Neutrinos: Yesterday, Today and Tomorrow

Sandip Pakvasa
University of Hawaii

So, what IS a Neutrino?

This IS a Neutrino

This was a Neutrino

Stable Elementary Particle
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!
Nature's building blocks

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

Some mass, but curiously little.
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 - Soon?
- Big Bang (here 330 /cm³) - Indirect Evidence
Outline:

- History of Invention/Discovery of Neutrino (1895-1930)
- Associated History of Elementary Particle Physics
- Discovery of all the neutrinos (1956-2000) and measurement of their properties
- Neutrino Oscillations etc
- Neutrinos from the sun, supernova, the cosmos, the earth, accelerators and reactors
- Neutrino Applications
November 1895: William Roentgen discovers X-rays from Cathode Ray Tubes (Wuerzburg)

- January 1896: Henri Becquerel (Paris) hears about the X-rays in a lecture by Poincare

- February 1896: H.B. discovers Radioactivity (in Uranium ore) while trying to find natural sources for X-rays!

- 1898: Ernest Rutherford and Marie (and Pierre) Curie start working on Radioactivity and studying its properties

- Rutherford found: (a) the exponential decay law; (b) three types of Activity. Beta (penetrating and easily deflected in magnetic fields, Alpha (“stoppable” and deflected not so easily) and Gamma (undeflected and most penetrating). Thus alphas and betas were charged and gammas were neutral.

- Curies found other stronger radioactive substances (Thorium, Radium, Polonium etc) and showed alphas were much heavier than betas (turned out to be electrons).
Alpha, beta and gamma radiation can be by using magnetic field. Alpha and beta particles have contrary charges - they undergo deflection in opposite directions gamma rays don't transfer any charge - they don't undergo deflection.
Life and Times of Charles Drummond Ellis:

- Beta spectrum very rich & complicated: Lines +Continuum........

- Chadwick and Ellis in Berlin and Cambridge (1914-1929)

- After some confusion and controversy with Lise Meitner, they finally showed convincingly that electron energy spectrum in beta decay is continuous.
Bohr: *At the present stage of atomic theory, however, we may say that we have no argument, either empirical or theoretical, for upholding the energy principle in the case of b-ray disintegrations*.
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 Li 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...
Dear radioactive ladies and gentlemen,

...I have hit upon a ‘desperate remedy’ to save...the law of conservation of energy. Namely the possibility that there exists in the nuclei electrically neutral particles, that I call neutrons...I agree that my remedy could seem incredible...but only the one who dare can win...

Unfortunately I cannot appear in person, since I am indispensable at a ball here in Zurich.

Your humble servant
W. Pauli

Note: this was before the discovery of the real neutron
December 1933: Enrico Fermi submits a paper to Nature: “Tentativo di Una Teoria Della Emissione di raggi Beta”

It was rejected: “speculations too remote from reality to be of interest to the readers”.

Eventually published in Nuovo Cimento This paper laid out the essential theory of beta decay that has survived almost unchanged until now, with “small” modifications. It predicted the spectrum, obtained the correct value for the coupling etc........

In the meantime back in Osaka, Japan, Hideyuki Yukawa was busy................
In 1934, Yukawa proposed a π meson as a carrier of the nuclear force, and from the known range of about $10^{-13}$ cm, deduced a mass of about 100 MeV.

Immediate confirmation (1938-9) in cosmic rays when particles of such a mass were seen. But soon it was found to behave strangely and not at all like Yukawa’s π meson was supposed to; wrong lifetime, no strong coupling etc. .........

It was proposed by Shoichi Sakata (1943) (with Inoue) that the funny particle was not π but μ, and that π decayed into $\mu + \nu_\mu$ and the μ decayed into $e + \nu_\mu + \nu_e$.

At the time, it was not clear if the two neutrinos, from beta decay and from π decay were the same or different.........
The Sakata Scheme of pi-mu decay was completely confirmed in 1947-8 by Powell et al (Bristol).

