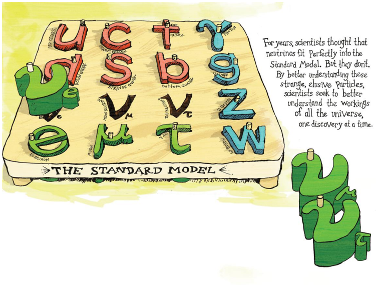
Neutrinos I

History and Properties
QuarkNet Workshop for High School Teachers, Jul 1-Jul 3, 2019, BNL

Mary Bishai
Brookhaven National Laboratory

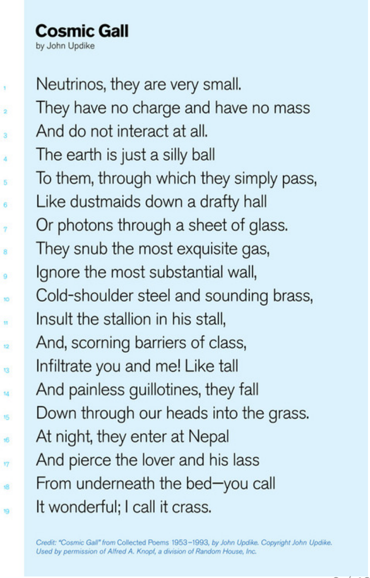
July 6th, 2018

About Neutrinos



For years, scientists thought that neutrinos fit perfectly into the Standard Model. But they don't. By better understanding these strange, elusive particles, scientists seek to better understand the workings of all the universe, one discovery at a time.

From Symmetry Magazine, Feb 2013



Cosmic Gall

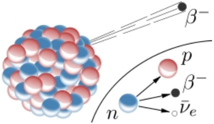
by John Updike

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.

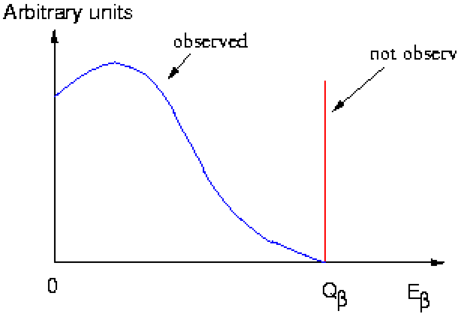
Credit: "Cosmic Gall" from Collected Poems 1953–1993, by John Updike. Copyright John Updike. Used by permission of Alfred A. Knopf, a division of Random House, Inc.

NEUTRINO HISTORY AND DISCOVERY

Neutrino Conception



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



Neutrino Conception

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

Wolfgang Pauli

Dear Radioactive Ladies and Gentlemen,

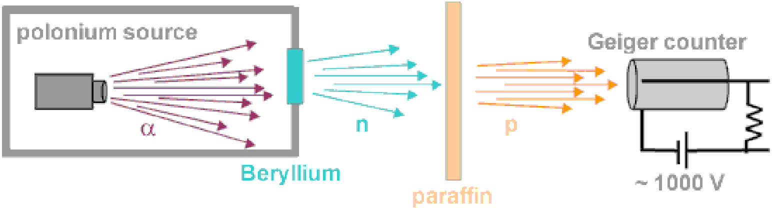
.........., I have hit upon a desparate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons.... The mass of the neutrons should be of the same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

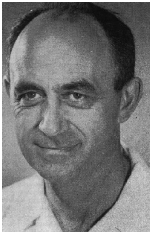
1932: James Chadwick discovers the neutron, $mass_{neutron} = 1.0014 \times mass_{proton}$ - its too heavy - cant be Pauli's particle

