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The Little Neutral One

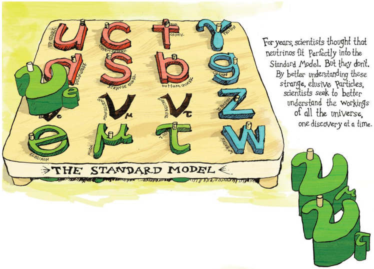
A brief history of neutrinos

Mary Bishai
Brookhaven National Laboratory

June 30th, 2020

Neutrinos in Popular Culture

1964



From Symmetry Magazine, Feb 2013

Cosmic Gall
by John Updike

Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall,
And, scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed—you call
It wonderful; I call it crass.

Neutrinos in Popular Culture

Jan 7, 2011

NASA's silly sci-fi film list – 2012 the most flawed
by Lin Edwards , PhysOrg.com
(PhysOrg.com) – At a conference held at the Jet Propulsion Laboratory in California, NASA experts have voted *2012* the most scientifically flawed and absurd science fiction film ever made.
The 2009 disaster film named 2012 was directed by Roland Emmerich and written by Emmerich and Harald Kloser and grossed almost $ 800 million.....
NASAs Donald Yeomans, who headed the Near Earth Asteroid Rendezvous mission, called the film an "exceptional and extraordinary" example of bad science in Hollywood movies. He pointed out that neutrino particles cannot interact with physical substances, and there is no possible way neutrinos carried to Earth by solar flares as depicted could cook the planets core and cause hurricanes or earthquakes or produce tsunamis big enough to overwhelm Mount Everest as shown in the film.

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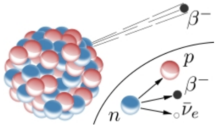
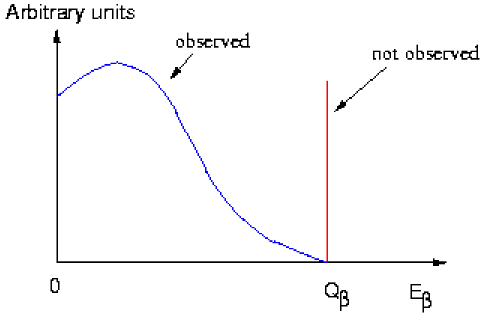
CONCEPTION OF THE NEUTRINO

Neutrino Conception



Before 1930's: beta decay spectrum continuous - is this energy non-conservation?



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Dec 1930: Wolfgang Pauli's letter to physicists at a workshop in Tubingen:

Wolfgang Pauli

Dear Radioactive Ladies and Gentlemen,

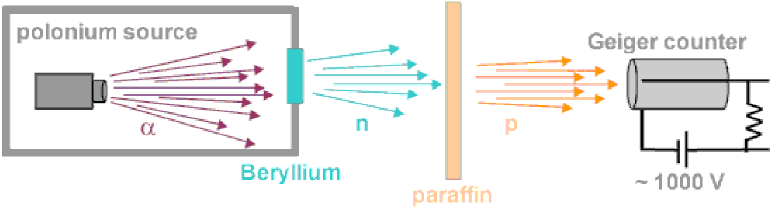
.........., I have hit upon a desparate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons.... The mass of the neutrons should be of the same 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..........
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.
Your humble servant

. W. Pauli

Neutrino Conception

1932: James Chadwick discovers the neutron, $\text{mass}_{\text{neutron}} = 1.0014 \times \text{mass}_{\text{proton}}$ - its too heavy - cant be Pauli's particle

James Chadwick



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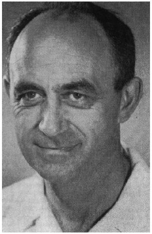
Solvay Conference, Bruxelles 1933: Enrico Fermi proposes to name Pauli's particle the "neutrino".



Enrico Fermi

Particle physics units and symbols

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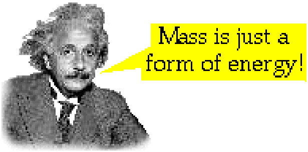
Symbols used for some common particles:

Symbol	Particle
ν, $\bar{\nu}$	Neutrino and anti-neutrino
γ	Photon
e^-	Electron
e^+	Anti-electron (positron)
p	proton
n	neutron
N	nucleon - proton or neutron



Particle physicists express masses in terms of energy, $E = mc^2$
Mass of proton $= 1.67 \times 10^{-24}$ g $\approx$ 1 billion (Giga) electron-volts (GeV)
1 thousand GeV = energy of a flying mosquito

The Theory of Weak Interactions

$\geq$ **1933:** **Fermi builds his theory of weak interactions and beta decay**

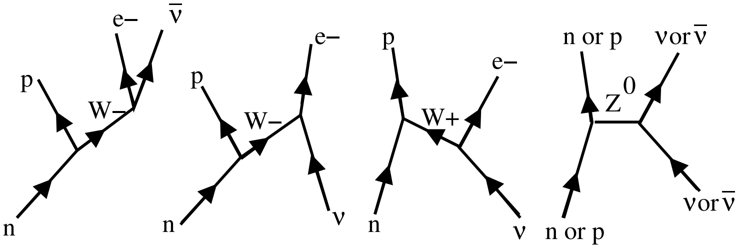
Charged current interactions

Decay of neutron

Neutrino interacts with neutron

Neutral current interactions

n or p interacts with neutrino or antineutrino



$n \rightarrow p + e^- + \bar{\nu}$

$n + \nu \rightarrow p + e^-$

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A little exercise:

$$\mathbf{n} \quad \rightarrow \quad \mathbf{p}^{+} + \mathbf{e}^{-} + \bar{\boldsymbol{\nu}}$$

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A little exercise:

$$\begin{aligned} \mathbf{n} &\rightarrow \mathbf{p}^{+} + \mathbf{e}^{-} + \bar{\nu} \\ \mathbf{n} + \nu &\rightarrow \mathbf{p}^{+} + \mathbf{e}^{-} \end{aligned}$$

The Theory of Weak Interactions

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The Theory of Weak Interactions

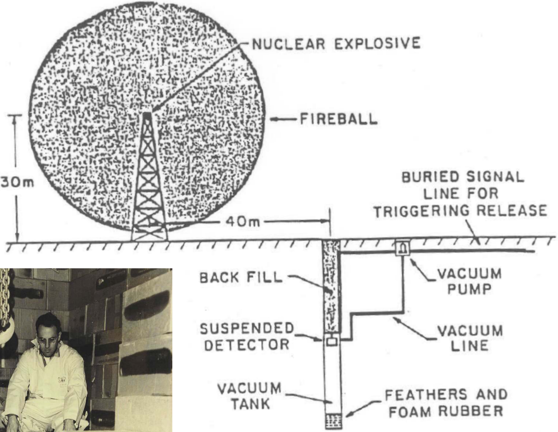
A little exercise:

$$\begin{aligned} \mathbf{n} &\rightarrow \mathbf{p}^+ + \mathbf{e}^- + \bar{\nu} \\ \mathbf{n} + \nu &\rightarrow \mathbf{p}^+ + \mathbf{e}^- \\ \mathbf{p}^+ + \bar{\nu} &\rightarrow \mathbf{n} + \mathbf{e}^+ \end{aligned}$$

FINDING NEUTRINOs

Finding Neutrinos.... 1st attempt

1950's: Fredrick Reines, protege of Richard Feynman proposes to find neutrinos



NOT ATTEMPTED !

Finding Neutrinos.... 2nd attempt

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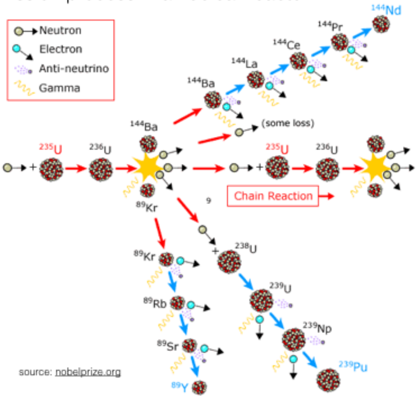
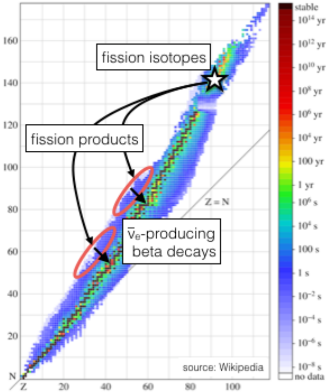
1950's: Fred Reines at Los Alamos and Clyde Cowan propose to use the Hanford nuclear reactor (1953) and the new Savannah River nuclear reactor (1955) to find neutrinos.

fission process in a nuclear reactor



source: nobelprize.org



source: Wikipedia

Finding Neutrinos.... 2nd attempt

1950's: Fred Reines at Los Alamos and Clyde Cowan propose to use the Hanford nuclear reactor (1953) and the new Savannah River nuclear reactor (1955) to find neutrinos.