Anti-$\nu_e$ Detection Reines-Cowan(1956): Idea was to use the radioactive Beta decays of fission products of Uranium:
$$U + n \rightarrow X + Y + \text{neutrons}$$

$X$ and $Y$ are neutron rich and beta decay:
$$X \rightarrow Z + e^- + \text{anti-$\nu_e$}$$

For detection they used liquid scintillator and the reaction:
$$\text{anti-$\nu_e$} + p \rightarrow n + e^+$$
Experiment attempted at Hanford in 1953, too much background. Repeated at Savannah River in 1955. [Flux: $10^{13}$ neutrinos/(cm$^2$ s)]
Neutrinos are Left-handed

Helicity of Neutrinos*

M. Goldhaber, L. Grodzins, and A. W. Sunyar

Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

A combined analysis of circular polarization and resonant scattering of $\gamma$ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu$^{152m}$, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,$^1$ 0$-$, we find that the neutrino is “left-handed,” i.e., $\sigma_{\nu} \cdot \hat{p}_{\nu} = -1$ (negative helicity).
This result that neutrino is left-handed is exactly what was expected in the 1957 V - A theory of George Sudarshan and Robert Marshak and was a confirmation of it.

The fact that weak interactions are V – A was crucial in constructing the Standard Model of electroweak interactions a la Glashow, Salam and Weinberg.
Confirmation that the second neutrino is different from the first!
Brookhaven 1962

Brookhaven experiment (1962)

Conceptual layout of an accelerator neutrino beam
Date: 1962
Intent: Measure weak force at high energies
Expectation: Since neutrinos are created with muons and electrons, the neutrino beam should create both electrons and muons in the detector.
Result: No electrons produced, only muons
Conclusion: There must be two kinds of neutrinos.
In 1975 Martin Perl et al. observed events at SLAC in $e^+e^-$ collisions which suggested the existence of a third lepton, christened the Tau.

There was a third neutrino expected to be associated with this charged lepton.

It required 25 years (2000) to confirm the existence of $\nu_\tau$ by direct detection (Fermilab)!
Observation of the third neutrino  FermiLab 2000

$\nu_\tau$ discovery: year 2000

DONUT experiment at Fermilab

Protons $\rightarrow$ target $\rightarrow X + D_s$

$I + \tau + \nu_\tau \rightarrow$ detector $\rightarrow \tau$

$I + X + \nu_\tau \rightarrow$ detector $\rightarrow \tau$
Neutrino masses, mixings and Oscillations

- When neutrinos have masses, the “flavor” states, such as $\nu_e$ and $\nu_\mu$
- do NOT have well defined masses,
- So the production is of these states, whereas the propagation afterwards
- is in terms of states with well defined masses.
- Z. Maki, M. Nakagawa and S. Sakata (1962)
- V. Gribov and B. Pontecorvo (1968)
\[
\begin{pmatrix}
\nu_e \\
\nu_\mu
\end{pmatrix}
= \begin{bmatrix}
\cos \theta & -\sin \theta \\
\sin \theta & \cos \theta
\end{bmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix}
\]

Important!

\[m_1 \neq m_2\]
\[ P(\nu_e \rightarrow \nu_\mu) \approx \sin^2(2\theta) \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) \]

\[ m_1 \neq m_2 \]
Sources of Neutrinos:

Natural:
(i) Atmospheric (10^{-4} s),
(ii) Solar (8 min),
(iii) Supernova (>10^4 yr),
(iv) Other astrophysical sources (GRB, AGN) (10^6 yr),
(v) Early Universe (10^{12} yr),
(vi) Earth’s Interior (0.01 s).

- Artificial (Man-made):
  - (i) Reactors (10^{-4} s)
  - (ii) Accelerators (0.001 s)
The first observations of Atmospheric Neutrinos made in Kolar Gold Fields near Bangalore, and in South Africa in 1965.