James Chadwick



Neutrino Conception

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



Enrico Fermi

The Theory of Weak Interactions

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

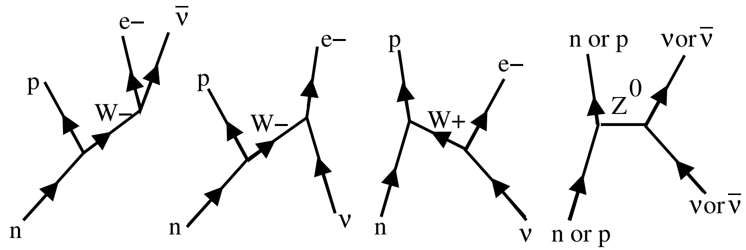
Charged current interactions

Decay of neutron

Neutrino interacts with neutron

Neutral current interactions

n or p interacts with neutrino or antineutrino

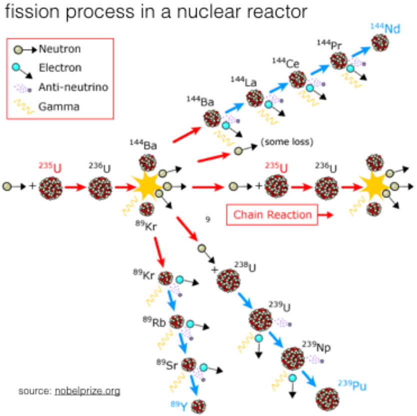


$n \rightarrow p + e^- + \bar{\nu}$

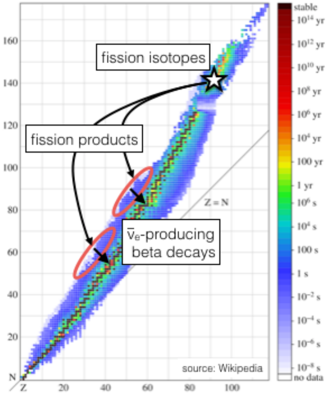
$n + \nu \rightarrow p + e^-$

Finding Neutrinos...

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


fission isotopes

fission products

$\bar{\nu}_e$-producing beta decays

source: Wikipedia

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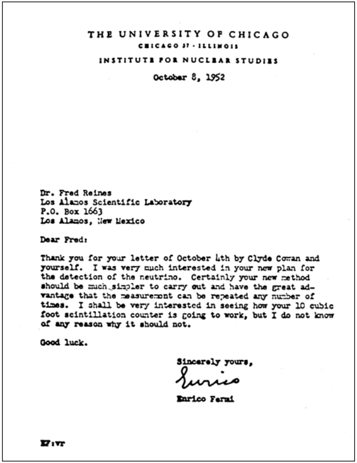


THE UNIVERSITY OF CHICAGO
CHICAGO 37 · ILLINOIS
INSTITUTE FOR NUCLEAR STUDIES

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.

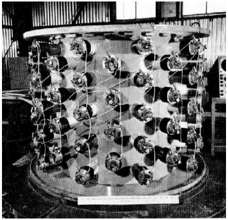
Good luck.

Sincerely yours,
Enrico
Enrico Fermi

EF:vr

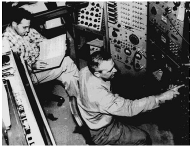
Finding Neutrinos...

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. $n +^{108} Cd \rightarrow^{109} Cd* \rightarrow^{109} Cd + \gamma$ $(\tau = 5\mu s)$.



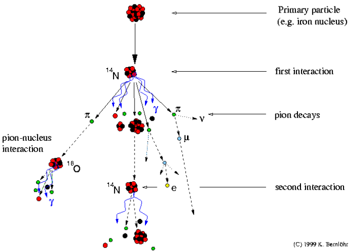
Neutrinos first detected using a nuclear reactor!

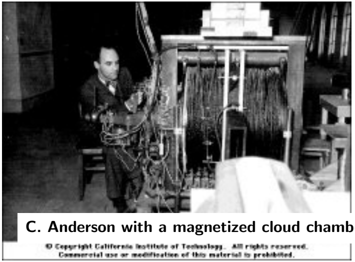
Reines shared 1995 Nobel for work on neutrino physics.

Discovery of the Muon (μ)

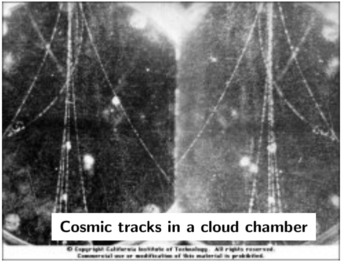
1936: Carl Andersen, Seth Neddermeyer observed an unknown charged particle in cosmic rays with mass between that of the electron and the proton - called it the μ meson (now muons).

