The Little Neutral One: History and Overview

African School of Fundamental Physics and Applications (ASP2024), Marrakech, Morocco, July 2024

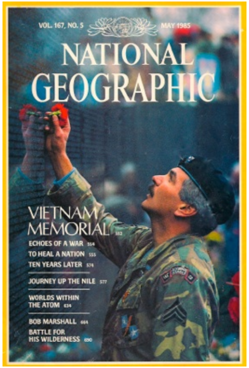
Mary Bishai
Brookhaven National Laboratory

Dec 9^{th}, 2022

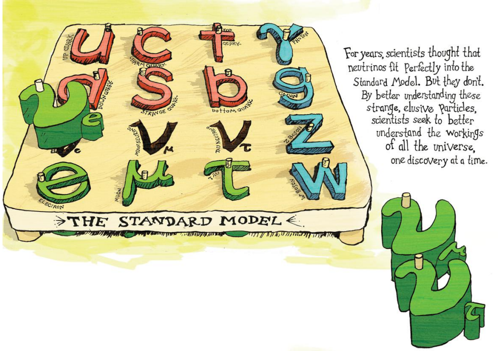
Mary Bishai, Distinguished Physicist, Brookhaven National Lab

- **Born in Egypt, lived in Nigeria till age 10, many summers in Cote D'Ivoire.**
- **1987-1989: Undergraduate at the American University in Cairo.**
- **1989-1991: B.A in Physics University of Colorado, Boulder**
- **1991-1998: Ph.D. in Experimental Particle Physics, Purdue University, Indiana, USA. Worked on charm baryon physics at the CLEO experiment and microstrip gas chamber R&D.**
- **1998-2004: Postdoc on the Collider Detector at Fermilab (CDF) experiment. Worked on silicon detectors, B physics**
- **2014: Elected Fellow of the American Physical Society**
- **2004-now: Staff scientist at BNL working on neutrino projects: MINOS, LBNE (Project Scientist), MicroBooNE, Daya Bay, DUNE**
- **Jan 2023: Elected co-spokesperson of DUNE experiment collaboration (1400 members, 36 countries)**

May 1985: inspired by "Worlds Within the Atom" National Geographic:



About Neutrinos



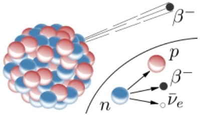
From Symmetry Magazine, Feb 2013

Cosmic Gall
by John Updike

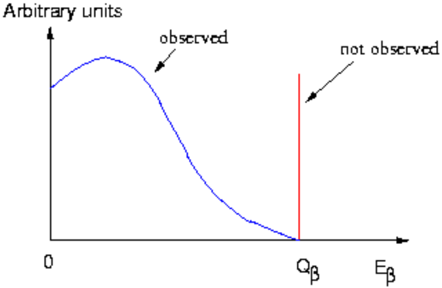
Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial 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.

NEUTRINO CONCEPTION

Neutrino Conception



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



Neutrino Conception

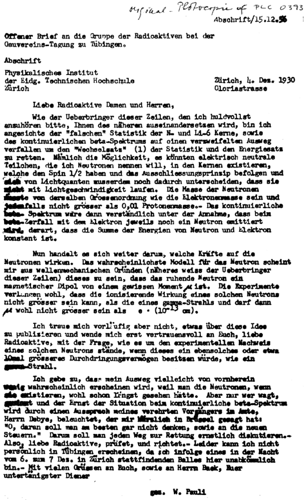
Dec 1930: Wolfgang Pauli's letter to physicists at a workshop in Tubingen:

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



Original - Photocopie of PLC 0393
Abschrift/15.12.56

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

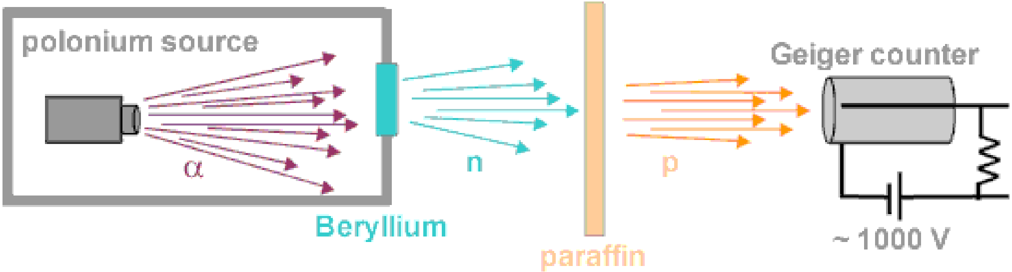
Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

Neutrino Conception

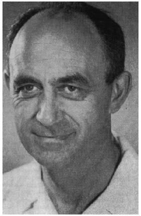
1932: James Chadwick discovers the neutron,
mass$_{\text{neutron}} = 1.0014 \times$ mass$_{\text{proton}}$ **- its too heavy - cant be Pauli's particle**

James Chadwick



Neutrino Conception

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

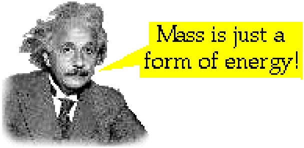


Enrico Fermi

Particle physics units and symbols

Symbols used for some common particles:

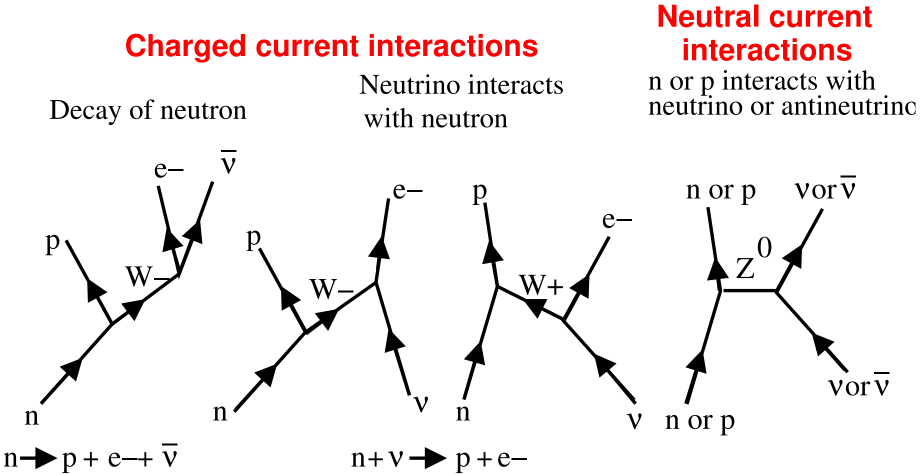
Symbol	Particle
ν, $\bar{\nu}$	Neutrino and anti-neutrino
γ	Photon
e^-	Electron
e^+	Anti-electron (positron)
p	proton
n	neutron
N	nucleon - proton or neutron



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

The Theory of Weak Interactions

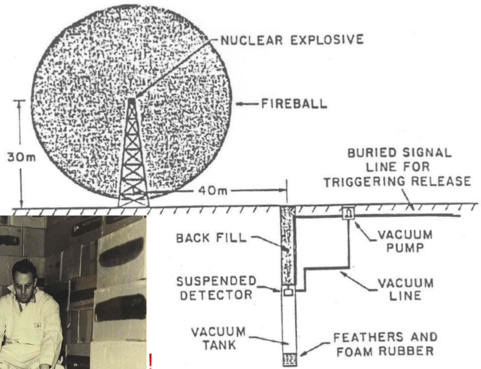
$\geq$ **1933:** **Fermi builds his theory of weak interactions and beta decay**

