“There is a theory which states that if ever anybody discovers exactly what the Universe is for and why it is here, it will instantly disappear and be replaced by something even more bizarre and inexplicable.”

“There is another theory which states that this has already happened.”

Douglas Adams
The Elusive Neutrino

Why Something That Does So Little Matters So Much

Mats Selen,
University of Illinois at Urbana Champaign
The Plan for Today:

- **Appetizer: Cosmic Rays**
  - How we can see them
    - Cloud chamber (demo)

- **Entrée 1: Introduction to Neutrinos**
  - Facts & Figures
  - How we detect them (demos)

- **Entrée 2: Some puzzles get solved**
  - Missing Solar Neutrinos
  - Missing Cosmic Neutrinos
  - Neutrino Mixing (demo)

- **Dessert: A big remaining puzzle**
  - Antimatter (demo)
Preferred units of Energy & Mass

(same since $E = mc^2$)

\[ 1 \text{eV} = \text{kinetic energy of an electron accelerated through a 1 volt potential difference} \]

\[ 1 \text{meV} = \frac{1}{1000} \text{eV} \quad \text{(relic neutrino energy - very small)} \]

\[ 1 \text{KeV} = 10^3 \text{eV} \quad \text{(about the energy of an X-ray photon)} \]

\[ 1 \text{MeV} = 10^6 \text{eV} \quad \text{(about twice the mass of an electron, about the energy of a solar neutrino)} \]

\[ 1 \text{GeV} = 10^9 \text{eV} \quad \text{(about the mass of a proton)} \]
Useful Info: Cosmic Rays

Energies from $10^6$ - $10^{20}$ eV
Cloud chamber demo
- alcohol

About 200 \( \mu \)'s per square meter per second at sea level.
(lots of neutrinos too...)
Useful Info: How a Cloud Chamber works:

Some of the vapor molecules along its path are ionized by the particle of interest...

Super-saturated vapor

"Zoomed in on" section of a cloud chamber

Charged particle (like a μ)
Useful Info: How a Cloud Chamber works:

The ionized molecules act as seeds for condensing droplets...

Super-saturated vapor

"Zoomed in on" section of a cloud chamber
Found much more than just protons, neutrons & electrons

Must be more to the story...
quarks & lepton charge

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Leptons</th>
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<tbody>
<tr>
<td>up +2/3</td>
<td>e -1</td>
</tr>
<tr>
<td>down -1/3</td>
<td>μ 0</td>
</tr>
<tr>
<td>charm</td>
<td>ν_e</td>
</tr>
<tr>
<td>top (truth)</td>
<td>ν_μ</td>
</tr>
<tr>
<td>strange</td>
<td>ν_τ</td>
</tr>
<tr>
<td>bottom (beauty)</td>
<td></td>
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Some Neutrino Facts

- Nuclear reactions in the Sun produce a lot of neutrinos. Each second, about than 10 million of these pass through an object the size of a penny here on Earth.
  - Our Sun is a pretty average star.
  - Other stellar objects produce even more neutrinos.

- There are about 300 neutrinos per cubic cm in the Universe that are “left over” from the Big Bang.
  - These have very low energy (meV)

- We make lots of neutrinos right here on earth
  - Accelerators & nuclear reactors

- Bottom Line:
  - There are a lot of neutrinos in the universe (~10 billion per atom).
  - They come from interesting places, some very far away.
  - Studying them will yield interesting info on a broad range of topics.
Brian doesn’t fall over dead!
Because...

- The same thing that makes neutrinos so interesting also makes them very hard to detect.
  - They are extremely shy (don't interact much).
  - Hence the name "weak interaction".

- If we filled the space between the earth and the sun with lead, less than 1 out of 10,000 neutrinos would notice!

Q: So how did we ever discover them in the first place??
A: Indirectly! (a very interesting story...)

Earth \[\nu\] lead Sun
How ν's were “discovered”:

It was known that for nuclear decays emitting γ rays, the energy of the observed γ ray was well known (energy conservation).

It was observed that energy did not seem to be conserved in nuclear decays emitting β rays.