THE UNIVERSITY OF CHICAGO
CHICAGO 37 · ILLINOIS
INSTITUTE FOR NUCLEAR STUDIES

October 8, 1952

Dr. Fred Reines
Los Alamos Scientific Laboratory
P.O. Box 1663
Los Alamos, New Mexico

Dear Fred:

Thank you for your letter of October 4th by Clyde Cowan and yourself. I was very much interested in your new plan for the detection of the neutrino. Certainly your new method should be much simpler to carry out and have the great advantage that the measurement can be repeated any number of times. I shall be very interested in seeing how your 10 cubic foot scintillation counter is going to work, but I do not know of any reason why it should not.

Good luck.

Sincerely yours,

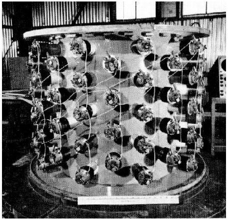
Enrico

Enrico Fermi

EF:vr

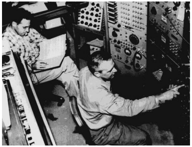
Finding Neutrinos.... 2nd attempt

1950's: Fred Reines at Los Alamos and Clyde Cowan propose to use the Hanford nuclear reactor (1953) and the new Savannah River nuclear reactor (1955) to find neutrinos.
A detector filled with water with $CdCl_2$ in solution was located 11 meters from the reactor center and 12 meters underground.



The detection sequence was as follows:

1. $\bar{\nu}_e + p \rightarrow n + e^+$
2. $e^+ + e^- \rightarrow \gamma\gamma$
3. $n +^{108} Cd \rightarrow^{109} Cd* \rightarrow^{109} Cd + \gamma$ $(\tau = 5\mu s)$.



Neutrinos first detected using a nuclear reactor!

Reines shared 1995 Nobel for work on neutrino physics.

ν: A Truly Elusive Particle!

Reines and Cowan were the first to estimate the interaction strength of neutrinos. **The cross-section is $\sigma \sim 10^{-43}\text{cm}^2$ per nucleon (N = n or p).**

$$\nu \text{ mean free path} = \frac{1}{\sigma \times \text{number of nucleons per cm}^3}$$

ν Exercise: What is the mean free path of a neutrino in lead?

(use Table of atomic and nuclear properties)

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(use Table of atomic and nuclear properties)

$$= \frac{1}{10^{-43}\mathrm{cm}^2 \times 11.4\mathrm{g/cm}^3 \times 6.02 \times 10^{23}\mathrm{nucleons/g}}$$
$$\approx 1.5 \times 10^{16}\mathrm{m}$$

How many light years is that? How does it compare to the distance from the sun to the moon?

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How many light years is that? How does it compare to the distance from the sun to the moon?

$$= \text{1.6 LIGHT YEARS OF LEAD}$$

$$= 100,000 \text{ distance earth to sun}$$

A proton has a mean free path of 10cm in lead

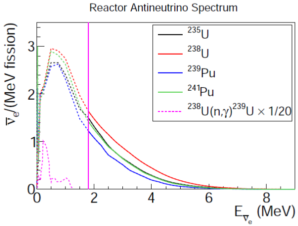
Reactor power and neutrinos

ν Exercise:

The following table shows the breakdown of energy released per fission from ^{235}U:

Fission fragment	Energy (MeV)
Fission products	175
$\langle 2.44 \rangle$ neutrons	5
γ from fission	7
γs and βs from beta decay	13
$\langle 6 \rangle$ neutrinos	10
Total	210

5% of a reactor's power is in neutrinos !



How many neutrinos are emitted per second from a 1 Gigawatt (thermal) reactor?

Reactor power and neutrinos

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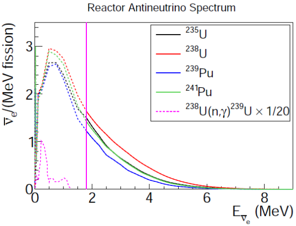

How many neutrinos are emitted per second from a 1 Gigawatt (thermal) reactor?

$$
\begin{aligned}
1 \times 10^{9} \text{ Joules/sec} &= 6.242 \times 10^{18} \text{ GeV/sec} \\
&= 3 \times 10^{19} \text{ fissions/sec} \\
&\sim 2 \times 10^{20} \ \nu/\text{sec} \\
&= 1.6 \times 10^{13}/\text{m}^2/\text{sec at 1 km}
\end{aligned}
$$

Reactor Power and Neutrinos

ν Exercise:

Using the rate of neutrinos emitted from a reactor ($= 2 \times 10^{20}$/sec/GW) and the average cross-section of the inverse beta decay process ($\bar{\nu}_e + p \rightarrow e^+ + n$) is $\sigma = 10^{-43}\mathrm{cm}^2$/proton, what is the rate of neutrino interactions per day in a detector containing 100 tons of scintillator (CH_2) located 1km from a 1GW reactor? Note that the IBD process only happens on free protons (H)

Reactor Power and Neutrinos

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Using the rate of neutrinos emitted from a reactor ($= 2 \times 10^{20}$/sec/GW) and the average cross-section of the inverse beta decay process ($\bar{\nu}_e + p \rightarrow e^+ + n$) is $\sigma = 10^{-43}\mathrm{cm}^2$/proton, what is the rate of neutrino interactions per day in a detector containing 100 tons of scintillator (CH_2) located 1km from a 1GW reactor? Note that the IBD process only happens on free protons (H)

 # interactions/day = flux (ν/cm^2/day) $\times$ σ (cm^2/p) $\times$ protons/Nucleons $\times$ Nucleons/gram $\times$ 10^8 g/100tons

Reactor Power and Neutrinos

ν Exercise:

Using the rate of neutrinos emitted from a reactor ($= 2 \times 10^{20}$/sec/GW) and the average cross-section of the inverse beta decay process ($\bar{\nu}_e + p \to e^+ + n$) is $\sigma = 10^{-43}\mathrm{cm}^2$/proton, what is the rate of neutrino interactions per day in a detector containing 100 tons of scintillator (CH_2) located 1km from a 1GW reactor? Note that the IBD process only happens on free protons (H)

 # interactions/day = flux (ν/cm^2/day) $\times$ σ (cm^2/p) $\times$ protons/Nucleons $\times$ Nucleons/gram $\times$ 10^8 g/100tons

 # interactions/day = 118

Precision ν expt: need 1 GW nuclear reactor ($1B) + 100's tons

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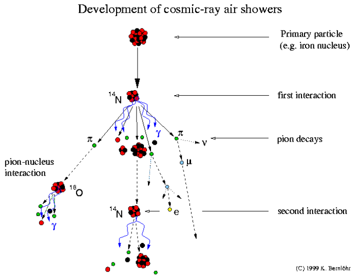
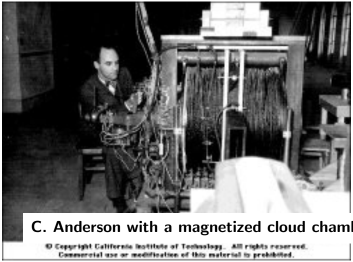
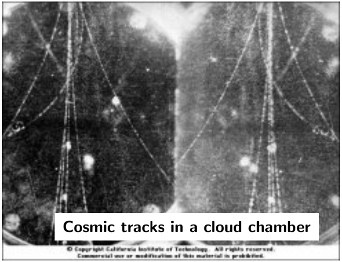
FINDING NEUTRINOS in NATURE

Discovery of the Muon (μ)

1936: Carl Andersen, Seth Neddermeyer observed an unknown charged particle in cosmic rays with mass between that of the electron and the proton - called it the μ meson (now muons).



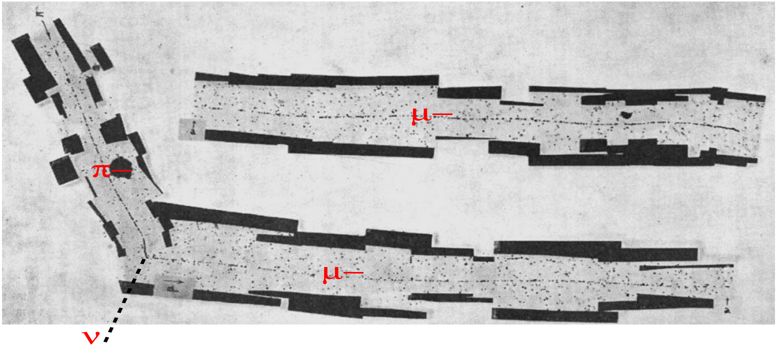

C. Anderson with a magnetized cloud chamber


Cosmic tracks in a cloud chamber

I. I Rabbi (founder of BNL): Who ordered THAT?

Discovery of the Pion: 1947

Cecil Powell takes emulsion photos aboard high altitude RAF flights. A charged particle is found decaying to a muon:



mass$_{\pi^-}$ = 0.1396 GeV/c^2 , τ = 26 nano-second (ns).
Pions are composite particles from the "hadron" family which includes protons and neutrons.