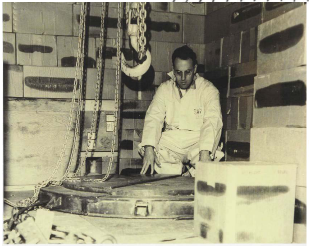


NEUTRINO DISCOVERY: NUCLEAR REACTORS

Finding Neutrinos.... 1st attempt

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





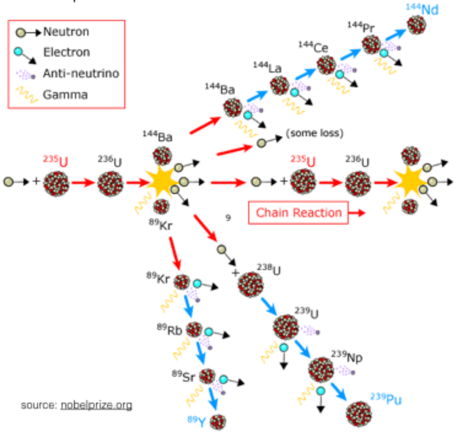
!

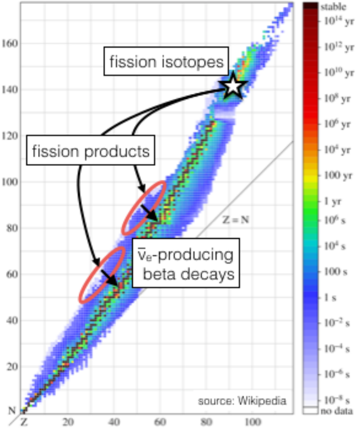
proposal didnt go ahead

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.

fission process in a nuclear reactor





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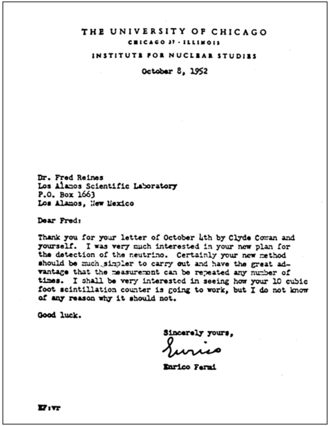

THE UNIVERSITY OF CHICAGO
CHICAGO 37 · ILLINOIS
INSTITUTE FOR NUCLEAR STUDIES

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.... 2nd attempt

A little exercise:

$$\mathrm{n} \;\longrightarrow\; \mathrm{p}^{+} + \mathrm{e}^{-} + \bar{\nu}$$

Finding Neutrinos.... 2nd attempt

A little exercise:

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

A little exercise:

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p^{+} + \bar{\nu} &\rightarrow
\end{aligned}
$$

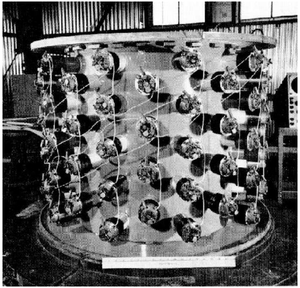
Finding Neutrinos.... 2nd attempt

A little exercise:

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

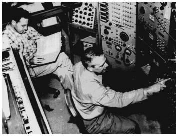
Finding Neutrinos.... 2^{nd} attempt

To detect neutrinos Reines and Cowen filled a detector with water with $CdCl_2$ in solution surrounded by photo-multiplier tubes (PMTs) and located it 11 meters from the reactor center and 12 meters underground.



The detection sequence was as follows:

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



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

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

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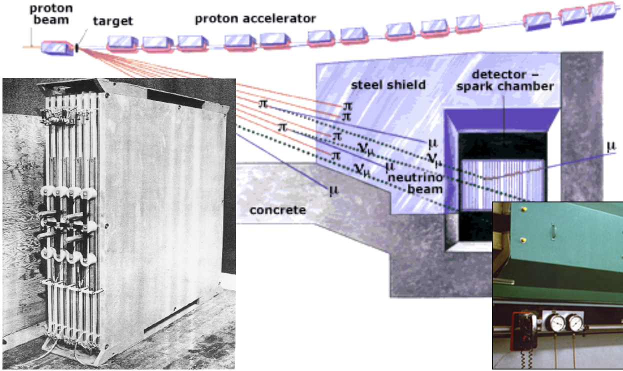
$$= \text{1.6 LIGHT YEARS OF LEAD}$$
$$= 100,000 \text{ distance earth to sun}$$