Development of cosmic-ray air showers





C. Anderson with a magnetized cloud chamber



Cosmic tracks in a cloud chamber

The Lepton Family and Flavors

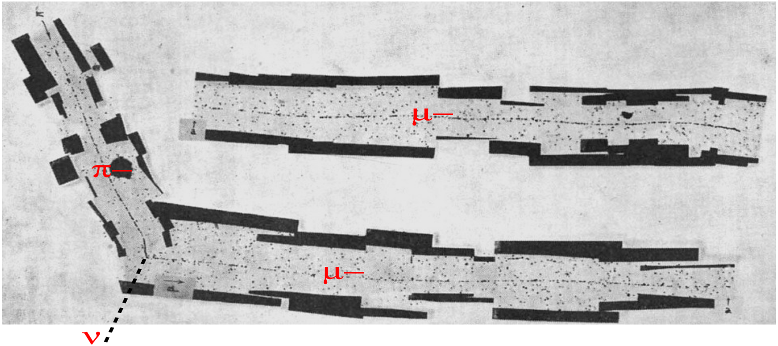
The muon and the electron are *different "flavors" of the same family of elementary particles called leptons***.**

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. **Do ν's have flavor too?**

Discovery of the Pion: 1947

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



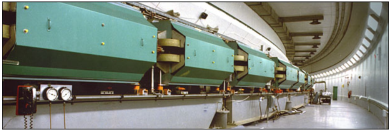
Weak decays of pi mesons (pions): $\pi^{+/-} \rightarrow \mu^{+/-} + \nu_X$

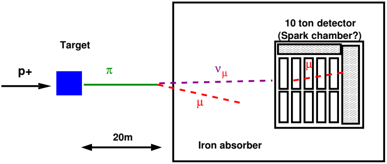
mass$_{\pi^-}$ = 0.1396 GeV/c^2 , τ = 26 nano-second (ns)

Pions are composite particles from the “hadron” family composed of quark/anti-quark pairs

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 $\pi \rightarrow \mu\nu_x$





The AGS **Making ν's**

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.

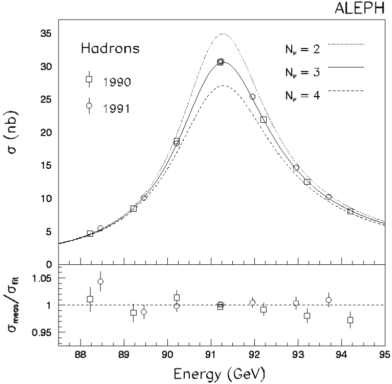
1988 NOBEL PRIZE

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

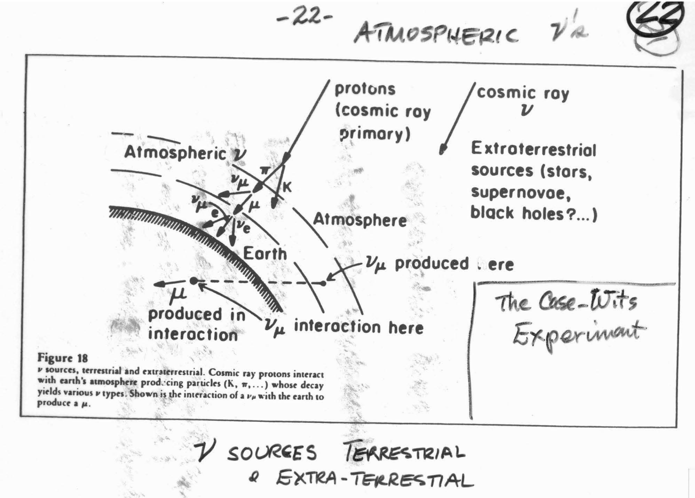
The 27km LEP ring was reused to build the Large Hadron Collider



