Neutrino Physics

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Part 1
Neutrino physics has become very interesting in the last dozen years.

It spans nuclear physics, particle physics, and astrophysics.

Nuclear physicists have played a leading role in making it so interesting.
What Are Neutrinos Good For?

Energy generation in the sun starts with the reaction —

\[ p + p \rightarrow d + e^+ + \nu \]

Spin: \( \frac{1}{2} \quad \frac{1}{2} \quad 1 \quad \frac{1}{2} \quad \frac{1}{2} \)

Without the neutrino, angular momentum would not be conserved.

Uh, oh ……
The Neutrinos

Neutrinos and photons are by far the most abundant elementary particles in the universe. There are 340 neutrinos/cc.

The neutrinos are spin – 1/2, electrically neutral, leptons.

The only known forces they experience are the weak force and gravity.

This means that their interactions with other matter have very low strength. Thus, neutrinos are difficult to detect and study.

Their weak interactions are successfully described by the Standard Model.
The Neutrino Revolution
(1998 – …)

Neutrinos have nonzero masses!

Leptons mix!
These discoveries come from the observation of neutrino flavor change (neutrino oscillation).
The Physics of Neutrino Oscillation — Preliminaries
The Weak Interaction Bosons

The weak interactions of the Standard Model are carried by the $W$ and $Z$ bosons:

$W$ boson:

- $p \rightarrow n, e^-, \bar{\nu}$
- 80 GeV

$Z$ boson:

- $\nu \rightarrow p, p, \nu$
- 91 GeV
The Neutrino Flavors

We define the three known flavors of neutrinos, $\nu_e$, $\nu_\mu$, $\nu_\tau$, by W boson decays:

As far as we know, neither

nor any other change of flavor in the $\nu \rightarrow \ell$ interaction ever occurs. With $\alpha = e, \mu, \tau$, $\nu_\alpha$ makes only $\ell_\alpha$ ($\ell_e \equiv e$, $\ell_\mu \equiv \mu$, $\ell_\tau \equiv \tau$).
If neutrinos have masses, and leptons mix, we can have —

The last decade has brought us compelling evidence that such flavor changes actually occur.
Flavor Change Requires *Leptonic Mixing*

The neutrinos $\nu_{e,\mu,\tau}$ of definite flavor

\[(W \rightarrow e\nu_e \text{ or } \mu\nu_\mu \text{ or } \tau\nu_\tau)\]

must be superpositions of the mass eigenstates:

\[|\nu_\alpha> = \sum_i U^*_{\alpha i} |\nu_i> \, .\]

Neutrino of flavor $\alpha = e, \mu, \text{ or } \tau$

(Unitary?) Leptonic Mixing Matrix

There must be *at least 3* mass eigenstates $\nu_i$, because there are 3 orthogonal neutrinos of definite flavor $\nu_\alpha$. 
The Meaning of $U$

The $\nu_i$ column of $U$: The linear combination of charged-lepton mass eigenstates that couples to $\nu_1$.

The $e$ row of $U$: The linear combination of neutrino mass eigenstates that couples to $e$. 

$U = \begin{pmatrix} \nu_1 & \nu_2 & \nu_3 \\ e & U_{e1} & U_{e2} & U_{e3} \\ \mu & U_{\mu1} & U_{\mu2} & U_{\mu3} \\ \tau & U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}$
The Meaning of $U$

\[ \ell_\alpha^+ \rightarrow g \frac{g}{\sqrt{2}} U_{\alpha i}^* \nu_i \rightarrow W \rightarrow \ell_\beta^- \]

**Semi-weak coupling constant**

\[ U = \begin{pmatrix} \nu_1 & \nu_2 & \nu_3 \\ e & \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \end{pmatrix} \\ \mu & \begin{pmatrix} U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \end{pmatrix} \\ \tau & \begin{pmatrix} U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \end{pmatrix} \]

The $e$ row of $U$: The linear combination of neutrino mass eigenstates that couples to $e$.

The $\nu_1$ column of $U$: The linear combination of charged-lepton mass eigenstates that couples to $\nu_1$. 
Slides on The Physics of Neutrino Oscillation go here.
What if the neutrino source is NOT constant in time?

The oscillation probabilities are still the same.

One can prove this taking into account entanglement.
Neutrino Flavor Change In Matter

Coherent forward scattering via this W-exchange interaction leads to an extra interaction potential energy —

\[ V_W = \begin{cases} +\sqrt{2}G_FN_e, & \nu_e \\ -\sqrt{2}G_FN_e, & \bar{\nu}_e \end{cases} \]

Fermi constant \( G_F \) \( N_e \) \( \nu_e \) \( \bar{\nu}_e \) Electron density

This raises the effective mass of \( \nu_e \), and lowers that of \( \bar{\nu}_e \).
The fractional importance of matter effects on an oscillation involving a vacuum splitting $\Delta m^2$ is —

$$\frac{\sqrt{2} G_F N_e}{\Delta m^2/2E} \equiv x.$$

The matter effect —

— Grows with neutrino energy $E$
— Is sensitive to $\text{Sign}(\Delta m^2)$
— Reverses when $\nu$ is replaced by $\bar{\nu}$