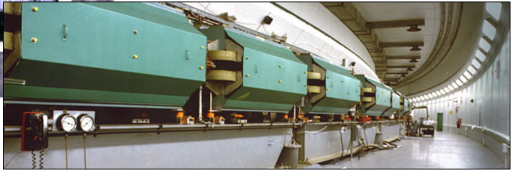
A proton has a mean free path of 10cm in lead

DISCOVERY OF NEUTRINO FLAVOR

Producing Neutrinos from an Accelerator: Two Neutrino Experiment

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 $\pi \rightarrow \mu\nu_x \Rightarrow$ two neutrino experiment





The Two-Neutrino Experiment

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.

<u>**Result:**</u> **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. 1998 NOBEL PRIZE

Neutrinos from Accelerators

To produce neutrinos from accelerators

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

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

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

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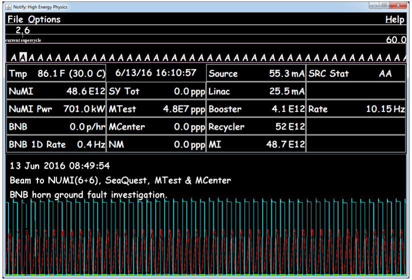
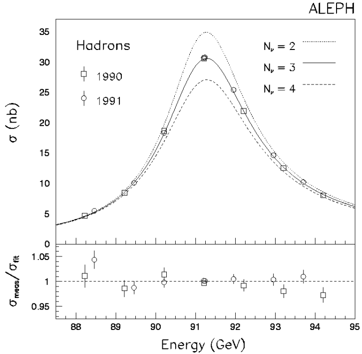
$$\begin{aligned} \text{Power} = \quad & \mathbf{120GeV/proton} \times 1.6 \times 10^{-10}\mathbf{Joules/GeV} \\ & \times 4.86 \times 10^{13}\text{protons/pulse} \\ & \times \mathbf{1\ pulse/1.33\ seconds} \\ = \quad & 702\text{kW} \end{aligned}$$



