The strange tale of tiny neutrinos
**Neutrinos were “invented” in 1930 by W. Pauli to explain some features of nuclear beta decay**

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant.........

I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

W. W. Pauli
Energy and momentum conservation fix the energy in 2-body decays. Example: $N \rightarrow N'+\alpha$

The continuum of energies observed in $\beta$ decay implies that either energy and momentum are not conserved... or that there is another particle difficult to detect $N \rightarrow N'+\beta+\nu$. 
Today neutrinos occupy an important role in particle physics...

<table>
<thead>
<tr>
<th>Leptons</th>
<th>Quarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$</td>
<td>$u$, $c$, $t$</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>$d$, $s$, $b$</td>
</tr>
<tr>
<td>$\nu_\tau$</td>
<td>$t$</td>
</tr>
</tbody>
</table>

25% of elementary particles are neutrinos
So... where can we find neutrinos?

A Google search for “neutrino” gives about 7,390,000 hits!

...a clear sign that neutrinos are everywhere!
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 (grams)</th>
<th>Strength (kN)</th>
<th>Gate Width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino</td>
<td>36</td>
<td>24</td>
<td>8</td>
</tr>
</tbody>
</table>
Sources of neutrinos: artificial and natural

- **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** - Soon?
- **Big Bang** (here 330 $\nu$/cm$^3$) - Indirect Evidence

TRIUMF Jan 18, 2013
We know of 4 types of fundamental interactions in nature:

- **Gravity**: every object is affected (it is actually a property of space-time)
- **Weak force**: affects most particles including neutrinos
- **Electromagnetism**: affects all particles with charge
- **Strong force**: affect only quarks

Neutrinos having no electric charge interact only by the weak force (and gravity) → *interact very little*
Radioprotection for neutrinos?

- Mean free path of neutrinos from a reactor in lead is \( \approx 0.3 \) light years!

- A big nuclear reactor makes \( 6 \cdot 10^{20} \) neutrinos/s: at 20 meter distance (just outside the building) only one neutrino every 3 sec interacts with our body!

---

Bethe & Peierls 1934: 
“... this implies that one evidently never will be able to detect Neutrinos.”
So neutrino detectors usually require massive shielding to screen away cosmic radiation. The only practical solution is to place them deep underground. There is a 6 orders of magnitude reduction in cosmic ray flux at sea level.
“There are people so stupid to go in caverns to see the stars” (Plinius the elder?)
Detectors tend to be large and require extensive shielding against natural radioactivity.

Material where neutrinos interact and are detected (1000 tons liquid scintillator... ever bought liquid scintillator in... bulk?)

Shielding oil (2.5 m thick, or about 2 kton)

2000 photomultipliers (20 inch diameter)
Make your own scintillator, underground
And it even works!

$^{238}\text{U} : ^{214}\text{Bi} \rightarrow ^{214}\text{Po} \rightarrow ^{210}\text{Pb}$

$\beta + \gamma$
$E = 3.27 \text{ MeV}$
$\tau = 28.7 \text{ min.}$

$\alpha$
$E = 7.69 \text{ MeV}$
$\tau = 237 \mu\text{s}$

Uranium mass fraction
$3.5 \cdot 10^{-18}$

Uranium in the Earth crust is $\sim 10^{-6}$
Some detectors detect Cherenkov radiation emitted by electrons scattered off by neutrinos.
Cherenkov Effect

Water

Scattering or Reaction

Neutrino

Electron or Muon (charged particle)

Ring shaped illumination

Light

Light
This is the optical analogous of the sonic boom produced by an aircraft
Let's use these tools...
\( \nu_e \) are abundant by-products of nuclear fusion in the sun

\[
p + p \rightarrow ^2H + e^+ + \nu_e + 0.42\,\text{MeV}
\]

"pp" 99.75%

\[
p + e^- + p \rightarrow ^2H + \nu_e + 1.44\,\text{MeV}
\]

"pep" 0.25%

\[
^2H + p \rightarrow ^3\text{He} + \gamma + 5.49\,\text{MeV}
\]

86%  

\[
^3\text{He} + ^3\text{He} \rightarrow \alpha + 2p + 12.86\,\text{MeV}
\]

14%  

\[
^3\text{He} + \alpha \rightarrow ^7\text{Be} + \gamma + 1.59\,\text{MeV}
\]

"hep" 2.4 \times 10^{-5}

"\(^7\text{Be}\)" 99.89%

\[
^7\text{Be} + e^- \rightarrow ^7\text{Li} + \gamma + \nu_e + 0.8617\,\text{MeV}
\]

0.11%  

\[
^7\text{Be} + p \rightarrow ^8\text{B} + \gamma + 0.14\,\text{MeV}
\]