Proposal to find Atmospheric Neutrinos

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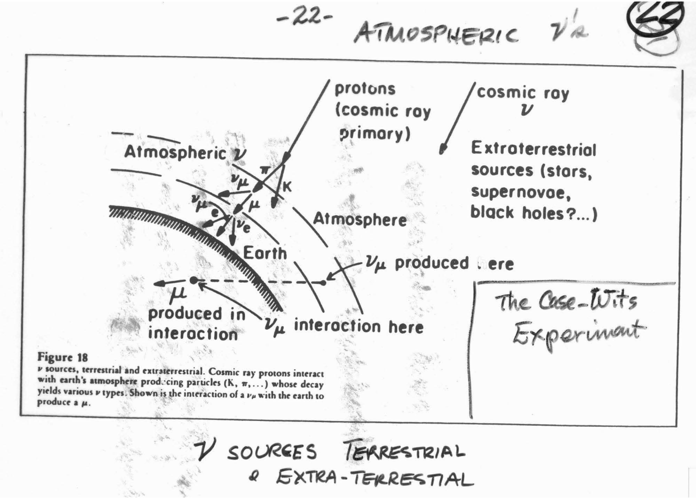
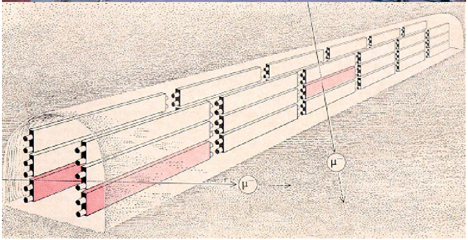
Slide to find atmospheri neutrinos by Fred Reines (Case Western Institute):



The CWI-SAND Experiment

1964: The Case Western Institute-South Africa Neutrino Detector (CWI-SAND) and a search for atmospheric ν_μ at the East Rand gold mine in South Africa at 3585m depth



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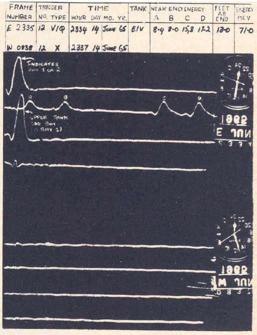
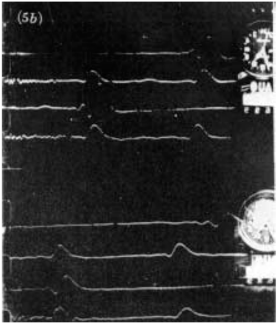


Downward-going Muon (background)



Horizontal Muon (neutrino signal)

Detection of the first neutrino in nature!

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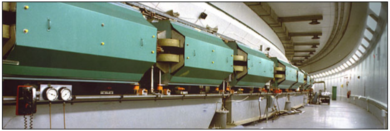
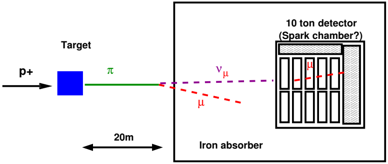
FLAVORS OF NEUTRINOS

Producing Neutrinos from an Accelerator

1962: Leon Lederman, Melvin Schwartz and Jack Steinberger use a proton beam from BNL's Alternating Gradient Synchrotron (AGS) to produce a beam of neutrinos using the decay $\pi \to \mu\nu_x$



The AGS



Making ν's

The Two-Neutrino Experiment

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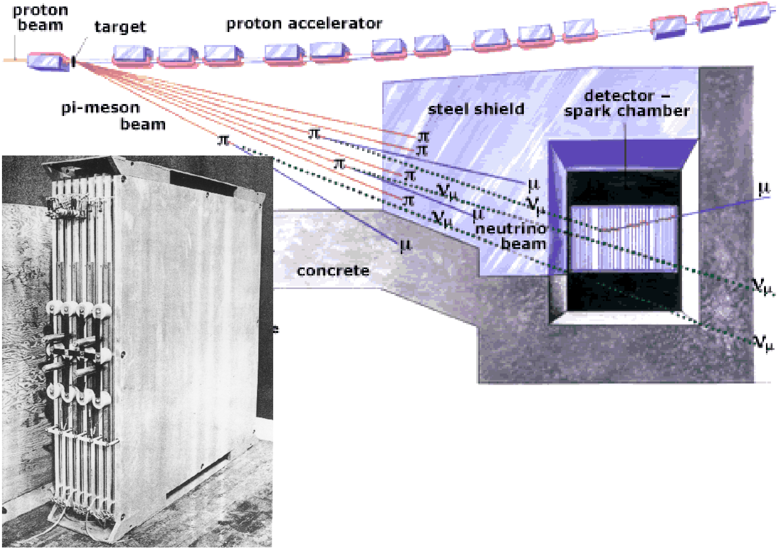

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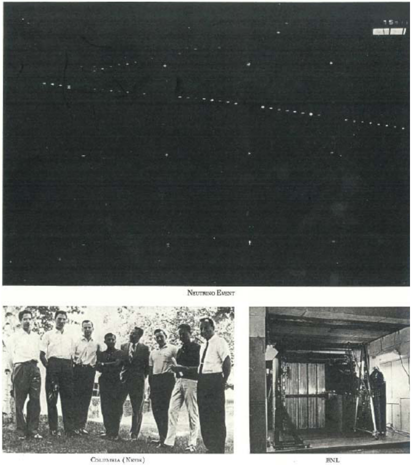

Classification of "Events"

Single Tracks

p_μ < 300 MeV/c[a]	49
p_μ > 300	34
> 400	19
> 500	8
> 600	3
> 700	2
Total "single Muon Events"	34

Vertex Events

Visible Energy Released < 1 BeV	15
Visible Energy Released > 1 BeV	7
Total vertex events	22

"Shower" Events

Energy of "electron" = 200 ± 100 MeV	3
220	1
240	1
280	1
Total "shower events"[b]	6

[a] These are not included in the "event" count.

[b] The two shower events which are so located that their potential energy release in the chamber corresponds to muons of less than 300 MeV/c are not included here.

The first event!

The Two-Neutrino Experiment

Result: **40 neutrino interactions recorded in the detector, 6 of the resultant particles where identified as background and 34 identified as** $\mu \Rightarrow \nu_x = \nu_\mu$

The first successful accelerator neutrino experiment was at Brookhaven Lab.

1988 NOBEL PRIZE

Neutrinos from Accelerators

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To produce neutrinos from accelerators

$\mathbf{p}^+ + \mathbf{A} \rightarrow \pi^\pm + \mathbf{X}, \quad \pi^\pm \rightarrow \mu^\pm + \nu_\mu/\bar{\nu}_\mu$

where A = Carbon (Graphite), Berillyium, Tungsten,
X is other particles

ν Exercise: The Main Injector accelerator at Fermilab delivers 4.86×10^{13} 120 GeV protons in a 10 microsecond pulse every 1.33 seconds to the NuMI neutrino beamline target. What is the average power of the proton beam delivered in megawatts?

Neutrinos from Accelerators

To produce neutrinos from accelerators

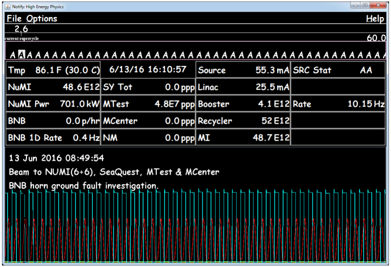
$\mathbf{p^+ + A \rightarrow \pi^\pm + X, \quad \pi^\pm \rightarrow \mu^\pm + \nu_\mu/\bar{\nu}_\mu}$

where A = Carbon (Graphite), Berillyium, Tungsten,

X is other particles

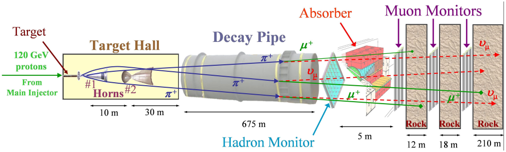
ν Exercise: The Main Injector accelerator at Fermilab delivers 4.86×10^{13} 120 GeV protons in a 10 microsecond pulse every 1.33 seconds to the NuMI neutrino beamline target. What is the average power of the proton beam delivered in megawatts?