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

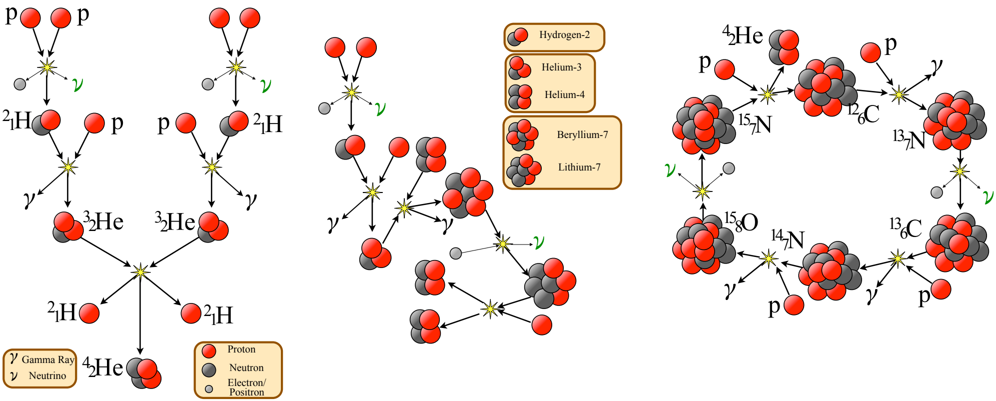


$N_\nu = 2.984 \pm 0.008$

NEUTRINO MIXING: SOLAR

Solar Neutrinos

Fusion of nuclei in the Sun produces solar energy and neutrinos



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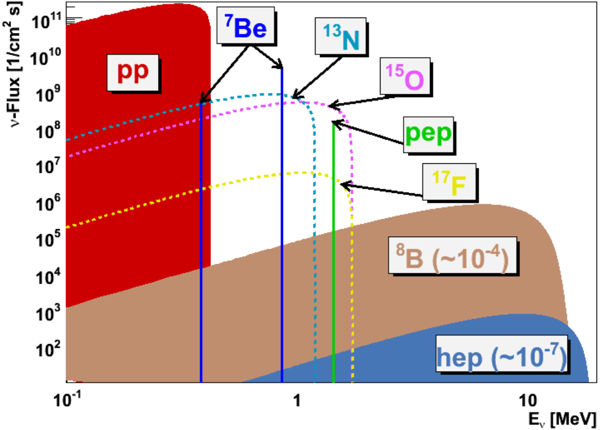
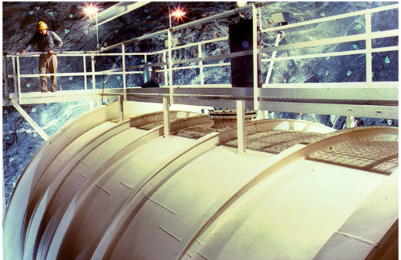


The Homestake Experiment

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

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

Ray Davis



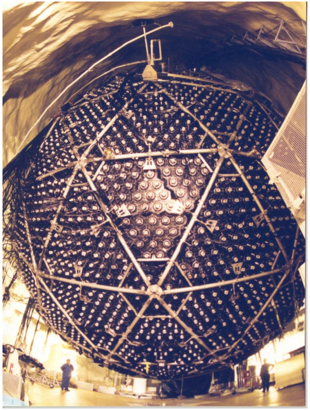
Results: 1969 - 1993 Measured 2.5 ± 0.2 SNU (1 SNU = 1 neutrino interaction per second for 10^{36} target atoms) while theory predicts 8 SNU. This is a ν_e^{sun} deficit of 69%.

Where did the suns ν_e's go?

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:



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

SNO measured:

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

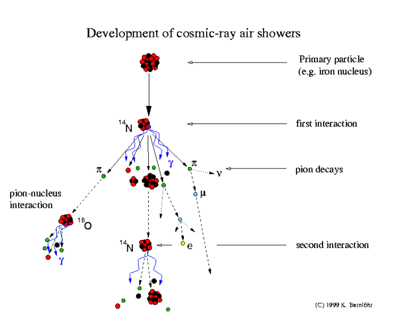
$\phi^{ES}_{SNO}(\nu_x) = 2.39 \pm 0.34(\mathrm{stat})^{+0.16}_{-0.14}(\mathrm{sys.}) \pm \times 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$

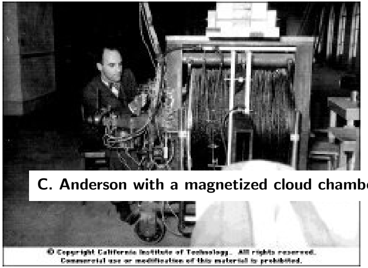
$\phi^{NC}_{SNO}(\nu_x) = 5.09 \pm 0.44(\mathrm{stat})^{+0.46}_{-0.43}(\mathrm{sys.}) \pm \times 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$

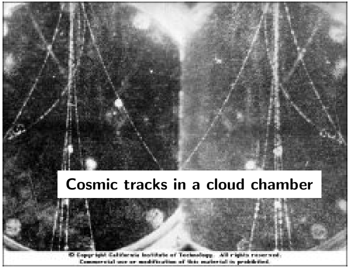
All the solar ν's are there but ν_e appears as ν_x!

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

The Lepton Family and Flavors

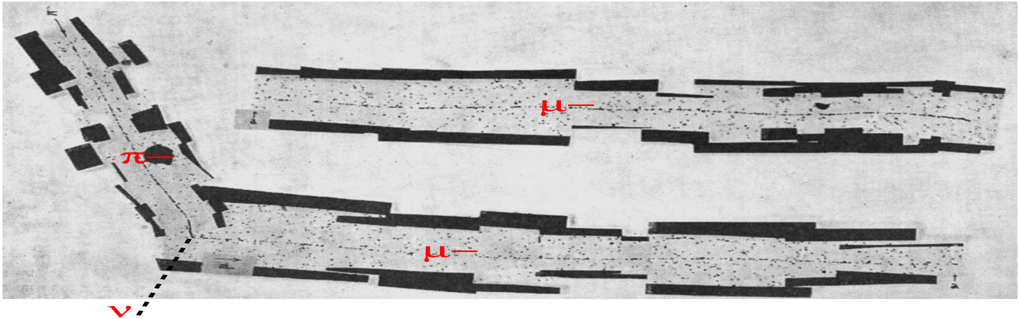
The muon and the electron are *different "flavors" of the same family of elementary particles called leptons***.**