- The Indian team was led by M. G. K. Menon et al.
- The South African team was led by F. Reines et al.
KGF – The 1st reported Atmospheric $\nu$

Several detectors in KGF mine at various depths.
3 $\nu$ evts published **15 Aug 65**

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**Table 1**

<table>
<thead>
<tr>
<th>Event number</th>
<th>Type of coincidence</th>
<th>Projected zenith angle</th>
<th>Date</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TEL. 2 N$_4$ + S$_4$</td>
<td>37°</td>
<td>30.3</td>
<td>20.04</td>
</tr>
<tr>
<td>2</td>
<td>TEL. 1 N$_1$ + S$_1$</td>
<td>48 ± 1°</td>
<td>27.4</td>
<td>18.26</td>
</tr>
<tr>
<td>3</td>
<td>TEL. 2 N$_6$ + S$_6$</td>
<td>75 ± 10°</td>
<td>25.5</td>
<td>20.03</td>
</tr>
</tbody>
</table>

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Detection of Muons Produced by Cosmic Ray Neutrino Deep Underground

C. V. Achar, M. G. E. Minon, V. S. Narasimham, P. V. Ramana Murthy
and B. V. Sreekantan,
Tata Institute of Fundamental Research, Colaba, Bombay
K. Hinotani and S. Miyake,
Osaka City University, Osaka, Japan
D. N. Creed, J. L. Osborne, J. M. Pattison and A. W. Wolfendale
University of Durham, Durham, U.K.

Received 15 July 1965
Detectors in KGF mine (1965-1991)

Proportional Tube element of proton decay detector and Monopole detector

α Telescope
Iron, flash tubes & scintillator
First ν
February 29, 1965
Recorded 100 (1/month)
1998: The Super-Kamiokande Announces observation of Neutrino Oscillations
Super-Kamiokande
Nucleon Decay Experiment

- $P \rightarrow e^+ p^0, K^+ n$, etc
- So far not seen
- Atmospheric neutrino main background

- Cosmic rays isotropic
- Atmospheric neutrino up-down symmetric
Super-Kamiokande

11 stories high
1,000 meters underground
50,000 tons of water
22,500 tons fiducial volume
11,200 photomultipliers
0.5 meter photomultiplier diameter
(old copper and zinc mine)
Half of $\nu_\mu$ lost!
K2K First Long Baseline Experiment

![Graph showing time difference vs. number of events](image1)

![Map of K2K-I and K2K-II](image2)

Null oscillation

Best fit

![Allowed regions of oscillation parameters](image3)

FIG. 4: Allowed regions of oscillation parameters. Dashed, solid and dot-dashed lines are 68.4%, 90% and 99% C.L. contours, respectively.
Cross check with man-made ν’s from Fermilab: MINOS
Good consistency with SK!

- MINOS result 2006

![Graphs showing data and fits, with axes labeled as shown in the image.]

- [Graph showing data points and fits for reconstructed energy vs. data/MC ratio.
- [Graph showing a 2D contour plot with axes for $\Delta m^2_{32}$ (eV$^2$/c$^4$) vs. $\sin^2(2\theta_{23})$.]
What we learnt from Atmospheric Neutrino Observations:

- \( \nu_{\mu} = (\nu_2 + \nu_3)/\sqrt{2} \)
- \( \nu_{\tau} = (\nu_2 - \nu_3)/\sqrt{2} \)

This corresponds to a mixing angle \( \theta \) of 45 deg. We also learnt that the squared mass difference is

\[ dm^2_{32} = 2.5 \times 10^{-3} \text{ eV}^2 \]
Solar Neutrinos: How the Sun burns

- The Sun emits light because nuclear fusion produces a lot of energy

\[ \Phi_v = \frac{2L_{\text{sun}}}{25\text{MeV} \, 4\pi(1\text{AU})^2} \cdot \frac{1}{25\text{MeV}} = 7 \cdot 10^{10} \text{ sec}^{-1} \text{ cm}^{-2} \]

Pioneers: Ray Davis and John Bahcall, starting in ’60’s
The Sun seen in Neutrinos from SuperK
Homestake Gold Mine

100,000 gallons of cleaning fluid $C_2Cl_4$

Expected 1.5 interactions per day
Measured 0.5 interactions per day

Sensitive to $^8B$ solar neutrinos only

$\nu_e + ^{37}Cl \rightarrow e^- + ^{37}Ar$

Ray Davis
John Bahcall
$^{71}\text{Ga} + \nu \rightarrow ^{71}\text{Ge} + e^-$

Sensitive to pp fusion in sun.