The ν was invented by Pauli in 1930 to fix this problem.
If there is another “unseen” particle (the $\nu$), the electron can have a range of energies.

**2-body decay**

Beta Energy

Air-track (carts & spring)
Balloon

**3-body decay**

Beta Energy

3-body decay
So how can we build a neutrino catcher?

- Make it really big!
  - We will detect about 1 solar neutrino per day per 100 tons of detector (1 ton = 1000 kg).
  - Better not cost too much per kilogram!

- Luckily, there is a way to do this!

- **Use Water**
  - Cheap
  - Transparent (turns out to be important).

- Lets learn about Cherenkov Radiation...
Here is the idea:

- Suppose a wave moves with a speed $V_w$
  - Throw a pebble into a pond and see how fast ripple moves outward
    » Demo in water talk

- Now suppose you are in a boat moving faster than $V > V_w$

- You will produce a “bow wave”
  - Demo in water talk
This is the same principle as a sonic boom

- Suppose sound moves with a speed $V_s$

- Now suppose you are in a plane moving faster than $V > V_s$

- Your plane will produce a "bow wave"
  
  ➔ When this wave passes you on the ground you hear a "sonic boom"

http://members.aol.com/nicholashi/waves/supersonic.html
An F-18 Breaking the Sound Barrier
**Sonic Boom...**

- The angle that the “cone” makes with the direction of travel depends on the speed of the airplane:
  - Same thing happens with the boat

**Key concept:** Object traveling faster than the speed of a wave creates bunched up “shockwave” that moves off at an angle that depends on how much faster it’s moving.
**Cherenkov Radiation: Shockwave of Light**

- In a material that has index of refraction $n$, light moves with speed $V_L = c/n$ ($c$ is the speed of light in vacuum = $3 \times 10^8$ m/s).
  - For water, $n = 1.33$
  - Light moves ~30% slower in water than in vacuum.

- It’s very common for a charged particle, like an electron, to go faster than this.
  - If its energy is high enough (a few MeV) then it will have a speed $V$ very close to $c$. 
We can see Cherenkov Radiation...

UMR Reactor Lab

Cherenkov light from Reactor

It can be detected with Photomultiplier Tubes!!
Quartz bar demo
What will a $\nu$ do in water?

Usually nothing!

But sometimes it will strike a nucleon and “knock out” an $e$ (or $\mu$) moving in the same direction as the $\nu$ was.

The $e$ (or $\mu$) will travel a short distance giving off Cherenkov light in the shape of a cone.
Conceptual design of a good $\nu$ detector:

- Tank full of water
- Array of PMT's

$\nu_e$
Conceptual design of a good $\nu$ detector:

- Tank full of water
- Array of PMT's

$\nu_e$
Conceptual design of a good $\nu$ detector:

The pattern of PMT's that detect light will be an oval.

The shape of the oval and the time that the light reaches each tube tells us the original direction of the neutrino!

The total amount of light detected tells us about the energy of the neutrino.

Carefully studying the shape and the energy can also tell us about the $\nu$ species.
Over 13,000 large PMT's

The Super Kamiokande Detector
Control Room

Inner Detector

Outer Detector

Linac cave

Tank

Water System

Entrance 2 km

Put far underground (2700m H₂O) to shield against cosmic rays

Mt. Ikeno
Super-Kamiokande

Run 8356 Event 11385639
100-02-19 18:35:49
Inner: 2296 hits, 10885 pe
Outer: 1 hits, 0 pe (in-time)
Trigger ID: 0x07
D wall: 5.12.3 cm
PC mu-like, p = 1298.2 MeV/c

Charge (pe)
- >26.7
- 23.3-26.7
- 20.2-23.3
- 17.3-20.2
- 14.7-17.3
- 12.2-14.7
- 10.0-12.2
- 9.0-10.0
- 6.2-8.0
- 4.7-6.2
- 3.3-4.7
- 2.2-3.3
- 1.3-2.2
- 0.7-1.3
- 0.2-0.7
- < 0.2

KEK Beam direction marked by diamond

Saturday Morning, 12/6/03
Neutrino picture of the Sun from Super-K

Simple:
Find the direction of each solar neutrino and see where it points...

