Applied Anti-neutrino Workshop
Introduction

Time to make nus work for us

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With much help from friends

With particular thanks to Gene Guillian, Hitoshi Murayama, Bob Svoboda, Georg Raffelt, and many others for graphics.
Outline

• Whazza Nu?
• Where you get ‘em
• How do we “see” them?
• Neutrino Tricks - shape shifters
• Who needs ‘em?
• Useful for nuclear security?
• What’s cooking down there?
• Other cool science we can do.
• Studies needed and gadgets we hope to build.
Neutrino Carabiner
by Black Diamond Equipment
Original Price: $8.50
Volume Discount: 6 for $7.83 each.

Named for a subatomic particle with almost zero mass, this is the lightest, full-service carabiner made. That means it's the best choice for anyone who demands super lightweight carabiners without a compromise in strength. The mere 36 grams provide a large rope-bearing surface, a nose hood to protect against "gate rub", and a basket very similar to a Quicksilver 2.

<table>
<thead>
<tr>
<th>Style</th>
<th>Weight</th>
<th>Strength</th>
<th>Gate Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino</td>
<td>36 grams</td>
<td>24 (kN) closed</td>
<td>8 (mm) open</td>
</tr>
</tbody>
</table>
$\nu_e$, $\nu_\mu$, $\nu_\tau$, $\nu_s$?
So, what IS 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

Seen one, you’ve seen ’em all! Complexity from Legos.
Nature's building blocks

Quarks:
- u (up)
- c (charm)
- t (top)
- d (down)
- s (strange)
- b (bottom)

Leptons:
- e (electron)
- μ (muon)
- τ (tauon)
- \( \nu_e \) (electron neutrino)
- \( \nu_\mu \) (muon neutrino)
- \( \nu_\tau \) (tau neutrino)

Three flavors or generations, and no more, and we do not know why.

Some mass, but curiously little.
### Where do Neutrinos come from?

<table>
<thead>
<tr>
<th>Source</th>
<th>Image</th>
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<tbody>
<tr>
<td>✅ Nuclear Reactors</td>
<td><img src="image" alt="Nuclear Reactors" /></td>
</tr>
<tr>
<td>(power stations, ships)</td>
<td><img src="image" alt="Nuclear Reactors" /></td>
</tr>
<tr>
<td>Sun</td>
<td><img src="image" alt="Sun" /></td>
</tr>
<tr>
<td>✅ Particle Accelerator</td>
<td><img src="image" alt="Particle Accelerator" /></td>
</tr>
<tr>
<td>Supernovae (star collapse)</td>
<td><img src="image" alt="Supernovae" /></td>
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<tr>
<td>SN 1987A</td>
<td><img src="image" alt="Supernovae" /></td>
</tr>
<tr>
<td>✅ Earth's Atmosphere (Cosmic Rays)</td>
<td><img src="image" alt="Earth's Atmosphere" /></td>
</tr>
<tr>
<td>Astrophysical Accelerators</td>
<td><img src="image" alt="Astrophysical Accelerators" /></td>
</tr>
<tr>
<td>Soon ?</td>
<td><img src="image" alt="Astrophysical Accelerators" /></td>
</tr>
<tr>
<td>✅ Earth's Crust (Natural Radioactivity)</td>
<td><img src="image" alt="Earth's Crust" /></td>
</tr>
<tr>
<td>Big Bang (here 330 ν/cm³)</td>
<td><img src="image" alt="Big Bang" /></td>
</tr>
<tr>
<td>Indirect Evidence</td>
<td><img src="image" alt="Big Bang" /></td>
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</table>

3 January 2008
Why did we “need” neutrinos?

Radioactive Beta Decay

Spectrum

Fig. 5. Energy distribution curve of the beta-rays.

“Neutron” (1930)

“Neutrino” (E. Fermi)

“Neutron” (1930)

Radioactive Beta Decay

Wolfgang Pauli (1900-1958) Nobel Prize 1945

Why did we “need” neutrinos?