50 metric tons of Gallium
They extract a few tens of atoms of Germanium

Measured: $77 \pm 6 \pm 3$ SNU
Predicted: $123 + 9 -7$ SNU
Different experiments are sensitive to different solar processes.

But all experiments show a marked deficit of electron neutrinos.

Could reflect ignorance of how the sun works?

Except.....
SNO
Sudbury Neutrino Observatory
In Sudbury, Ontario

• Cerenkov detector
• Heavy water (can do solar model independent measurements)
• 6800 feet underground
• 9600 PMTs
**Charged interactions** convert neutron to proton. Sensitive only to $\nu_e$. 30 events/day

**Neutral interactions** disassociate deuteron into neutron and proton. Sensitive to $\nu_e$, $\nu_\mu$, $\nu_\tau$. 30 events/day

**Electron scattering** mostly sensitive to $\nu_e$, with small contribution from $\nu_\mu$, $\nu_\tau$. 3 events/day

Comparison of SNO results with Super K indicates that the neutrino flux from the sun contains muon neutrinos, supporting neutrino oscillations.

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**SNO Physics and Results**

**Announcement:**

June 18, 2001
SNO clinches case for solar neutrino problem as not due to solar model
Terrestrial “Solar Neutrino”

- Can we convincingly verify oscillation with 
  \[ P_{\text{surv}} = 1 - \sin^2 2\theta \sin^2 \left( 1.27 \frac{\Delta m^2 c^4}{eV^2} \frac{L}{E_\nu} \frac{\text{km}}{\text{km}} \right) \] ?

- Hard for low \( \Delta m^2 \)
- To probe LMA, need \( L \sim 100\text{km}, 1\text{kt} \)
- Need low \( E_\nu \), high \( \Phi_\nu \)
- Use neutrinos from nuclear reactors
Proper time $L_0 = 180$ km

And $\sim$ same as solar neutrinos

And $\sim$ same as solar neutrinos
Summary of what we learn from Solar+ Reactor Neutrino Observations:

- P-P cycle supplies the bulk of solar energy
- Standard Solar Models in good shape: give correct neutrino flux and are consistent with helioseismology (to few percent)
- \( \nu_e = (\sqrt{2} \nu_1 + \nu_2)/\sqrt{3} \)
- Mass difference squared: \( dm^{2}_{21} = 8.10^{-5} \text{eV}^2, \; m_2 > m_1 \)
- Matter effects very important (Wolfenstein, Mikheyev, Smirnov) in interpreting the solar neutrino results
The Status of the Neutrino Mixing Matrix (MNS)

In addition, the offset from zero not known!

\[
U_{MNS} = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\]

\[
= \begin{pmatrix}
1 & c_{13} \cos \delta - i s_{13} \sin \delta \\
c_{23} & s_{23} & 1 \\
-s_{23} & c_{23} & -s_{13} \sin \delta
\end{pmatrix}
\]

\[
U_{MNS} \sim \begin{pmatrix}
0.8 & 0.5 & \ast \\
0.4 & 0.6 & 0.7 \\
0.4 & 0.6 & 0.7
\end{pmatrix}
\]

Neutrinos

\[
V_{CKM} \sim \begin{pmatrix}
1 & 0.2 & 0.08 \\
0.2 & 1 & 0.04 \\
0.08 & 0.04 & 1
\end{pmatrix}
\]

Quarks

\[
\ne \to \mu \\
\mu \to e \\
\tau \to \mu
\]
2 Minute Summary of 50 years of Research on **Supernova Neutrinos**:

- Type II Supernova: Naive Picture (other types do not emit neutrinos)
- Massive Star (typically 50 solar masses), the core is mostly iron, cannot sustain by fusion
- Gravitational Collapse (implosion)
- Neutronization$(e^-+p^+\rightarrow n+\nu_e)$ lasts for few millisec.
- Explosion, with mantle being thrown off
- End up as neutron star $\rightarrow$ neutrinosphere from $e^+ e^- \rightarrow$ nus (this lasts about 1-10 sec)
- Supernovae have been recorded since 1002 A.D. (in our galaxy), Neutron Stars seen since 1967
- Neutrinos from SN not seen until Feb. 28, 1987: SN1987A!
- None since!
Neutrino Burst of Supernova 1987A

Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ±50 ms

Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~ 0.7/day
Clock uncertainty +2/-54 s

Within clock uncertainties, signals are contemporaneous
<table>
<thead>
<tr>
<th>SN 1987A</th>
<th>Future supernova</th>
</tr>
</thead>
<tbody>
<tr>
<td>General confirmation of core-collapse paradigm (total energy, spectra, time scale)</td>
<td>Detailed test by high-statistics signal</td>
</tr>
<tr>
<td></td>
<td>Detection of unexpected features</td>
</tr>
<tr>
<td>No unexpected energy-loss channel: Restrictive limits on axions, large extra dimensions, right-handed neutrinos (couplings, mixings, dipole moments), Majorons, light SUSY particles, ...</td>
<td>Should be generally confirmed (low-statistics signal enough), but uncertainty dominated by theory (processes in a dense nuclear medium)</td>
</tr>
<tr>
<td>Neutrinos gravitate as expected (Shapiro time delay relative to photons)</td>
<td>Requires photon observations (IR if obscured) and depends on distance</td>
</tr>
<tr>
<td>Nothing useful about absolute $m_{\nu}$</td>
<td>Time variation of signal in IceCube?</td>
</tr>
<tr>
<td>• Nothing useful about oscillations</td>
<td>Neutrino mass hierarchy and/or information on $\Theta_{13}$ (with luck)</td>
</tr>
<tr>
<td>• Hints that flavor dependence of spectra indeed is not large</td>
<td></td>
</tr>
</tbody>
</table>
High Energy Astrophysical Neutrino Sources

- Wide variety expected

- Gamma Ray Bursters, Active Galactic Nuclei etc.....

- None have been observed yet, but many very large detectors under construction or taking data, under-water, under-ice...
40Km SE Toulon
Depth 2400m
Shore Base
La Seyne-sur-Mer

40 km
2400 m
Submarine cable

ANTARES SITE
AMANDA & ICECUBE at South Pole

1.5 km

Depth, 1,500 m

- Optical module
- Main cable
- HV divider
- Pressure housing
- Silicon gel
- PMT
- Light diffuser ball

Depth, 2,000 m
Neutrinos from early Universe:

- $T = 2^\circ K$, or $E = 10^{-4} \text{ eV}$
- $n(\text{number density}) = 330/\text{cc}$ (including all flavors, and antineutrinos)
- Total energy density in neutrinos about 2% of total, compared to 4.5% in baryons!

Neutrinos can play a significant role in determining the dark energy/cosmological constant and hence the fate of the universe!
Detecting these relic neutrinos?

It is very difficult to conceive of techniques to detect these very very low energy neutrinos directly.

So far no practical ideas have emerged, despite many attempts.

(A trip to Stockholm awaits a great idea!!!)
Why do we exist?

Matter Anti-matter Asymmetry
Matter and Anti-Matter
Early Universe

Matter

Anti-matter

1,000,000,001

1,000,000,000
Matter and Anti-Matter
Current Universe

us

1

Matter Anti-matter

The Great Annihilation
Baryogenesis

- What created this tiny excess matter?
- *Necessary* conditions for baryogenesis (Sakharov):
  - Baryon number non-conservation
  - CP violation
    - (subtle difference between matter and anti-matter)
  - Non-equilibrium
    - $G(DB>0) > G(DB<0)$
- It looks like neutrinos have no role in this...
Leptogenesis

- You generate *Lepton Asymmetry* first.
- Generate $L$ from the direct CP violation in right-handed neutrino decay

$$\Gamma(N_1 \rightarrow \nu_i H) - \Gamma(N_1 \rightarrow \bar{\nu}_i H) \propto \text{Im}(h_{1j} h_{1k}^* h_{lk}^* h_{lj}^*)$$

- $L$ gets converted to $B$ via EW anomaly
  
  More matter than anti-matter
  
  *We have survived "The Great Annihilation"*
Neutrinos From the Earth:

- The Earth emits about 50TW of energy (sum of all manmade reactors ≈1TW).