Super-K accumulated lots of good data before this happened...
Oooops...

Being rebuilt!
**Puzzle: Case of the Missing $\nu$'s**

- “Homestake” experiment was the first to detect neutrinos from the Sun in early 70’s. Observed about HALF the expected number.
  - This was a very hard experiment.
    - Had to find ~ 1 Ar atom produced each day
  - People did not have great confidence in theoretical “expectation” either.

- The same problem persists today:
  - Experiments are much more accurate
    - E.g. Super Kamiokande
  - Theoretical expectation is solid.

- Half the neutrinos are still missing!

615 tons of perchloroethylene (dry-cleaning fluid). $\text{Cl} \rightarrow \text{Ar}$

2002 Nobel Prize

5000' underground in SD
Solar Neutrinos Are Counted At Brookhaven

The gun barrel is one of four that are used in the basement of the Chemistry building as shields against stray radiation in low level counting experiments. Originally the gun barrels were procured from surplus, and brought to BNL for conversion to more peaceful uses. The long guns were cut into 8-foot sections, weighing about 16,000 pounds each. These guns are made from “old” iron (before the use of atom and hydrogen bombs) and contain a very small amount of residual radioactivity.

Dr. Ray Davis of Chemistry is shown placing a low level counter in a cut-down navy gun barrel which acts as a shield from stray cosmic radiation. This equipment is used in the Brookhaven Solar Neutrino Experiment.
Puzzle: Case of the Missing $\nu$'s

Cosmic Ray protons illuminate the earth evenly from all directions.

These produce lots of $\nu$'s when they crash into Earth's atmosphere.

Super-K studied these cosmic ray neutrinos as a function of direction...
Super-K Results

Number of $\nu_\mu$

Half as many are observed from below as from above
The case of the Missing $\nu$'s

- Puzzle Summary:

  ➔ Half of all $\nu_e$'s from the sun don’t make it to Earth.

  ➔ Half of the $\nu_{\mu}$'s produced by cosmic rays in our atmosphere on the other side of the Earth don’t make it through to our side.

  ➔ Seems like we can lose half of a given neutrino species just by waiting long enough!
The case of the Missing $\nu$'s

- **Solution:** Neutrinos don't really vanish, they just change their name.
  - Not as stupid as it sounds

- Suppose on the way to earth all of the solar $\nu_e$'s start spending half their time being $\nu_\mu$'s.
  - The experiments on earth will measure half as many $\nu_e$'s as we expect to see.
The case of the Missing $\nu$’s

- **Solution**: Neutrinos don’t really vanish, they just change their name.
  - Not as stupid as it sounds

- Suppose on their way through the earth all of the atmospheric $\nu_\mu$’s start spending half their time being $\nu_\tau$’s.
  - The experiments on earth will measure half as many “upward going” $\nu_\mu$’s as we expect to see.
This is called \( \nu \) "Mixing"

- Why should we believe this; it sounds contrived (& crazy):
  - Well known phenomena in particle physics.
  - Observed in neutral mesons many decades ago.
- The idea (& math) is the same as a coupled pendulum: demo

---

Start the red one going with the blue at rest...

Soon the red is at rest, the blue one is moving!

And the cycle repeats...
Note: this is a slight oversimplification since all 3 flavors mix

On average, the neutrino only spends half its time being the flavor it started out as!

This is what we observe. Too good to be a coincidence!

**Alternative**: Many independent experiments are all wrong in exactly the same way. This is quite unlikely.
Exciting Implications:

- The “Standard Model” is incomplete.
  ➔ This is really great...up to now its worked too well!

- Neutrinos have mass!
  ➔ Even though this mass is probably quite small, this is important because there are so many neutrinos in the Universe.

- There is probably more exciting physics hiding in the world of neutrinos.
  ➔ CP violation in leptons could explain the embarrassing Matter - Antimatter asymmetry we observe but cant quite understand!
Where is all of the Antimatter??

- Our current understanding leads us to conclude that right after the Big Bang there was as much matter as there was antimatter.

- As far as we can tell, antimatter is a rare commodity today.
  