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

Proposal to find Atmospheric Neutrinos

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



-22- ATMOSPHERIC ν's ㉒

Figure 18

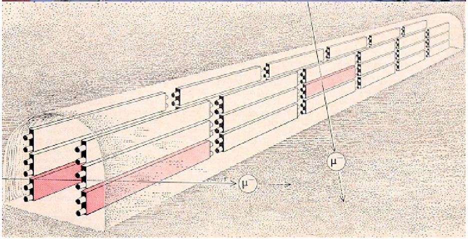
ν sources, terrestrial and extraterrestrial. Cosmic ray protons interact with earth's atmosphere producing particles (K, π, ...) whose decay yields various ν types. Shown is the interaction of a ν_μ with the earth to produce a μ.

The Case-Wits Experiment

ν SOURCES TERRESTRIAL & EXTRA-TERRESTIAL

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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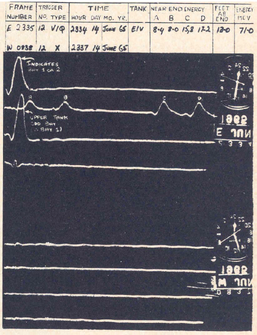
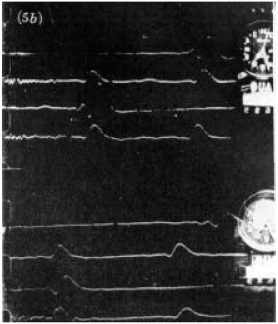


FRAME NUMBER	TRIGGER NO.	TRIGGER TYPE	TIME HOUR	DAY	MO. YR.	TANK	NEAR END ENERGY A	B	C	D	FEET AB END	ENERGY MEV
E 2335	12	V/Φ	2334	14	June 65	E/V	8·4	8·0	15,8	17·2	13·0	71·0
W 0838	12	X	2337	14	June 65							

Downward-going Muon
(background)

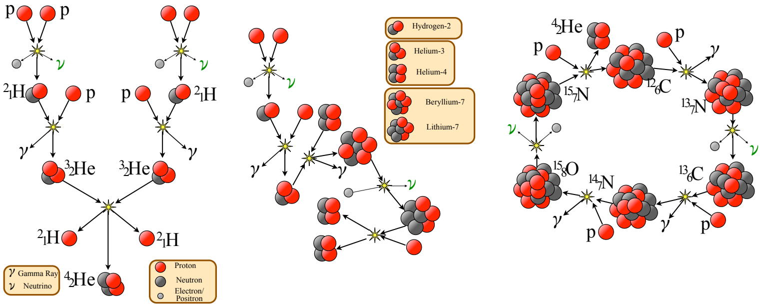


Horizontal Muon
(neutrino signal)

Detection of the first neutrino in nature!

Solar Neutrinos

Fusion of nuclei in the Sun produces solar energy and neutrinos

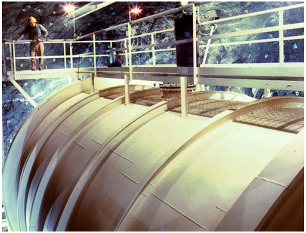


The Homestake Experiment

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

Ray Davis

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



Results: 1969 - 1993 Measured 2.5 ± 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% .

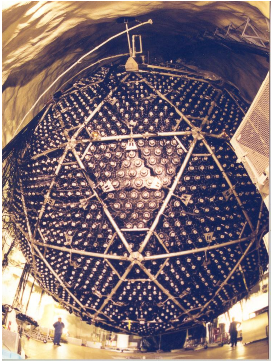
Where did the suns ν_e's go?