Power = 120 GeV $\times$ 4.86 10^{13} protons $\times$ 1.6 10^{-10} Joules/GeV $\times$ 1/1.33s = 702 kW

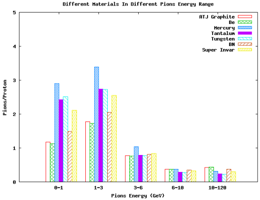


Neutrinos from Accelerators

Neutrinos at the Main Injector (NuMI) Beamline



The result of a FLUKA simulation of pion production from 120 GeV protons is shown on the right :

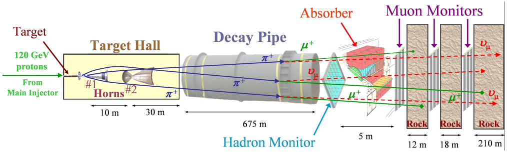


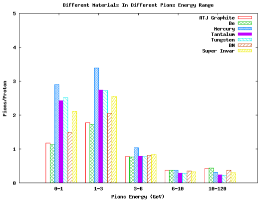
(work by Yi LU, a HS student intern)

ν Exercise: What fraction of 6 GeV pions from the NuMI target will decay to neutrinos before reaching the end of the evacuated NuMI decay pipe of 675m long? The π^+ rest mass and lifetime are 140 MeV and 26 ns

Neutrinos from Accelerators

Neutrinos at the Main Injector (NuMI) Beamline





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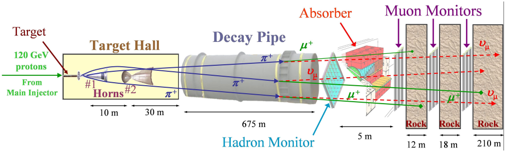
ν **Exercise:** **What fraction of 6 GeV pions from the NuMI target will decay to neutrinos before reaching the end of the evacuated NuMI decay pipe of 675m long? The π^+ rest mass and lifetime are 140 MeV and 26 ns**

6 GeV π^+ lifetime: $\tau = \gamma\tau_0 = \frac{E}{m_0 c^2} \times 26\text{ns} = 1.1\mu s$, $c\tau = 334$ m

Neutrinos from Accelerators

Neutrinos at the Main Injector (NuMI) Beamline



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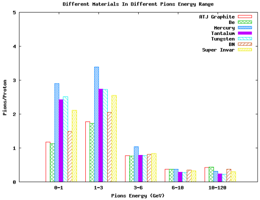

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6 GeV π^+ lifetime: $\tau = \gamma\tau_0 = \frac{E}{m_0c^2} \times 26\text{ns} = 1.1\mu\text{s}, \; c\tau = 334$ m

$F_{decays} = (1 - \exp^{-l/c\tau})\mathcal{F}(\pi \to \mu\nu_\mu) = (0.87)(0.99) = 0.86$

The Lepton Family and Flavors

The muon and the electron are *different "flavors" of the same family of elementary particles called leptons***.**

Generation	**I**	**II**	**III**
Lepton	e^-	μ	τ
Mass (GeV)	**0.000511**	**0.1057**	**1.78**
Lifetime (sec)	**stable**	2.2×10^{-6}	2.9×10^{-13}

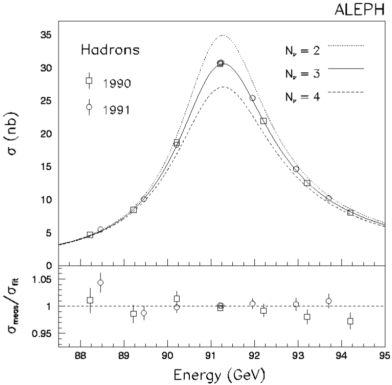
Neutrinos are neutral leptons.

Number of Neutrino Flavors: Particle Colliders

1980's - 90's: The number of neutrino types is precisely determined from studies of Z^0 boson properties produced in e^+e^- colliders.

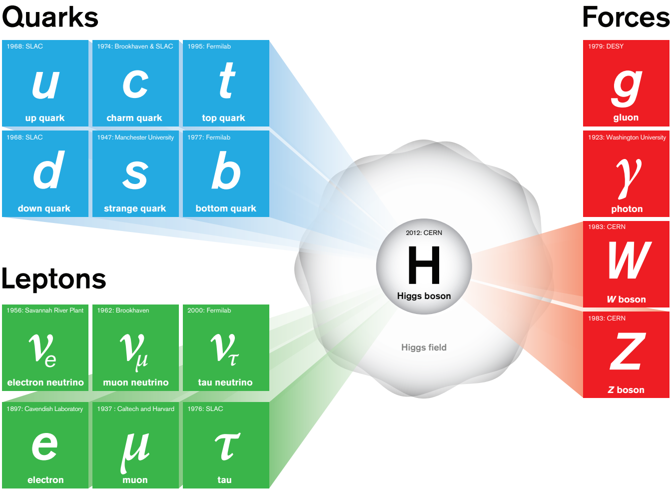
The LEP e^+e^- collider at CERN, Switzerland

The 27km LEP ring was reused to build the Large Hadron Collider



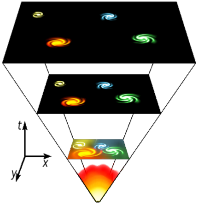
$$N_\nu = 2.984 \pm 0.008$$

The Particle Zoo



Neutrino Sources

Big Bang

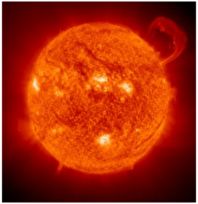


10^{-4} eV
300/cm^3

Reactors

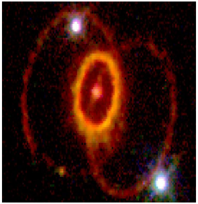
few MeV
10^{21}/GW$_{th}$/s

Sun



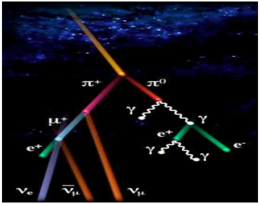
0.1-14 MeV
10^{10}/cm^2/s

SuperNova



$\sim$ 10 MeV
10^9/cm^2/s

Atmosphere

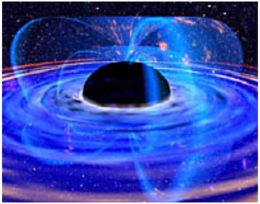


$\sim$ 1 GeV
few/cm^2/s

Accelerators

1-20 GeV
10^6/MW/cm^2/s (at 1km)

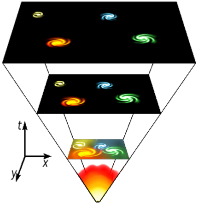
Extragalactic

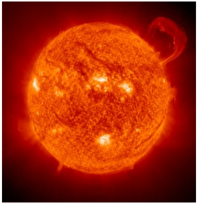


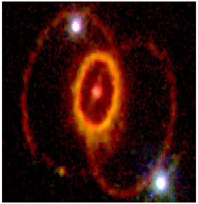
TeV-PeV
varies

Neutrino Experiments

Big Bang | Reactors | Sun | SuperNova







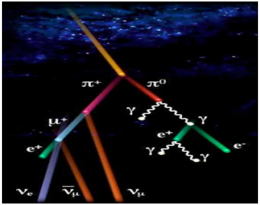
PTOLEMY: $300/cm^3$

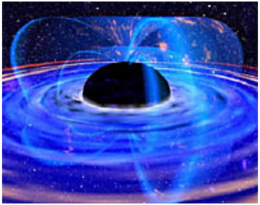
Daya Bay: $10^{21}/GW_{th}/s$

BOREXino: $10^{10}/cm^2/s$

IMB, Kamiokande: $10^9/cm^2/s$

Atmosphere | Accelerators | Extragalactic





SuperK: few$/cm^2/s$

T2K, NOνA: $10^6/MW/cm^2/s$ (at 1km)

IceCUBE: varies

Neutrinos and Todays Universe

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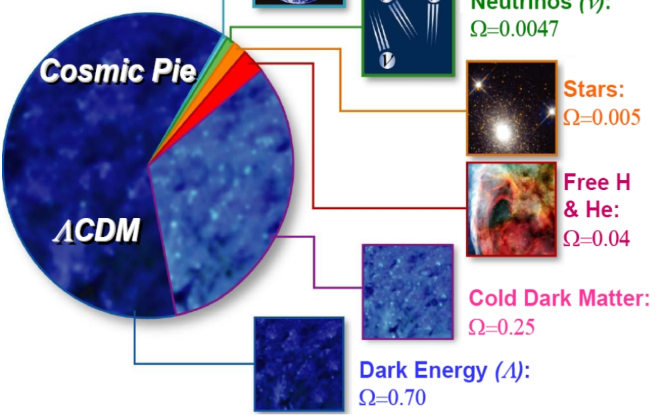
Neutrino mass < 1 eV (beta-decay limits)

$$\Omega_i \equiv \rho_i / \rho_{\mathrm{CRITICAL}}$$

$$\Omega_{\mathrm{TOTAL}} = 1$$



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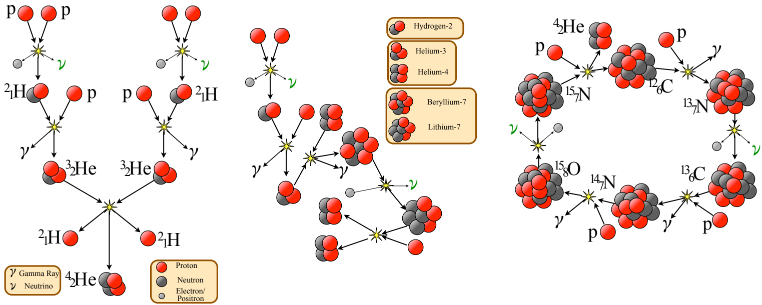
NEUTRINO MIXING AND OSCILLATIONS

Solar Neutrinos

Fusion of nuclei in the Sun produces solar energy and neutrinos



The Homestake Experiment

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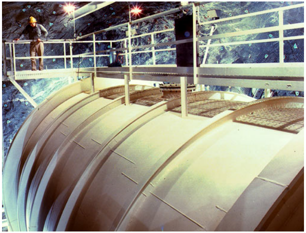
1967: Ray Davis from BNL installs a large detector, containing 615 tons of tetrachloroethylene (cleaning fluid), 1.6km underground in Homestake mine, SD.