This last is a “fake CP violation”, but the matter effect is negligible when $x \ll 1$. 
Highlights of the Experimental Evidence
### Evidence For Flavor Change

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Solar Neutrinos

History –

Nuclear reactions in the core of the sun produce $\nu_e$. Only $\nu_e$. 
Theorists, especially John Bahcall, calculated the produced $\nu_e$ flux vs. energy $E$. 
Ray Davis’ Homestake experiment measured the higher-E part of the $\nu_e$ flux $\phi_{\nu_e}$ that arrives at earth.
The Homestake experiment could detect only $\nu_e$. It found:

\[
\frac{\phi_{\nu_e} (\text{Homestake})}{\phi_{\nu_e} (\text{Theory})} = 0.34 \pm 0.06
\]

The Possibilities:

The theory was wrong.

The experiment was wrong.

Both were wrong.

Neither was wrong. Two thirds of the $\nu_e$ flux morphs into a flavor or flavors that the Homestake experiment could not see.
The Resolution —

Sudbury Neutrino Observatory (SNO) measures, for the high-energy part of the solar neutrino flux:

\[ \nu_{\text{sol}d} \rightarrow e \, p \, p \ \Rightarrow \phi_{\nu_e} \]

\[ \nu_{\text{sol}d} \rightarrow \nu \, n \, p \ \Rightarrow \phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau} \]

From the two reactions,

\[ \frac{\phi_{\nu_e}}{\phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}} = 0.301 \pm 0.033 \]

Clearly, \( \phi_{\nu_\mu} + \phi_{\nu_\tau} \neq 0 \). Neutrinos change flavor.

\[ P(\nu_e \rightarrow \nu_e) = 0.3 \]
Change of flavor does not change the total number of neutrinos.

The total flux, $\phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}$, should agree with Bahcall’s prediction.

SNO: $\phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau} = (5.54 \pm 0.32 \pm 0.35) \times 10^6$/cm$^2$sec

Theory*: $\phi_{\text{total}} = (5.69 \pm 0.91) \times 10^6$/cm$^2$sec

*Bahcall, Basu, Serenelli

John Bahcall and Ray Davis both stuck to their results for several decades, and both were right all along.
Reactor (Anti)Neutrinos In KamLAND

The KamLAND detector studies $\overline{\nu}_e$ produced by Japanese nuclear power reactors ~ 180 km away.

Our understanding of solar neutrino behavior implies that a considerable fraction of these reactor $\overline{\nu}_e$ should disappear before reaching KamLAND.

KamLAND does see a disappearance of about 1/3 of the $\overline{\nu}_e$. 
The solar and KamLAND data are both described by the same, single set of neutrino parameters:

\[ \Delta m_{\text{sol}}^2 = 7.50 \times 10^{-5} \text{eV}^2, \quad \tan^2 \theta_{\text{sol}} = 0.44 \]
Atmospheric Neutrinos

Isotropy of the $\geq 2$ GeV cosmic rays + Gauss’ Law + No $\nu_\mu$ disappearance

$$\Rightarrow \frac{\phi_{\nu_\mu}(\text{Up})}{\phi_{\nu_\mu}(\text{Down})} = 1.$$ 

But Super-Kamiokande finds for $E_\nu > 1.3$ GeV

$$\frac{\phi_{\nu_\mu}(\text{Up})}{\phi_{\nu_\mu}(\text{Down})} \approx \frac{1}{2}.$$
Multi-GeV \( \mu \)-like + PC

Number of Events

\[ \cos \theta_z \]

(Super-K)
Voluminous atmospheric neutrino data are well described by —

\[ \nu_\mu \rightarrow \nu_\tau \]

with —

\[ \Delta m^2_{\text{atm}} \approx 2.4 \times 10^{-3} \text{ eV}^2 \]

and —

\[ \sin^2 2\theta_{\text{atm}} \approx 1 \]
Accelerator Neutrinos

Two experiments: K2K and MINOS

Source

Near Detector

\(\nu_\mu\)

250 or 735 km

Far Detector

Expectation

Observation
A single pair of parameters, with $\sim$ maximal mixing, fits both the atmospheric and accelerator neutrino data.
KamLAND Evidence for Oscillatory Behavior
The KamLAND detector studies $\bar{\nu}_e$ produced by Japanese nuclear power reactors $\sim 180$ km away.

For KamLAND, $x_{\text{Matter}} < 10^{-2}$. Matter effects are negligible.

The $\bar{\nu}_e$ survival probability, $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$, should oscillate as a function of $L/E$ following the vacuum oscillation formula.

In the two-neutrino approximation, we expect —

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta \sin^2 \left[ 1.27 \Delta m^2 (eV^2) \frac{L(km)}{E(GeV)} \right].$$
$L_0 = 180$ km is a flux-weighted average travel distance.

$P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ actually oscillates!