RAY DAVIS SHARES 2002 NOBEL PRIZE

SNO Experiment: Solar ν Measurments

$1 \leftrightarrow 2$ mix ing

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:



$$\begin{aligned} &1)\ \nu_e + d \rightarrow e^- + p + p \text{ (CC)}.\\ &2)\ \nu_x + d \rightarrow p + n + \nu_x \text{ (NC)}.\\ &3)\ \nu_x + e^- \rightarrow e^- + \nu_x \text{ (ES)}. \end{aligned}$$

SNO measured:

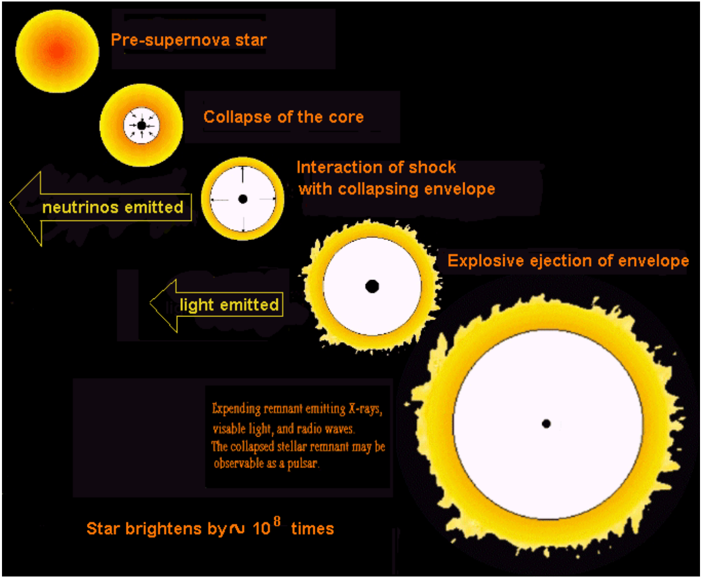
$$\phi^{CC}_{SNO}(\nu_e) = 1.75 \pm 0.07(\text{stat})^{+0.12}_{-0.11}(\text{sys.}) \pm 0.05(\text{theor}) \times 10^6 cm^{-2} s^{-1}$$

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

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

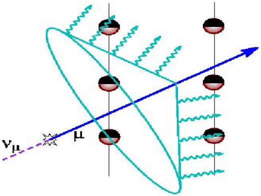
All the solar ν's are there but ν_e appears as ν_x!

Supernova Neutrinos

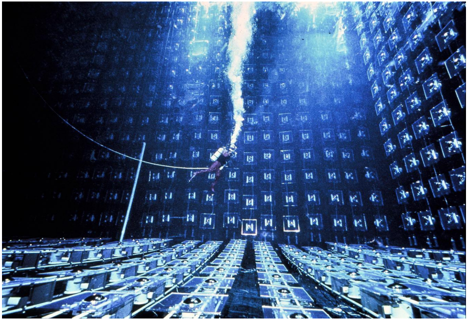


The Irvine-Michigan-Brookhaven (IMB) Detector

A relativistic charged particle going through water, produces a ring of light

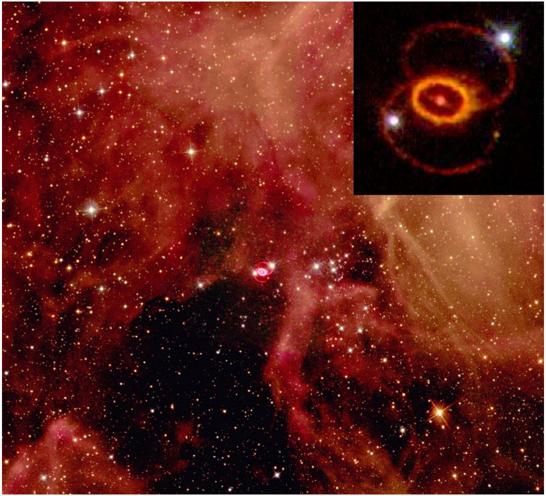


The Irvine-Michigan-Brookhaven Detector



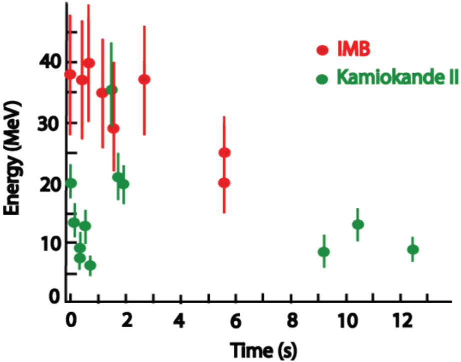
IMB consisted of a roughly cubical tank about 17 17.5 23 meters, filled with 2.5 million gallons of ultrapure water in Morton Salt Fariport Mine, Ohio. Tank surrounded by 2,048 photomultiplier tubes. IMB detected fast moving particles produced by proton decay or neutrino interactions

IMB/Kamioka Detect First Supernova Neutrinos!