1. $\nu_e^{sun} + ^{37}CL \rightarrow e^- + ^{37}Ar, \ \tau(^{37}Ar) = 35$ days.
2. Number of Ar atoms $\approx$ number of ν_e^{sun} interactions.

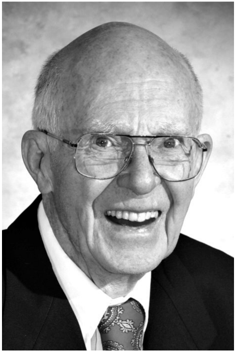
Ray Davis



Results: 1969 - 1993 Measured 2.5 $\pm$ 0.2 SNU (1 SNU = 1 neutrino interaction per second for 10^{36} target atoms) while theory predicts 8 SNU. This is a ν_e^{sun} deficit of 69%.

Where did the suns ν_e's go?

2002 Nobel Prize

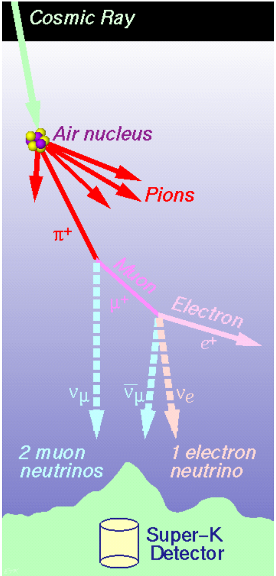


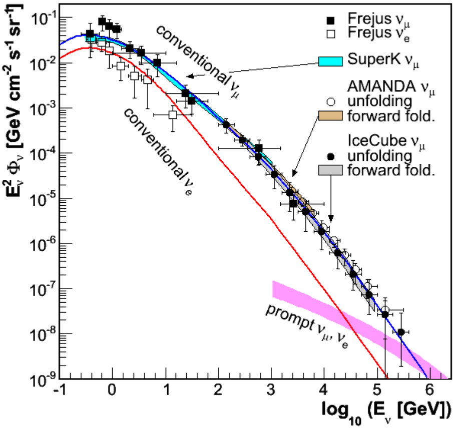
Ray Davis
Brookhaven Lab, USA
(Homestake experiment)

Masatoshi Koshiba
University of Tokyo, USA
(Kamiokande experiment)

The Nobel Prize in Physics 2002 was awarded 1/4 to Ray Davis and 1/4 Masatoshi Koshiba *"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos."*

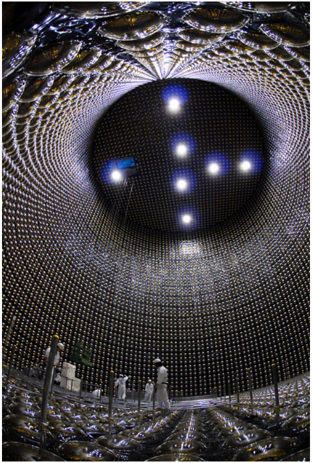
The Super-Kamiokande Experiment. Kamioka Mine, Japan





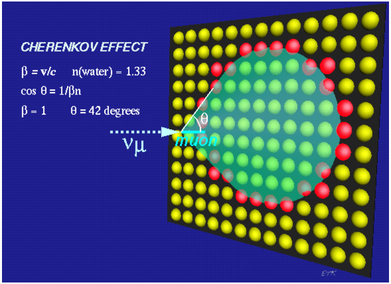
Many decades in E

The Super-Kamiokande Experiment. Kamioka Mine, Japan



50kT double layered tank of ultra pure water surrounded by 11,146 20" diameter photomultiplier tubes.

Neutrinos are identified by using CC interaction $\nu_{\mu,e} \rightarrow e^{\pm}, \mu^{\pm}X$. The lepton produces Cherenkov light as it goes through the detector:



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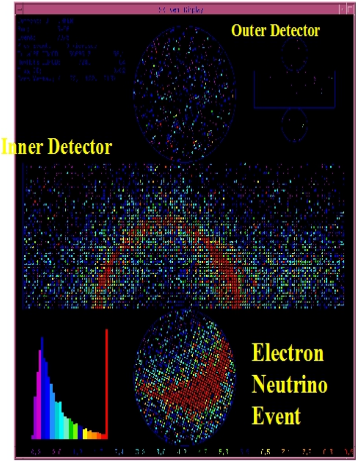
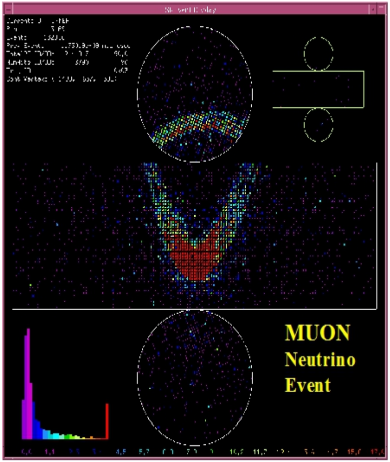
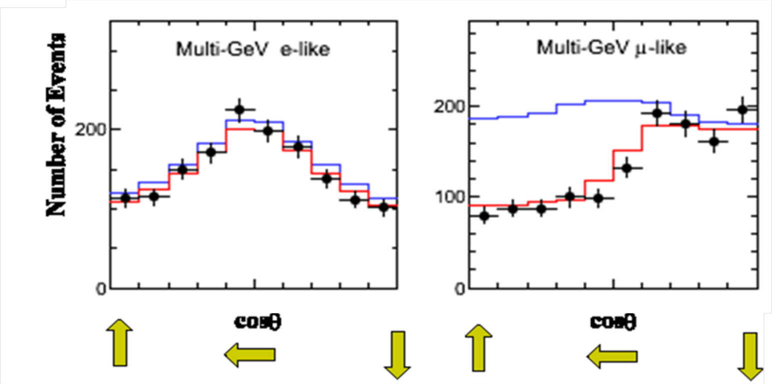




More Disappearing Neutrinos!!



All the ν_e are there! But what happened to the ν_μ ??

SNO Experiment: Solar ν Measurments

$1 \leftrightarrow 2$ mix ing

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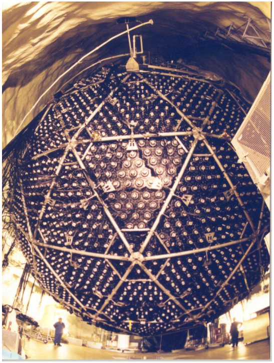
2001-02: Sudbury Neutrino Observatory. Water Čerenkov detector with 1 kT heavy water (0.5 B$ worth on loan from Atomic Energy of Canada Ltd.) located 2Km below ground in INCO's Creighton nickel mine near Sudbury, Ontario. Can detect the following ν^{sun} interactions:



1) $\nu_e + d \rightarrow e^- + p + p$ **(CC).**
2) $\nu_{e,x} + e^- \rightarrow e^- + \nu_x, \quad \sigma^{ES}_{nu_e} : \sigma^{ES}_{\nu_x} = 6:1$ **(ES).**
3) $\nu_x + d \rightarrow p + n + \nu_x, \quad x = e, \mu, \tau$ **(NC).**

SNO measured:

$$\phi^{CC}_{SNO}(\nu_e) = 1.75 \pm 0.07(\mathrm{stat})^{+0.12}_{-0.11}(\mathrm{sys.}) \pm 0.05(\mathrm{theor}) \times 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

$$\phi^{ES}_{SNO}(\nu_x) = 2.39 \pm 0.34(\mathrm{stat})^{+0.16}_{-0.14}(\mathrm{sys.}) \pm \times 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

$$\phi^{NC}_{SNO}(\nu_x) = 5.09 \pm 0.44(\mathrm{stat})^{+0.46}_{-0.43}(\mathrm{sys.}) \pm \times 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

All the solar ν's are there but ν_e appears as ν_x!

Some Quantum Mechanics

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1924: Louis-Victor-Pierre-Raymond, 7th duc de Broglie proposes in his doctoral thesis that all matter has wave-like and particle-like properties.