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**MeV-Scale Electron Anti-Neutrino Detection**

**Production** in reactors and natural decays

Production of neutrinos in reactors and natural decays involves the transformation of a nucleus with a neutron excess into a nucleus with a proton excess. This process can be represented as

\[ \beta^- \rightarrow e^- + \bar{\nu}_e + \text{energy} \]

Neutron-rich nucleus

\[ \beta^- \rightarrow e^- + \bar{\nu}_e + \text{energy} \]

Nucleus with one more proton and one less neutron

**Detection**

Detection of electron anti-neutrinos involves the measurement of two flashes of light, close in space and time, which correspond to the initial (prompt) and delayed (200 µs) emissions of gamma rays. The standard "inverse β-decay" coincidence is used, with the following conditions:

- \( E_{\text{vis}} = E_{\nu} - 0.8 \text{ MeV} \) (prompt)
- \( E_{\text{vis}} = 2.2 \text{ MeV} \) (delayed)

The reaction is sensitive to neutrinos with energies greater than 1.8 MeV and provides rate and spectrum information without directional specificity.

Key: 2 flashes, close in space and time, 2\textsuperscript{nd} of known energy, eliminate background

Reines & Cowan, 1955

- Standard "inverse β-decay" coincidence
- \( E_{\nu} > 1.8 \text{ MeV} \)
- Rate and spectrum only - no direction
Neutrinos from the core of the sun!
Neutrinos are “shapeshifters”

- First strong evidence at SuperKamiokande experiment in 1998.

- Now much more evidence, including new work from KamLAND which clinch case.

- Oscillation from one flavor to another implies finite, though small, mass. Formerly thought to be mass-less.

- No predictions from theory... mixing much larger than anticipated.

- experimentalists game, and a strange one too.
Confirmation with man-made neutrino beams

K2K experiment report in 2006:
158±9 events if no oscillation
112 events observed
Deficit at 4.3 sigma level

Now confirmed with 2 more experiments in US and Europe
\( \nu \) Survival Probability: L/E Variation

Oscillations: 1\(^{\text{st}}\) and 2\(^{\text{nd}}\) reappearance!

\[ L_0 = 180\text{km flux-weighted average reactor distance} \]

Expected neutrino survival probability for point source at 180km baseline

KamLAND data
- best-fit osci.
- expected Geo \( \bar{\nu}_e \)

CHOOZ data

Survival Probability: Survival Probability:

L/E Variation

\( \nu \) Oscillations: 1\(^{\text{st}}\) and 2\(^{\text{nd}}\) reappearance!

KamLAND Detector
Neutrinos may play crucial role in the genesis of excess matter over anti-matter in the universe.
Mass-Energy Inventory of the Universe

- **Dark Energy** (Cosmological Constant)
- Normal Matter (of which ca. 10% luminous)
- Dark Matter
- Neutrinos
  - min. 0.1%
  - max. 6%

Copernicus!
The Particle Universe

- photons
- neutrinos
- protons
- electrons
- neutrons
- dark matter

number / cm$^3$
Neutrino Conclusions

• Neutrinos do indeed exist and are *weird* shapeshifters

• **Small but finite neutrino mass:**
  Need drastic new ideas to understand it

• **Neutrino mass may be responsible for our existence (or even the universe itself)**

• A lot more to learn in the next few years

• In any event they now appear to be useful here on earth, for **geology, security** and other future applications.
Practical Application: Monitoring Reactors

- Expected proliferation of reactors in near future as oil runs out.
- Need to keep track of “special materials”.
- Close-up (10-100m), intermediate range (1-10 km) and remote (100-1000 km) monitoring of nuclear reactors is possible.
- Giant neutrino detector network will help.
Near and Intermediate Distance Monitoring

- **Intermediate Range**
  - 1 – 10 km
  - 1 10 kT
  - Measure details
  - Technology: LS
  - **Segmentation needed**
  - Directionality possible
  - Study needed

- **Close-in**
  - 10 – 100 m
  - 1-100 Tons
  - Measure details
  - Technology: LS or water
  - In operation San Onofre
  - Much study with Double Chooz and Daya Bay experiments.
Reactor Monitoring from Afar

Lines are for San Onofre and a generic 100 MWt reactor required mass versus distance for two extreme purposes:
- the larger gets one 4000 events per month from that source to measure fuel mix;
- the smaller gets one 100 events per year, 10% measure of total power and hence production.