1987: Supernova in large Magellanic Cloud (168,000 light years)

IMB/Kamioka Detect First Supernova Neutrinos!



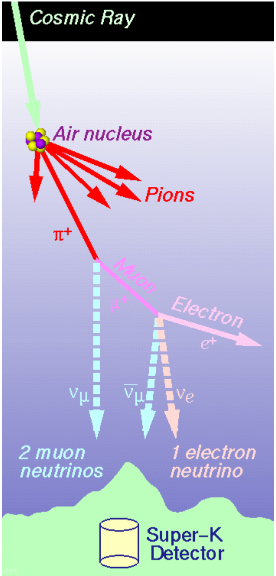
2-3 hrs earlier: IMB detects 8 neutrinos

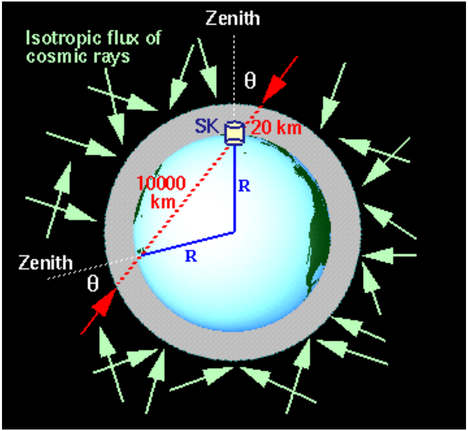
AND Kamioka detector (Japan) detects 11 neutrinos

Masatoshi Koshiba (Kamiokande, SuperKamiokande) shares 2002 Nobel Prize with Ray Davis for detection of Cosmic Neutrinos

NEUTRINO MIXING AND OSCILLATIONS

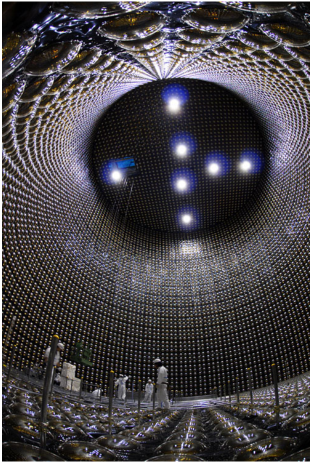
Neutrinos from our Atmosphere: $\nu_\mu, \nu_e, \bar{\nu}$





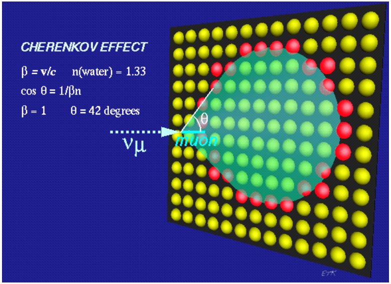
$L = 0$ **to 13,000 km**

The Super-Kamiokande Experiment. Kamioka Mine, Japan

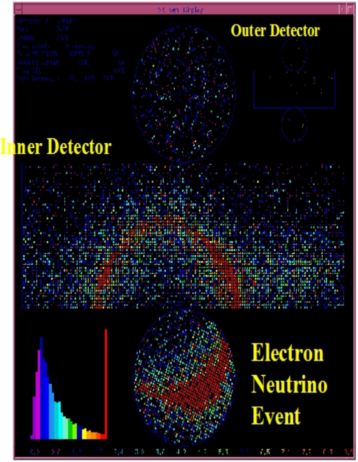


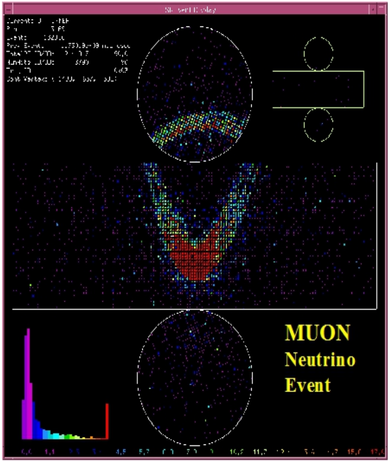
50kT double layered tank of ultra pure water surrounded by 11,146 20" diameter photomultiplier tubes.

