of track
- **Fermat surface**
  \[ \equiv \text{earliest possible photons} \]
  \[ \approx \text{Cherenkov + earliest scintillation} \]
- **Center of time**
  (using Fermat surface photons)
  fits near one end of track
- And connect dots!

Fit to 14 Neutrinos in KamLAND from J-Parc

Tag pure beam neutrinos due to having spill times

Map

Agreement with MC
(K-S test p-value = 0.65)

Not official KL result yet
A Simple Ellipticity Particle ID

<table>
<thead>
<tr>
<th></th>
<th>e+</th>
<th>mu-</th>
</tr>
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<tbody>
<tr>
<td>Entries</td>
<td>238</td>
<td>214</td>
</tr>
<tr>
<td>Mean</td>
<td>-0.8755</td>
<td>-3.52</td>
</tr>
<tr>
<td>RMS</td>
<td>0.6605</td>
<td>1.343</td>
</tr>
</tbody>
</table>

- Fiducial volume cut: < 3 m radius
- Event selection efficiency:
  \[ e^+ \quad \implies \quad 2.4\% \]
  \[ \mu^- \quad \implies \quad 2.1\% \]

Probably can do much better in future

Sakai Thesis
Sakai Used Back-Propagation in KamLAND to seek Dark Matter Annihilation Neutrinos

Not official KL Results, yet
Working Principle of the Topological Reconstruction

- Use all photon hits from all PMTs
- Divide result by local detection efficiency
  → Number density of emitted photons
- "Connect information" in multiple iterations
  → Use prior result as "prior information" in next iteration

*XY-projection*

Decrease cell size

Access to dE/dx seems possible!
What is the point?

We can have low threshold (MeV) and we can achieve cm scale resolution at higher energies (GeV) to cover a huge range in energy and great reach in physics in a single large deep scintillation detector.
MiniTimeCube Small and Directional Inverse Beta Detector

- Small portable 2.2 liter scintillating cube with neutron capture doping.
- Contain positron, lose gammas
- Do imaging with fast timing, not optics (time reversal imaging).
- Get some neutrino directionality between positron origin and neutron capture point.
- Reject noise on the fly; no shielding needed (if far from reactor)
- 4 x 6 MCP (x64 pixels each) fast (<100 ps) pixel detectors on surrounding faces
- ~10/day anti-neutrino interactions (inverse beta decay signature) from reactor.
- Data taken at NIST, being analyzed at present
Fitting the Positron Track in mTC

GEANT Event in mTC

Positron track, and fitting to it
NuLat a new type of 3D pixelated detector

Stack of optically isolated scintillating cubes

Light transmitted largely to 3 directions

6 PMTs get coincident, strong light

Lithiated plastic cubes now available

Alternate design for large version with LS

NB, log scale
Reconstructing 3D Energy Deposition in NuLat

Allows breaking multi-dimensional degeneracies

Not the case in 2D or 1D detectors....

Very important in identifying events and eliminating backgrounds
NuLat as a reactor neutrino detector

- Reactor power cycles and fuel composition
- New tool in non-proliferation arsenal
- Detection of special nuclear materials
- See talk at Applied Antineutrino Physics 2015
NuLat Demonstrator Being Assembled Now

- A $5 \times 5 \times 5$ ROL with $^6\text{Li}$-loaded scintillator
- Contract with Eljen for 130 cubes
- Instrumented with 150 PMTs, Spring 2017
- Demonstrate reactor monitoring
  - Deploy at commercial power plant
- Measure backgrounds for NuLat
  - Deploy at NIST in NuLat shielding
NuLat at a 20MW Reactor

Plan to take to NIST
Same location as mTC
5 m from core
Spring 2017
Gamma-induced false prompt events

- Multiple Compton scattering: Energy outside of vertex
  - Accept $0.2 \text{ MeV} < E < 1.0 \text{ MeV}$
  - This alone removes $\sim 60\%$ of gammas
• Pulse shape discrimination
  - Different dE/dx → different scintillator

PSD for background rejections

Neutrino studies are mature

We have a good 3 neutrino model

Campaigns progressing for hierarchy, lowest mass, CP violation

A few mysteries and many challenges remain

New detection techniques are being developed... only discussed two which we have been exploring... (mTC and NuLat)

Seems to be growing international desire for a huge scintillation detector at great depth, low threshold, and 10x existing size

Solution: Theia? SuperKamLAND? Other?

Join the fun and stay tuned