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, Cesar Lattes and Giusseppe Occhialini collect emulsion photos of cosmic rays on top of mountains and aboard high altitude RAF flights. A charged particle is found decaying to a muon:

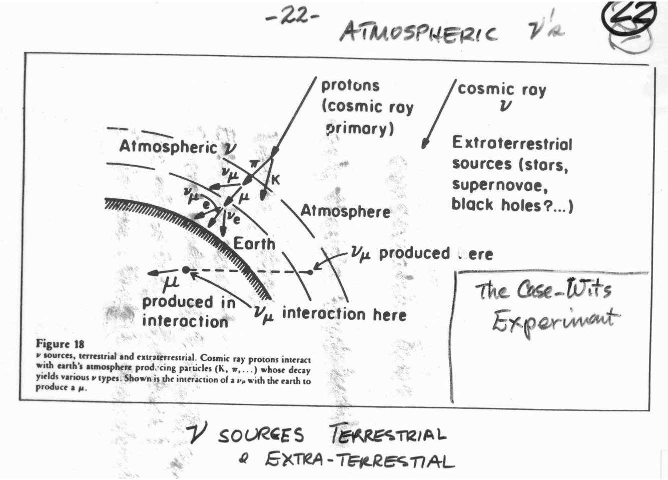


mass$_{\pi^-}$ = 0.1396 GeV/c^2 , $\tau = 26$ ns.

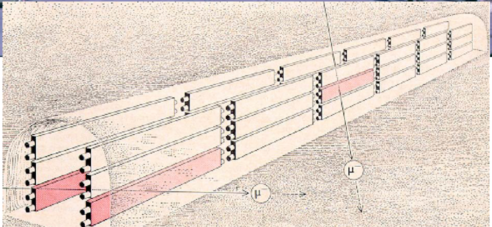
Pions are composed of $q\bar{q}'$ pairs. Weak decays produce neutrinos like in beta decay.

1950 Nobel prize for Powell

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



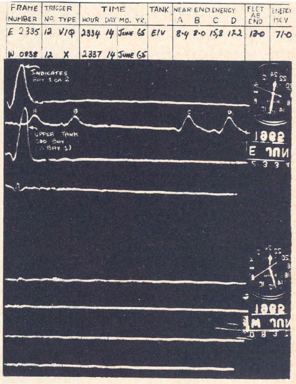
1964: The Case Western Institute-South Africa Neutrino Detector (CWI-SAND) and a search for atmospheric ν_μ at the East Rand gold mine in South Africa at 3585m depth



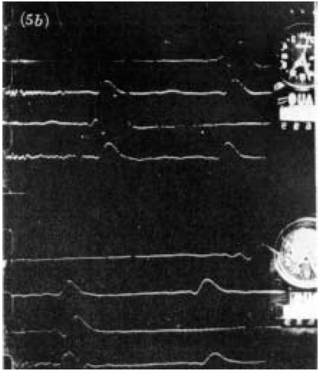
The CWI-SAND Experiment

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

Detection of the first natural neutrino



Downward-going Muon (background)



Horizontal Muon (neutrino signal)

Quantum Mechanics

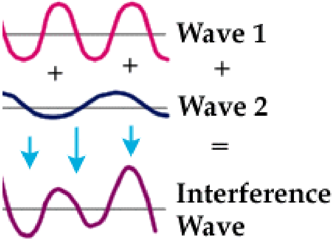
1924: Louis-Victor-Pierre-Raymond, 7th duc de Broglie proposes in his doctoral thesis that all matter has wave-like and particle-like properties.