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:

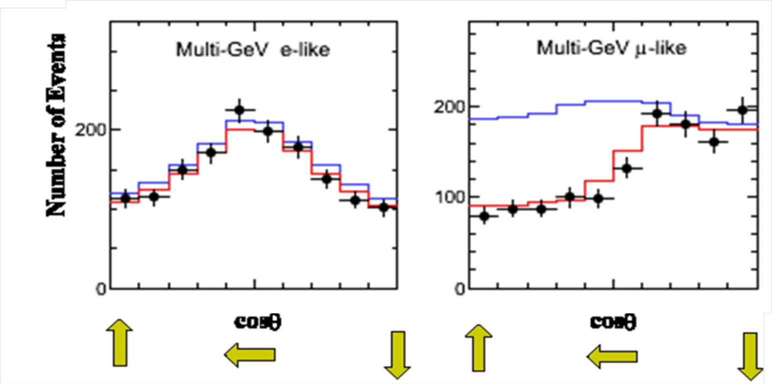


The Super-Kamiokande Experiment. Kamioka Mine, Japan





More Disappearing Neutrinos!!



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

Quantum Mechanics

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

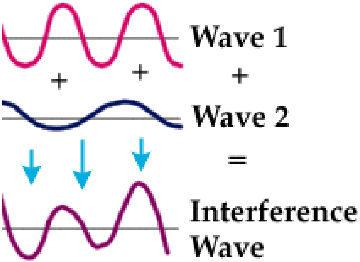
For highly relativistic particles : energy ≈ momentum

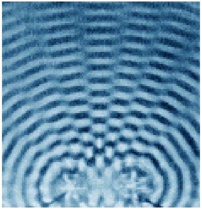
De Broglie

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

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

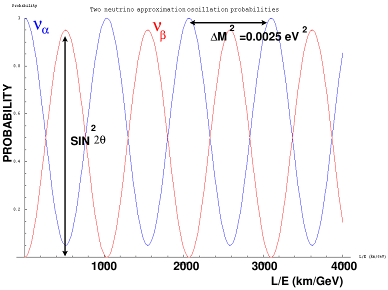
Neutrino Mixing ⇒ Oscillations

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

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

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

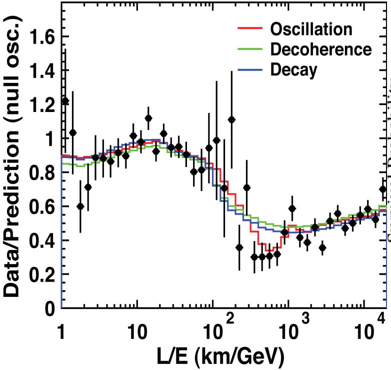
where $\Delta m^2_{21} = (m^2_2 - m^2_1)$ in eV^2, L (km) and E (GeV).



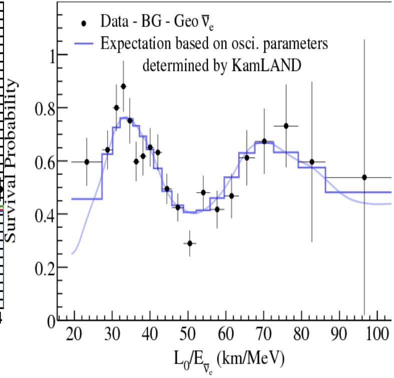
Observation of oscillations

implies non-zero mass eigenstates

Two Different Mass Scales!