Fuel mix measurement is not and will not be practical for small reactors beyond 100km, even in the fairly far term.

A Hanohano (10KT) scale device can accomplish annual production monitoring out to 40km from a small reactor, and reach to 400 km for a large reactor complex.

A next generation 10 MT detector can monitor Small reactor production out to >1000 km.
Detection of Clandestine Bomb Testing

Number of Detected Events from a 10 kton Bomb

Detector Mass (Mega-ton H₂O)

Distance (km)

Number of Detected Events
- 1 Event
- 10 Events
- 100 Events
Neutrino Application: Answer some Big Picture Questions in Earth Sciences

What drives plate tectonics?

What is the Earth’s energy budget?

What is the Th & U conc. of the Earth?

Energy source driving the Geodynamo?

Via measurement of anti-neutrinos from earths mantle and core.
Predicted Geoneutrino Flux

Reactor Flux - irreducible background

Geoneutrino flux determinations
- continental (KamLAND, SNO+, LENA? DUSEL?)
- oceanic (Hanohano)

synergistic measurements
Reactor “Background”

- KamLAND was designed to measure reactor antineutrinos.
- Reactor antineutrinos are the most significant background in Japan region.
Go to deep ocean to measure mantle/core geonus.

Simulated Geoneutrino Origination Points

Assumes homogeneous mantle & no core source

KamLAND

50% within 500km
25% from Mantle

In Mid-Ocean
70% Mantle
30% Other
KamLAND, SNO+, LENA and Others will measure neutrinos from crust

• KamLAND will continue for years
• SNO+ nearly approved
• LENA proposed as part of MEMPHYS
• Dutch proposal EARTH for Curasao
• DUSEL in US may have KamLAND-like detector

1 kT SNO+ Sudbury Canada

• All of these will be useful to determine the crustal U/TH content.
• Together with at least one deep ocean detector we can start to learn where the U/Th in the earth resides

50 kT LENA perhaps in Finland
Hawaii Anti-Neutrino Observatory

Hanohano

Idea: detector based on KamLAND technology adapted for deep ocean, but >10KT larger (for good counting rate)

Make it mobile, sinkable and retrievable.

Geology: mid-Pacific and elsewhere for geo-neutrinos from mantle.

Physics: off-shore from reactors for neutrino oscillations studies.
Additional Physics/Astrophysics

Big low-energy neutrino detectors can do much excellent science.

- Nucleon Decay: SUSY-favored kaon modes
- Supernova Detection: special $\nu_e$ ability
- Relic SN Neutrinos
- GRBs and other rare impulsive sources
- Exotic objects (monopoles, quark nuggets, etc.)
- Long list of ancillary, non-interfering science, with strong discovery potential
Summary

- Neutrino detectors can play important societal roles in the future, monitoring nuclear reactors, checking on bomb testing, and further in future, tomography and even weapons control.

- Initial prototype detectors can accomplish transformational geophysics, geochemistry, particle physics and astrophysics: answers to key, big questions in multiple disciplines. Enormous discovery potential. Build strong community of interest and experience.

- Key technology issues are development of new photodetectors, better target materials, full understanding of backgrounds, exploration of direction sensing, lower thresholds (K40), and radically new detection means (coherent).

- Future, much science and many applications for low energy neutrino detection with huge instruments.

- It is a very exciting time in the neutrino business as you will see and hear in the following talks.