- About half is supposed to come from radioactivity of $^{238}\text{U}$, $^{232}\text{Th}$, and $^{40}\text{K}$ which produce anti-$\nu_e$'s.
Geoneutrinos

- Geoneutrinos are produced by
  
  \[ ^{238}\text{U} \rightarrow ^{206}\text{Pb} + 8\ ^{4}\text{He} + 6\ e^- + 6\ \overline{\nu}_e \]
  
  \[ ^{232}\text{Th} \rightarrow ^{208}\text{Pb} + 6\ ^{4}\text{He} + 4\ e^- + 4\ \overline{\nu}_e \]
  
  \[ ^{40}\text{K} \rightarrow ^{40}\text{Ca} + e^- + \overline{\nu}_e \]

- Direct measurement of HPE
  
  U: \sim 8\ TW, Th: \sim 8\ TW, K: \sim 3\ TW

- Geoneutrinos are detected by
  
  \[ \overline{\nu}_e + p \rightarrow e^+ + n \]

- Two consecutive signals
- Threshold 1.8 MeV

- Not sensitive to \(^{40}\text{K}\); other targets discussed
  [M.C.Chen (2005)]
KamLAND: The First Detector Sensitive to Geoneutrinos

- Liquid Scintillator 1000 ton
  - Contained in plastic balloon

- Surrounded by
  - 17-inch PMT 1325
  - 20-inch 554
  - (PMT: Photo Multiplier Tube, a photo sensor)

Liquid Scintillator

- Yields light on ionization (8000 photons/MeV)
- Mainly consists of only C and H
- Fiducial Radius: 6.0 m (but uses L-selection cut to suppress accidental backgrounds)
- Livetime: 1491 days
- Exposure: $2.44 \times 10^{32}$ proton-year (corresponding to 2881 ton-year)
- Energy resolution: 6.5%/\sqrt{E(\text{MeV})}$
- Analysis threshold: 0.9 MeV
- Geonu flux from Enomoto et al. model: 16TW U+Th total
- U&Th strongly anti-correlated
- Mauve band from Enomoto geo model, shows 20% uncertainty (maybe too too small)
KamLAND New Results – Geonu Spectrum

1491 day data set

![Graph showing data and spectral analysis](image-url)
Future
What do we want to know?

- Actual Neutrino Masses
- Remaining mixing angles and phases in the mixing matrix, and the mass hierarchy
- Is neutrino its own antiparticle?
- Right handed neutrinos? Sterile neutrinos?
- Are all neutrinos stable?
- If not, what are the lifetimes and decay modes?
- Where are the high energy astrophysical neutrinos?
- Can we see the big bang neutrinos?
- Distribution of U and Th in the earth
- Many experiments under way on all these questions....
- AND applications are coming (reactor monitoring)
Double Chooz, France, 2010
Daya Bay

Empty detectors: moved to underground halls through access tunnel.
Filled detectors: swapped between underground halls via horizontal tunnels.

Far site
1600 m from Ling Ao
2000 m from Daya Bay
Overburden: 350 m

Mid site
~1000 m from Daya Bay
Overburden: 208 m

Ling Ao Near
500 m from Ling Ao
Overburden: 98 m

Ling Ao-II NPP (under const.)