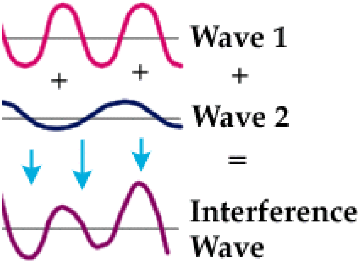
For highly relativistic particles : energy ≈ momentum

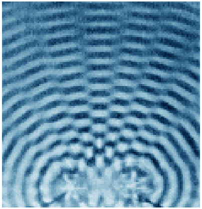
De Broglie

$$\text{Wavelength (nm)} \approx \frac{1.24 \times 10^{-6}\ \text{GeV.nm}}{\text{Energy (GeV)}}$$

Neutrino Mixing

1957,1967: B. Pontecorvo proposes that neutrinos of a particular flavor are a mix of quantum states with different masses that propagate with different phases:





The interference of water waves coming from two sources.

The inteference pattern depends on the difference in masses

Neutrino Mixing ⇒ Oscillations

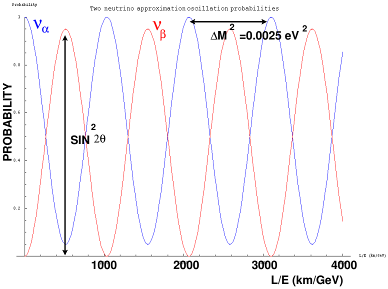
$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \to \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2 t} - e^{-iE_1 t}|^2 \end{aligned}$$

$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2_{21} L}{E}$$

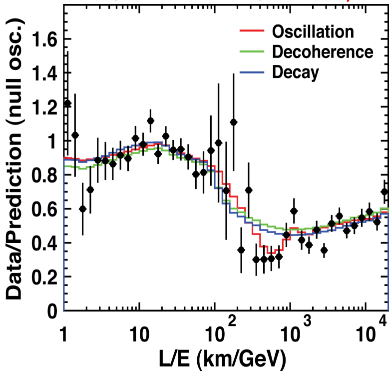
where $\Delta m^2_{21} = (m^2_2 - m^2_1)$ in eV^2, L (km) and E (GeV).

Observation of oscillations implies non-zero mass eigenstates

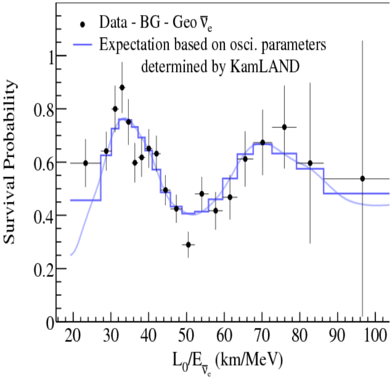


Two Different Mass Scales!

Super-K, atmospheric ν_μ



KamLAND, reactor $\bar{\nu}_e$



Global fit 2013:

$$\Delta m^2_{atm} = 2.43^{+0.06}_{-0.10} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2\theta_{atm} = 0.386^{+0.24}_{-0.21}$$

Atmospheric L/E ∼ 500 km/GeV

Global fit 2013:

$$\Delta m^2_{solar} = 7.54^{+0.26}_{-0.22} \times 10^{-5}\ \mathrm{eV}^2$$
$$\sin^2\theta_{solar} = 0.307^{+0.18}_{-0.16}$$

Solar L/E ∼ 15,000 km/GeV

2015 Nobel Prize

Takaaki Kajita
University of Tokyo, Japan
(SuperKamiokande)

Arthur B. MacDonald
Queens University, Canada
(SNO)

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

Neutrino Mixing: 3 flavors, 3 amplitudes, 2 mass scales

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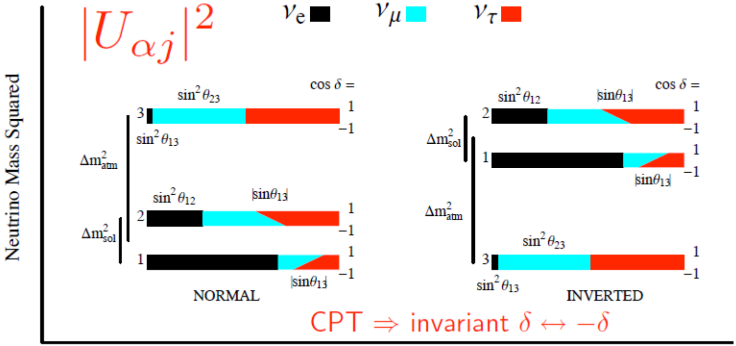


Fractional Flavor Content varying cos δ

The "mixing angles" $(\theta_{13}, \theta_{12}, \theta_{23})$ represent the fraction of ν_e, ν_μ in the 3 mass states. They determine the probability of oscillation from one flavor to the other

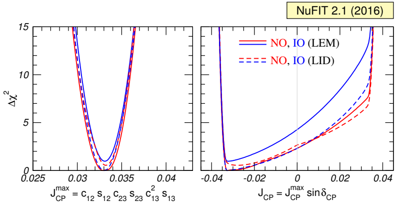
$\sin^2\theta_{12} \approx \sin^2\theta_{\mathrm{solar}}$, $\sin^2\theta_{23} \approx \sin^2\theta_{\mathrm{atmospheric}}$

3 quantum states interfering ⇒ phase δ

CP Violation in PMNS (leptons) and CKM (quarks)

In 3-flavor mixing the degree of CP violation is determined by the Jarlskog invariant:

$$J_{CP}^{PMNS} \equiv \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\theta_{13} \sin\delta_{CP}.$$



(JHEP 11 (2014) 052, arXiv:1409.5439)

Given the current best-fit values of the ν mixing angles :

$$J_{CP}^{PMNS} \approx 3 \times 10^{-2} \sin\delta_{CP}.$$

For CKM (mixing among the 3 quark generations):

$$J_{CP}^{CKM} \approx 3 \times 10^{-5},$$

despite the large value of $\delta_{CP}^{CKM} \approx 70°$.

$\nu_\mu \rightarrow \nu_e$ Oscillations in the 3-flavor ν SM

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In the ν 3-flavor model matter/anti-matter asymmetries in neutrinos are best probed using $\nu_\mu/\bar{\nu}_\mu \rightarrow \nu_e/\bar{\nu}_e$ oscillations (or vice versa). With terms up to second order in $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31} = 0.03$ and $\sin^2\theta_{13} = 0.02$, (M. Freund. Phys. Rev. D 64, 053003):

$$P(\nu_\mu \rightarrow \nu_e) \cong P(\nu_e \rightarrow \nu_\mu) \cong \underbrace{P_0}_{\theta_{13}} + \underbrace{P_{\sin\delta}}_{\text{CP violating}} + \underbrace{P_{\cos\delta}}_{\text{CP conserving}} + \underbrace{P_3}_{\text{solar oscillation}}$$

where **for oscillations in vacuum:**

$$P_0 = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(\Delta),$$

$$P_{\sin\delta} = \alpha\, 8J_{cp}\sin^3(\Delta),$$

$$P_{\cos\delta} = \alpha\, 8J_{cp}\cot\delta_{CP}\cos\Delta\sin^2(\Delta),$$

$$P_3 = \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2(\Delta),$$

where $\Delta = 1.27\Delta m^2_{31}(\text{eV}^2)L(\text{km})/E(\text{GeV})$

For $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, $\underbrace{P_{\sin\delta} \rightarrow -P_{\sin\delta}}_{\text{CP asymmetry}}$,

$\nu_\mu \to \nu_e$ Oscillations in the 3-flavor ν SM

The Little Neutral One

Mary Bishai
Brookhaven National Laboratory

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In the ν 3-flavor model matter/anti-matter asymmetries in neutrinos are best probed using $\nu_\mu/\bar{\nu}_\mu \to \nu_e/\bar{\nu}_e$ oscillations (or vice versa). With terms up to second order in $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31} = 0.03$ and $\sin^2\theta_{13} = 0.02$, (M. Freund. Phys. Rev. D 64, 053003):

$$P(\nu_\mu \to \nu_e) \cong P(\nu_e \to \nu_\mu) \cong \underbrace{P_0}_{\theta_{13}} + \underbrace{P_{\sin\delta}}_{\text{CP violating}} + \underbrace{P_{\cos\delta}}_{\text{CP conserving}} + \underbrace{P_3}_{\text{solar oscillation}}$$

where **for oscillations in matter with constant density:**

$$P_0 = \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(A-1)^2}\sin^2[(A-1)\Delta],$$

$$P_{\sin\delta} = \alpha\frac{8J_{cp}}{A(1-A)}\sin\Delta\sin(A\Delta)\sin[(1-A)\Delta],$$

$$P_{\cos\delta} = \alpha\frac{8J_{cp}\cot\delta_{CP}}{A(1-A)}\cos\Delta\sin(A\Delta)\sin[(1-A)\Delta],$$

$$P_3 = \alpha^2\cos^2\theta_{23}\frac{\sin^2 2\theta_{12}}{A^2}\sin^2(A\Delta),$$

where $\Delta = 1.27\Delta m^2_{31}(eV^2)L(km)/E(GeV)$ and $A = \sqrt{2}G_F N_e 2E/\Delta m^2_{31}$.