"\(^8\text{B}\)" 0.11%

\[
^7\text{Li} + p \rightarrow \alpha + \alpha + 17.35\,\text{MeV}
\]

\[
^8\text{B} \rightarrow ^8\text{Be} + e^+ + \nu_e + 14.6\,\text{MeV}
\]

\[
^8\text{Be} \rightarrow \alpha + \alpha + 3\,\text{MeV}
\]
3 types of experiments detecting solar neutrinos

- **Chlorine**: $^{37}\text{Cl} + \nu_e = ^{37}\text{Ar} + e^-$
  1 exp running >30 yrs (US)
  
- **Gallium**: $^{71}\text{Ga} + \nu_e = ^{71}\text{Ge} + e^-$
  3 exp (Russia, Italy)

- **Cerenkov**: $e^- + \nu_x = e^- + \nu_x$
  $\nu_e + ^2\text{H} = p + p + e^-$
  3 exp (Japan, Canada)

\[ L = 10^8 \text{km} \]
30 years of solar neutrinos with the Chlorine detector

Ray Davis, 2003 Physics Nobel Prize
Conclusion 1:

- We detect $\nu$s! nuclear fusion powers the sun
- The sun is still shining (this is not trivial: it takes $\sim 1$Myr for a photon to emerge from the sun)
Conclusion 2:

We do not see enough ννs!

→ something happens to the neutrinos in their journey from the core of the sun to the earth

Data collected with the SNO detector:
- 1 kton of heavy water
- ~2000 m underground in Ontario
In Quantum Mechanics there are 2 representations for our neutrinos if $m_\nu \neq 0$:

- "Weak interaction eigenstate"

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
\]

this is the state of definite flavor: interactions couple to this state

- "Mass eigenstate"

\[
\begin{pmatrix}
\nu_{m1} \\
\nu_{m2} \\
\nu_{m3}
\end{pmatrix}
\]

this is the state of definite energy: propagation happens in this state
The 2 eigenstates are connected by a $3 \times 3$ matrix ("mixing matrix")

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_{m1} \\
\nu_{m2} \\
\nu_{m3}
\end{pmatrix}
\]
A source produces -say- $\nu_e$ always via weak interactions.

To see what propagates to the detector I have to project this flavor state onto the mass state using the matrix inverse of $U$

$$\nu_m = U^{-1} \nu_e$$
Now each of the $\nu_m$ will evolve in time as prescribed by the wave functions:

$$\nu_{m_1}(t) = e^{-i(E_1t - p_1L)} \nu_{m_1}$$
$$\nu_{m_2}(t) = e^{-i(E_2t - p_2L)} \nu_{m_2}$$
$$\nu_{m_3}(t) = e^{-i(E_3t - p_3L)} \nu_{m_3}$$

but note that the periodic term contains the neutrino mass via $E_i = m_i c^2$.

So at the end of their flight -at the detector- the mix of $\nu_{m_1}$, $\nu_{m_2}$, $\nu_{m_3}$ will not necessarily be the one that makes “exactly” $\nu_e$!
The neutrinos are then detected via weak interactions and so we need to find again the composition in terms of $\nu_e$, $\nu_\mu$, $\nu_\tau$.

Formally

$$\left| \nu_j \right\rangle = \sum_{j'} \sum_l U_{lj} e^{-i(E_j t - p_j L)} U^*_{j'l} \left| \nu_{j'} \right\rangle$$

So after some propagation one can “find” a neutrino of a flavor that was not originally present.

This is a pure quantum-mechanical effect, there is no classical interpretation of it (this is why it looks so weird).

It can ONLY happen if the mass is non-0.
The situation is analogous to the case of beats in sound.

The wavefunctions of the two neutrino mass eigenstates need to be combined in a linear combination to obtain the flux of a particular flavor eigenstate.

The beat represents the oscillating intensity of a detected neutrino flavor.

So this quantum mechanical “beat” phenomenon allows us to detect extremely small neutrino masses.
Can we detect oscillations in phenomena other than solar neutrinos?
~1 km high Mt Ikenoyama
69 reactor cores from Japan and (South) Korea

Baseline is limited:
85.3% of signal has 140 km < L < 344 km

The total electric power produced “as a by-product” of the ☩ is:
• ~60 GW or…
• ~4% of the world’s manmade power or…
• ~20% of the world’s nuclear power
The result from reactors agrees very well with what expected from the phenomenon of solar neutrinos.
So, we have now observed neutrino oscillations and hence we know that neutrinos have a finite mass.

However measuring beats only provide information about the difference between two frequencies...

→ We still do not know the neutrino mass scale!
Summary of knowledge on neutrino masses

- The tritium endpoint gives a mass upper limit of $<2.8\,\text{eV}$.
- The $0\nu\beta\beta$ endpoint gives a mass upper limit of $<0.3\,\text{eV}$.
- If $v$ is Majorana, then $\nu\beta\beta$ can occur.