Daya Bay Near
360 m from Daya Bay
Overburden: 97 m

Total tunnel length: ~2700 m

Entrance portal
Remaining angle
NO  A

19kt

32-plane block
Admirer

L=810km

NOoA
Soudan
Duluth
MN
WI
MI
IA
IL
IN
MO
Fermilab
Lake Michigan
Lake Superior
Very Long Baseline Experiment
Do neutrinos and anti-neutrinos oscillate differently? (CP violation)

Beam from Fermilab to DUSEL probable in a few years

T2K Beam starting in Fall 2009
Other experiments:

- KATRIN (neutrino mass measurements)
- Neutrinoless Double beta decay searches
- (Related direct dark matter searches)
- Search for very high energy GZK neutrinos: ANITA, SALSA etc...
- Next generation Long-Baseline Experiments
- Neutrino Factory
- Etc., etc........
Revival of Experimental Neutrino Physics in India after over 25 years:
INO=India-based Neutrino Observatory

PUSHEP : 11.5°N 76.6°E, 6.5 km from Masinagudi, 96.5 km from Mysore, 5 hrs from Bangalore, Coimbatore, Calicut
3.4 Environment and forest clearances

- Rapid EIA Study: SACON, Coimbatore - June 2007
HANOHANO: A Deep Ocean Antineutrino Observatory

Locals: Steve Dye, John Learned, John Mahoney (Geology), Michinari Sakai, Gary Varner, Sandip Pakvasa, Marc Rosen, Stefanie Smith

University of Hawaii

(HANOHANO consists of about 20 institutions, collaboration not yet official, including U. Tohoku, U. Maryland, U. Alabama, Stanford, Caltech, UC Davis, U. Munich, and more)
Far Future:

- Uses/Applications of Neutrinos:

- Many obvious ones: As Probes to study interiors of many objects such as Nuclei, Nucleons, the Earth, the Sun, other stars, early universe........

- More ambitious/imaginative proposals.................
Neutrinos are alive and well…. And we cannot get rid of them.

This is the Century of Neutrinos.

We will be kept busy learning about neutrinos and learning to use them.
Sum of All Reactor Power

- Total of 440 power reactors, 2GWe/reactor
- 2574 TWe-Hrs in 2002, equiv \( \sim 0.881 \) TWt
- Rate in \( \text{km}^3 \) about 17,000 nuebar/day
- \( 1 \sigma \sim 130/\text{day} \), measure to 0.77%/sqrt(days)
- Typical reactor 1000 km away, 1543 cts/day implies about 12 \( \sigma \) measurement each day!
Tomography

- Most power reactors well known (1-2%, maybe better) in output as function of time, day by day at least (IAEA).
- A new unknown reactor (2GW) will contribute average of 43 counts/day at 6000km.
- Pin down location to \( \sim 20 \) km in one year.
- Can use oscillations and directionality as well.
- Numerical simulations studying resolution and detector siting.
What is a nuclear weapon?

1. **Ignition by explosives**
2. Shock wave is created, density wave makes $^{239}\text{Pu}$ and $^{238}\text{U}$ go beyond the critical point
3. Initiator gets broken (aluminum foil)
4. In $10^{-6}$ sec super-critical fission reaction occurs everywhere in the core
5. Tamper works to suppress “fizzle explosion”
6. Full explosion produces a bomb yield of $\sim 20$ kt
Mean free paths of neutrinos

- Calculated at the tree level
- Only two flavors ($u$ and $d$ quarks) are included
- Scaling functions with no QCD corrections
- No neutrino oscillation is assumed
- Protons and neutrons are uniformly distributed inside the Earth
- If one includes several effects, the cross-sections will become a few times larger, leading to smaller mean free paths
How to eliminate them from the other side of the Earth?

\[ E_n \sim 100 - 1000 \text{ TeV} \]
Mean free path = diameter of the Earth

1. Hadron shower hits the target bomb and causes sub-critical nuclear fissions
2. The temperature of the bomb increases
3. Above 250 degrees the surrounding explosives (dynamite) get ignited
4. The rest of the process is the same as the `ordinary` nuclear bomb explosion
The important difference!

1. The bomb is exposed to hadron beams which play the role of initiator.
2. The beams cause sub-critical chain reactions to start before the shock wave reaches the center.
3. Such a phenomenon is well known as the "fizzle explosion".
4. This makes the destruction of the nuclear bomb relatively safe.