For $\bar{\nu}_\mu \to \bar{\nu}_e$, $\underbrace{P_{\sin\delta} \to -P_{\sin\delta}}_{\text{CP asymmetry}}$, $\underbrace{A \to -A}_{\text{matter asymmetry}}$

Osc. vs L/E

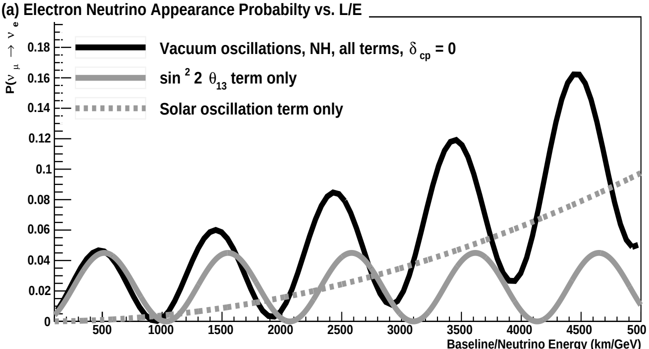
$\sin^2 2\theta_{13} = 0.09, \sin^2\theta_{23} = 0.5, \Delta m^2_{31} = \pm 2.4\times 10^{-3}\mathrm{eV}^2$

ν Exercise: Use your favorite plotting package and reproduce the plots shown below

The $\nu_\mu \to \nu_e$ oscillation probability maxima occur at

$$\frac{L\ (\mathrm{km})}{E_n(\mathrm{GeV})} = \left(\frac{\pi}{2}\right)\frac{(2n-1)}{1.27\times\Delta m^2_{31}(\mathrm{eV}^2)} \approx (2n-1)\times\frac{515\ \mathrm{km}}{\mathrm{GeV}}$$

Oscillations in vacuum - different terms ($\delta_{CP} = 0$)



Osc. vs L/E

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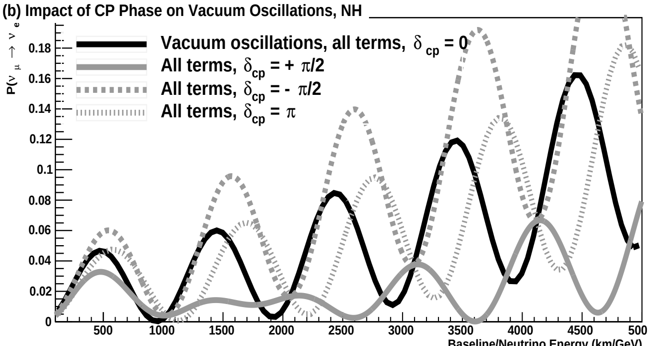
Impact of δ_{CP} on oscillations in vacuum, $\Delta m^2_{31} > 0$ (NH)



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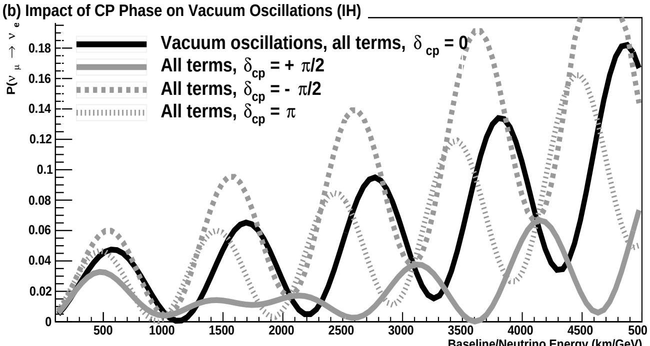
Impact of δ_{CP} on oscillations in vacuum, $\Delta m^2_{31} < 0$ (IH)



Osc. vs L/E

$\sin^2 2\theta_{13} = 0.09, \sin^2\theta_{23} = 0.5, \Delta m^2_{31} = \pm 2.4 \times 10^{-3} \mathrm{eV}^2$

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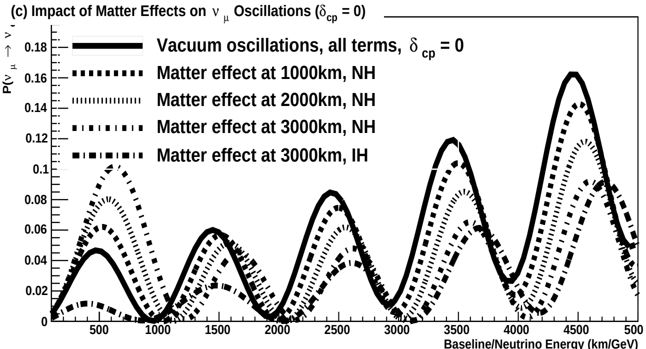
Impact of matter effect on ν_μ oscillations ($\delta_{CP} = 0$)



Osc. vs L/E

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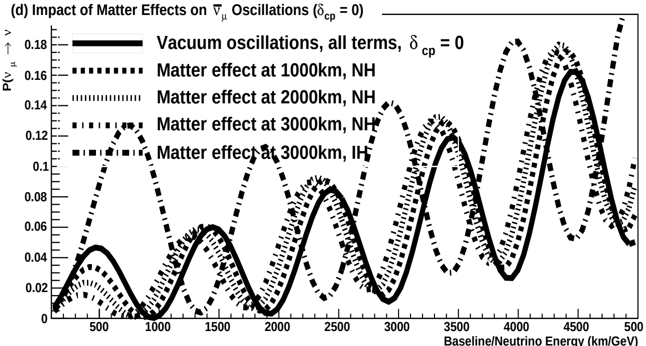
Impact of matter effect on $\bar{\nu}_\mu$ oscillations ($\delta_{CP} = 0$)



Expected Appearance Signal Event Rates

ν Exercise: The total number of electron neutrino appearance events expected for a given exposure from a muon neutrino source as a function of baseline is given as

$$N_{\nu_e}^{\rm appear}(L) = \int \Phi^{\nu_\mu}(E_\nu, L) \times P^{\nu_\mu \to \nu_e}(E_\nu, L) \times \sigma^{\nu_e}(E_\nu) dE_\nu$$

Assume the neutrino source produces a flux that is constant in energy and using only the dominant term in the probability(no matter effect)

$$\begin{aligned}
\Phi^{\nu_\mu}(E_\nu, L) &\approx \frac{C}{L^2}, \quad C = \text{number of } \nu_\mu/\text{m}^2/\text{GeV/sec at 1 km} \\
P^{\nu_\mu \to \nu_e}(E_\nu, L) &\approx \underbrace{\sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(1.27\Delta m^2_{31} L/E_\nu)}_{P_0} \\
\sigma^{\nu_e}(E_\nu) &= 0.7 \times 10^{-42}(\text{m}^2/\text{GeV/N}) \times E_\nu, \quad E_\nu > 1\ \text{GeV}
\end{aligned}$$

Prove that the rate of ν_e appearing integrated over a constant range of L/E is independent of baseline!

Expected Appearance Signal Event Rates

$$\mathbf{N_{\nu_e}^{appear}(L) \propto \text{constant term} \times \int \frac{\sin^2(ax)}{x^3} dx,}$$

$$\mathbf{x \equiv L/E_\nu, \;\; a \equiv 1.27 \Delta m^2_{31} \;\; GeV/(eV^2.km)}$$

ν Exercise:
$C \approx 1 \times 10^{17}$ $\nu_\mu/m^2/GeV/yr$ at 1 km (from 1MW accelerator)
$\sin^2 2\theta_{13} = 0.084$, $\sin^2\theta_{23} = 0.5$, $\Delta m^2_{31} = 2.4 \times 10^{-3} eV^2$

Calculate the rate of ν_e events observed per kton of detector integrating over the region $x = 100$ km/GeV to 2000 km/GeV. Use ROOT to do the integral!