  ➔ Don’t see much of it anywhere.
  ➔ We can make tiny amounts our labs.
  ➔ See small amounts in radioactive decays etc.

  ➔ As soon as it encounters matter, it annihilates (poof!)
  ➔ $^{22}$Na demo.

So where did it all go? That’s a great question!
Let's annihilate some Antimatter!

Sodium 22 decays by emitting:

- 1 photon (1.3 MeV) We know how to measure this (Ge detector)
- 1 positron (0.55 MeV) This is antimatter...how do we measure it??

Let the positron find an electron and they will annihilate each other (poof)
Positron meets electron...

They annihilate into 2 photons.

Each photon has exactly the energy equal to the mass of one electron

\[ E_\gamma = m_e c^2 \]

Finding photons that have an energy of 0.511 MeV is smoking gun evidence that we annihilated antimatter!
What to remember:

Neutrinos are everywhere.
Trillions pass through you every second.

Neutrinos interact very rarely.
Hard to catch. Quite ghostly.
The experiments are very cool!

Neutrinos may hold the answer to some important questions.
Where is the anti-matter (lepton CP Violation)?
Extra Slides
Remnants of Supernova SN1006

Used to be a star (tiny dot on this scale) until it exploded in 1006 AD

Observation of these bright areas lead us to think that this may be a possible source of cosmic rays...
Cosmic Ray event seen in Cloud Chamber

Cloud chamber demo - alcohol

Saturday Morning, 12/6/03
quarks & anti-quarks  (The leptons all have anti-particles too)

\begin{align*}
+\frac{2}{3} & \quad \underline{u} & \quad -\frac{2}{3} & \quad \bar{u} \\
-\frac{1}{3} & \quad \underline{d} & \quad +\frac{1}{3} & \quad \bar{d} \\
& \quad \underline{s} & \quad \underline{c} & \quad \underline{\bar{c}} \\
& \quad \underline{b} & \quad \underline{\bar{t}} & \\
\end{align*}

Rule: Quarks cannot exist alone, but only in 2’s and 3’s

Now we can easily build any of the particles we have discovered (and predict some we haven’t)

proton  neutron  anti-proton (baryons)

\(\pi^+\)  \(D^0\)  \(B_s\) (mesons)

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Forces (interactions)

Atoms:
- Photons
  - Electromagnetic Force

Nuclei:
- Gluons
  - Strong Nuclear Force
**Most Interesting:**

- Weak Nuclear Force

**W** boson couples top-row quarks (leptons) and bottom-row quarks (leptons).

<table>
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<tr>
<td>$+\frac{2}{3}$</td>
<td>up, charm, top</td>
<td>e, $\nu_e$</td>
</tr>
<tr>
<td>$-\frac{1}{3}$</td>
<td>down, strange, bottom</td>
<td>$\mu, \nu_\mu, \nu_\tau$</td>
</tr>
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</table>

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Useful Info:
**Matter & Anti-Matter Created Equal**

- Whenever a particle is created by the strong or electromagnetic interaction, so is the corresponding anti-particle.
  - Has to be this way to conserve charge:
    - Also conserves “lepton number” and “baryon number”
- This had to be true in the Big Bang also
  - There should be as much anti-matter as matter in the Universe
Useful Info: Photomultiplier Tubes (PMT’s)

Many shapes & sizes

- Incident Light
- Photocathode
- Focusing Electrodes
- Dynodes
- Electron Multiplier
- Anode

They all work the same way

Bottom Line: A Photomultiplier Tube detects one (or more) photons and produces an electrical pulse of corresponding size.

Quartz bar demo

Saturday Morning, 12/6/03
Useful Info: Solid State Detector:

Backward biased: no current flows.

cold finger  Ge diode
Photon smacks into crystal and knocks some charges loose.

LN$_2$ (77K)
cold finger Ge diode

Photon smacks into
crystal and knocks loose
some charges
Charges flow, causing a current pulse in the circuit which we amplify and measure.

The size of the current pulse tells us the energy of the photon.
Current pulse

Multi Channel Analyzer

Photon Energy # Photons

PC

Saturday Morning, 12/6/03