The diagram shows the mass-squared differences ($m^2$) for the three lightest neutrino states ($\nu_e$, $\nu_\mu$, $\nu_\tau$) with known limits:

- $m_1^2$: solar $\sim 5 \times 10^{-5}\,\text{eV}^2$
- $m_2^2$: atmospheric $\sim 3 \times 10^{-3}\,\text{eV}^2$
- $m_3^2$: solar $\sim 5 \times 10^{-5}\,\text{eV}^2$

The mass hierarchy is $m_1 < m_2 < m_3$. The question mark indicates the unknown hierarchy for the heavier states.
Allright, this is lots of fun but... can we use these neutrinos for something useful?!

The answer is usually “no”, among other things because neutrinos are so difficult to detect...

...but, remember the story of M. Faraday and the King...

Let's go back to a device that makes LOTS of antineutrinos: a nuclear reactor

We can turn things around and use antineutrinos to “peek inside” the reactor's core (neutrinos don't care that there are heavy walls!)
The antineutrino count rate varies in a known way as Pu is produced even at constant power.

Example: 20 kg of fuel containing Pu are replaced with fresh U and then the reactor is restarted at the same power level.
Technology demonstration detector being prepared at the San Onofre Nuclear Generating Station (CA) [Sandia Natl Lab]

Set the 1m³ detector in the “tendon gallery” 24.5 m from the core

Heavy reactor building provides shielding from cosmic rays

Expect 2600 ν/day with 40% detector efficiency
Earth sciences and the neutrinos

Structure of the Earth

- From seismic data
- 5 basic regions:
  - inner core,
  - outer core,
  - mantle,
  - oceanic crust,
  - continental crust and sediments

- All these regions behave like solids except the outer core.
Only a shallow layer has been sampled for chemical composition by drilling/sampling

- Deepest bore-hole (12km) is only ~1/500 of the Earth's radius
- Oceans and southern hemisphere substantially less studied
Both $^{238}\text{U}$ and $^{232}\text{Th}$ are primordial radioactive isotopes with long decay chains including $\beta^-$ decays.
Detecting Geoneutrinos!

9 Mar 02 – 4 Nov 09
4133 ton-yr

A.Gando et al (KamLAND),
Nature Geoscience 4 (2011) 647
Supernovae and the neutrinos

Explosion of the “type II” SN in the Crab; Jul 4, 1054 AD
(as recorded by the VLT, Cerro Paranal, Chile)

The Crab Nebula formed by the expelled outer shell of the same star (as recorded by the VLT, Cerro Paranal, Chile)

The World of Neutrinos
Type II supernovae: explosive phase of a star with $M > 6$ to $8 \, M_{\odot}$

- Nuclear fuel burnt through Fe: no mechanism to hold further gravitational collapse
- $T = 0.8 \times 10^{10} \, K = 0.7 \, MeV$
  $\rho = 3 \times 10^9 \, g/cm^3$ (this is a billion times the density of the earth, or the entire KamLAND in a teaspoon)
- The pressure causes the reaction $p + e^- \rightarrow n + \nu_e$ to occur
  - Very intense $\nu_e$ flash ($\sim 1$ s duration)
- Neutrinos cool the star that collapses further
- The collapsing soup become so dense to be opaque to $\nu$ (!)
- Following mechanisms that we do not completely understand the fireball re-bounces blowing up the outer envelope (eventually like the Crab photo)
- $\nu$ of all flavors escape when density low enough (after $\sim 10$ s)
SN1987A reconstruction from real astronomical images
Only hours later the density is low enough for light to escape the star and the supernova flash appears

99% of the supernova explosive energy is carried away by neutrinos

...~3.8*10^{33} \text{ erg, in 10 s it would take the sun 2000 billion years to produce that much energy}!
We have seen the neutrinos from a supernova only once

Feb 23, 1987 about 20 $\nu$ events were detected from an explosion in the Large Magellanic Cloud: SN1987A
Primordial neutrinos were produced when nuclei formed, at the time the Universe was 1 second old.

We believe that they are still among us.

**Cosmology**

The earliest snapshot we have of the universe

- Primordial nucleosynthesis
- Electroweak symmetry breaking
- GUT symmetry breaking
- Planck scale

**Neutrino decoupling**

Age of astronomy

TRIUMF Jan 18, 2013

The World of Neutrinos
Relic neutrinos have been “red-shifted” by the expansion of the Universe. Their temperature now is supposed to be ~2K, lower than the temperature (3K) of the microwave background radiation that was produced when the Universe was 30,000 years old. We do not have the technology to directly detect these neutrinos. But... we can see how their presence shaped the density fluctuations of matter in the early Universe as imaged by the microwave background radiation.
Neutrinos, mysterious ambassadors from the microworld to the remote cosmos, what lessons do you have for us next?