Expected Appearance Signal Event Rates

$$N_{\nu_e}^{\text{appear}}(L) \propto \text{constant term} \times \int \frac{\sin^2(ax)}{x^3} dx,$$

$$x \equiv L/E_\nu, \quad a \equiv 1.27\Delta m^2_{31}\ \text{GeV}/(\text{eV}^2.\text{km})$$

ν Exercise:

$C \approx 1 \times 10^{17}\ \nu_\mu/\text{m}^2/\text{GeV}/\text{yr}$ at 1 km (from 1MW accelerator)
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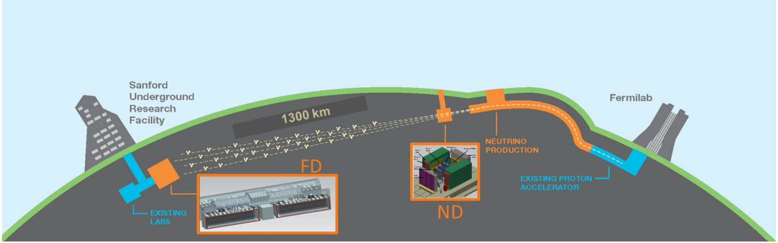
Calculate the rate of ν_e events observed per kton of detector integrating over the region $x = 100$ km/GeV to 2000 km/GeV. Use ROOT to do the integral!

$$N_{\nu_e}^{\text{appear}}(L) \approx (2 \times 10^6 \text{events/kton/yr}) \cdot (\text{km/GeV})^2 \int_{x_0}^{x_1} \frac{\sin^2(ax)}{x^3} dx,$$

$$N_{\nu_e}^{\text{appear}}(L) \sim \mathcal{O}(20 - 30)\ \text{events/kton/yr}$$

The Deep Underground Neutrino Experiment (DUNE) Coming online ∼ 2028-2030



- **A very long baseline experiment:** **1300km from Fermilab in Batavia, IL to the Sanford Underground Research Facility (former Homestake Mine) in Lead, SD.**
- **A highly capable near detector at Fermilab.**
- **A very deep (1 mile underground) far detector: massive 40-kton Liquid Argon Time-Projection-Chamber with state-of-the-art instrumentation.**
- **High intensity *tunable* wide-band neutrino beam from LBNF produced from upgraded MW-class proton accelerator at Fermilab.**

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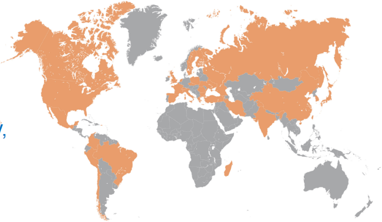
As of Jan 2018:

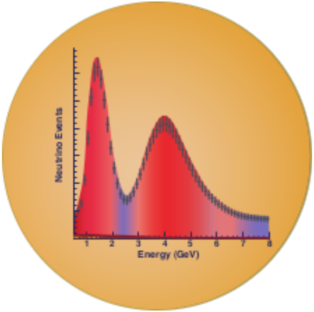
60 % non-US

1061 collaborators from 175 institutions in 31 nations

Armenia, Brazil, Bulgaria, Canada, CERN, Chile, China, Colombia, Czech Republic, Finland, France, Greece, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Paraguay, Peru, Poland, Romania, Russia, South Korea, Spain, Sweden, Switzerland, Turkey, UK, Ukraine, USA

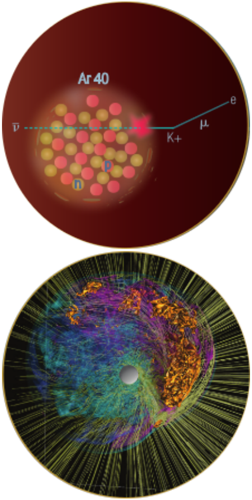


Scientific Objectives of DUNE



1. **precision measurements of the parameters that govern $\nu_\mu \rightarrow \nu_e$ oscillations; this includes precision measurement of the third mixing angle θ_{13}, measurement of the charge-parity (CP) violating phase δ_{CP}, and determination of the neutrino mass ordering (the sign of $\Delta m^2_{31} = m^2_3 - m^2_1$), the so-called mass hierarchy**
2. **precision measurements of the mixing angle θ_{23}, including the determination of the octant in which this angle lies, and the value of the mass difference, —Δm^2_{32}—, in $\nu_\mu \rightarrow \nu_{e,\mu}$ oscillations**

Scientific Objectives of DUNE



3. search for proton decay, yielding significant improvement in the current limits on the partial lifetime of the proton (τ/BR) in one or more important candidate decay modes, e.g., $p \rightarrow K^{+}\overline{\nu}$

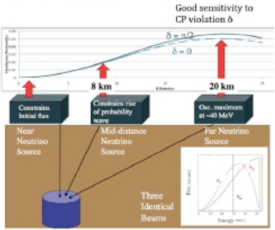
4. detection and measurement of the neutrino flux from a core-collapse supernova within our galaxy, should one occur during the lifetime of DUNE

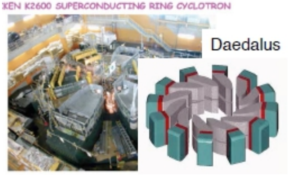
PRACTICAL APPLICATIONS of ν

Practical Applications of Technologies for ν Experiments

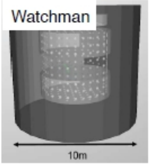
Synergies and Applications - Examples

Cyclotrons for neutrino physics
(and industrial applications)





Neutrino detectors for reactor monitoring and non-proliferation



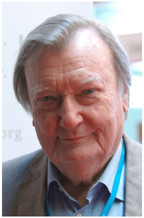
remote discovery of undeclared nuclear reactors with large detectors at km scale

US Short-Baseline Experiment

reactor antineutrino studies at short baselines

Multi-MW Accelerators Driving Thorium Reactors

First proposed by Carlo Rubbia in 1995 (1984 Nobel Prize winner)



Global energy resources in ZetaJoules

Resource	*Type*	*Yearly consumption (1999) ZJ*	*Resources ZJ*	*Consumed until 1999 (ZJ)*
Oil	Conventional	0.13	12.08	4.85
	Unconventional	0.01	20.35	0.29
	Total oil	0.14	32.42	5.14
Natural gas	Conventional	0.08	16.56	2.35
	Unconventional	0.00	33.23	0.03
	Total gas	0.08	49.79	2.38
Coal	Total coal	0.09	199.67	5.99
Total Fossils		0.31	281.88	13.51
Uranium	Thermal reactors	0.04	5.41 (2'000, sw)	
	Breeder	0	324 (120'000, sw)	
Thorium			1'300'000	

sw: including sea water
1 ZJ (ZetaJoule)= 10^3 EJ(ExaJoule)= 10^{21} J(Joule)

Requires proton accelerators with powers of 10 MW. Currently neutrino and neutron experiments are driving the technology of high power MW class proton beams.

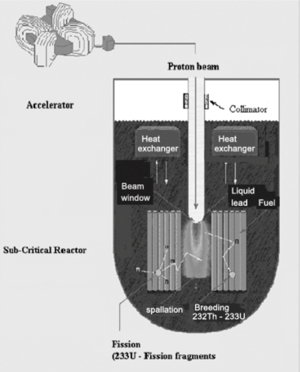
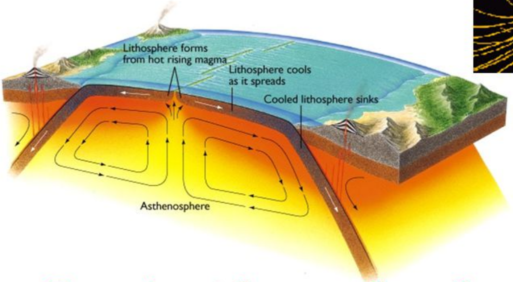
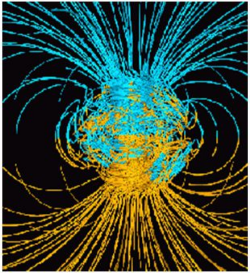


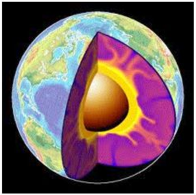
Figure 1. Schematic representation of Energy Amplifier proposed by Rubbia [4]

Neutrinos and Earth's Geology

Plate Tectonics, Convection, Geodynamo



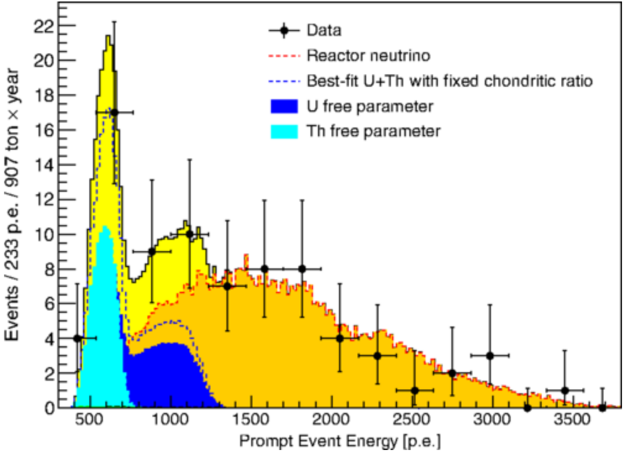




Does heat from radioactive decay drive the Earth's engine?

Neutrinos and Earth's Geology

Signal of $\bar{\nu}_e$ from radioactive decays of U/TH in the earth observed in the BOREXINO solar neutrino experiment:



Summary and Further Study

- **Neutrinos have been at the forefront of fundamental discoveries in particle physics for decades.**
- **Discoveries of neutrino properties like the very small mass, large almost maximal mixing, are the** *ONLY direct evidence for physics beyond the Standard Model of particle physics, and new hidden symmetries.*
- **The future T2HK and LBNF/DUNE projects are ambitious multi-billion dollar, multi-national neutrino experiments designed to probe matter/anti-matter asymmetries, neutrino oscillations and cosmological neutrinos with unprecedented precision.**
- **Studying neutrinos is advancing new technologies in accelerators, non-proliferation, geology...etc**

THANK YOU

Click for Neutrino rap!!