Super-K, atmospheric ν_μ



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

Global fit 2013:

$$\Delta m^2_{\rm atm} = 2.43^{+0.06}_{-0.10} \times 10^{-3}\ {\rm eV}^2$$

$$\sin^2\theta_{\rm atm} = 0.386^{+0.24}_{-0.21}$$

Atmospheric L/E $\sim$ 500 km/GeV

Global fit 2013:

$$\Delta m^2_{\rm solar} = 7.54^{+0.26}_{-0.22} \times 10^{-5}\ {\rm eV}^2$$

$$\sin^2\theta_{\rm solar} = 0.307^{+0.18}_{-0.16}$$

Solar L/E $\sim$ 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"*

The Implications of 3-Neutrino Mixing

We know now of 3 flavours of neutrinos: The 3 flavour PMNS mixing matrix was developed in 1962 by Maki-Nakagawa-Sakata based on Pontecorvo's earlier work:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Commonly paramterized as $U_{\rm PMNS} =$

$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\nu_\mu \text{ disappearance}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{i\delta_{\rm CP}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\rm CP}} s_{13} & 0 & c_{13} \end{pmatrix}}_{\nu_\mu \to \nu_e, \text{ reactor } \bar{\nu_e} \text{ disappear}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar } \nu_e, \bar{\nu_e} \text{ disappear}}$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$.

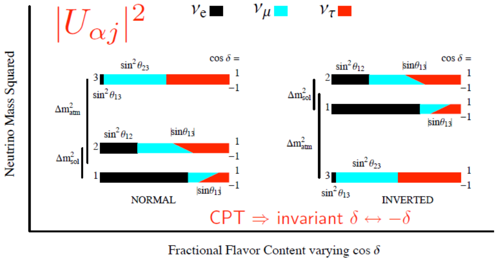
$\sin^2\theta_{13}$: Amount of ν_e in ν_3

$\tan^2\theta_{23}$: Ratio of $\frac{\nu_\mu}{\nu_\tau}$ in ν_3

$\tan^2\theta_{12}$: $\frac{\text{Amount of } \nu_e \text{ in } \nu_2}{\text{Amount of } \nu_e \text{ in } \nu_1}$

There are 3 quantum states mixing $\Rightarrow$ there is an overall phase: $\delta_{\rm CP}$.

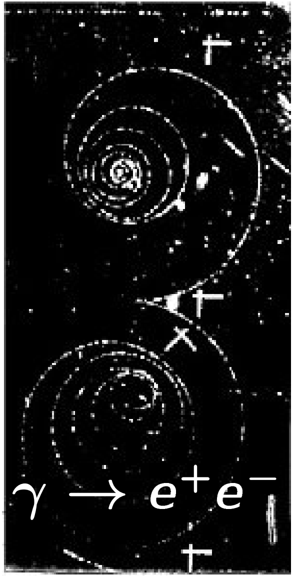
Neutrino Mixing: 3 flavors, 3 amplitudes, 2 mass scales, 1 phase



- What is the neutrino mass hierarchy? ($\delta m^2_{31} \equiv m^2_3 - m^2_1 > 0$)
- Is ν_3 mostly ν_μ or ν_τ ? $(\theta_{23} < \pi/4 \;\; \text{or} > \pi/4)$
- Is CP Violated in Neutrino Oscillations? ($\delta \neq 0, \pi$)

Charge-Parity Symmetry

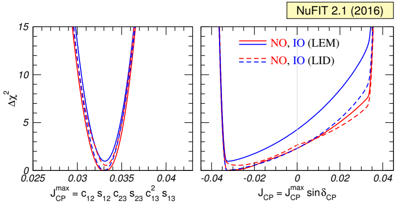
Charge-parity symmetry: **laws of physics are the same if a particle is interchanged with its anti-particle and left and right are swapped.**
A violation of CP ⇒ matter/anti-matter asymmetry.



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

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

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



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

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

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

For CKM (mixing among the 3 quark generations):

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

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

NEUTRINOS II: ν EXPERIMENTS OF THE 21^{st} CENTURY