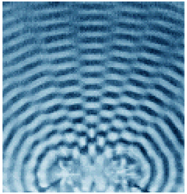
For highly relativistic particles : energy ≈ momentum

De Broglie

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

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 $\Rightarrow$ Oscillations

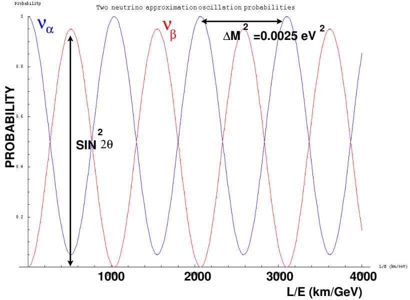
$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \to \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2t} - e^{-iE_1t}|^2 \end{aligned}$$

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

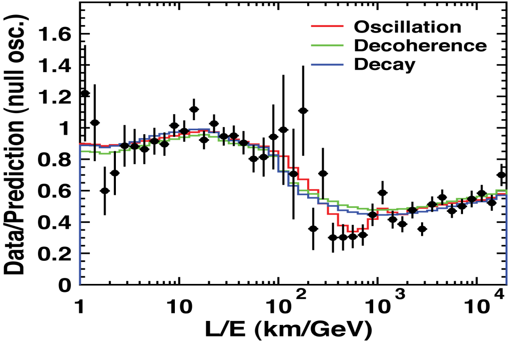
where $\Delta m_{21}^2 = (m_2^2 - m_1^2)$ in eV^2, L (km) and E (GeV).

Observation of oscillations
implies non-zero mass eigenstates

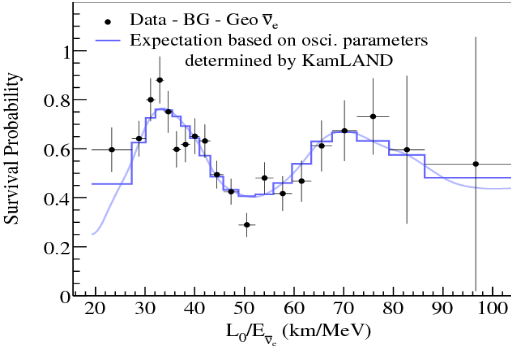


Two Different Mass Scales! $\Delta m^2(\mathbf{eV^2}) = \frac{1}{1.27}\frac{\pi}{2}\frac{\mathbf{E(GeV)}}{\mathbf{L(km)}}$

Super-K, atmospheric ν_μ



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



Global fit 2013:

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

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

Global fit 2013:

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

Solar L/E $\sim$ 15,000 km/GeV

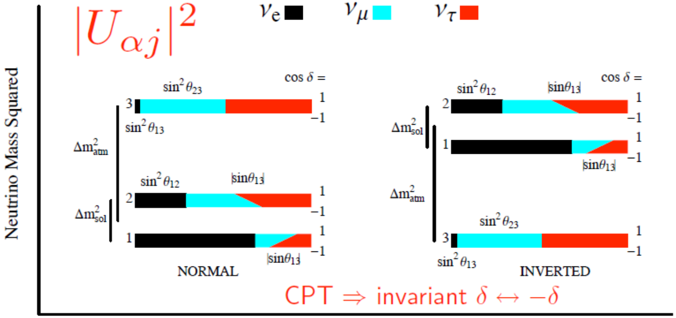
2015 Nobel Prize

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"*

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



Fractional Flavor Content varying $\cos\delta$

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

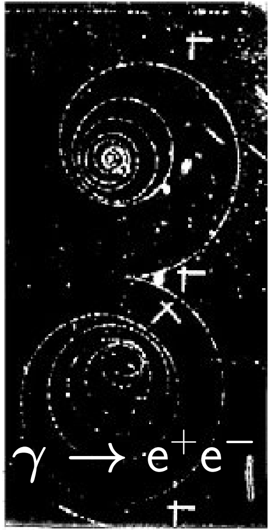
$\sin^2\theta_{12} \approx \sin^2\theta_{solar}$, $\sin^2\theta_{23} \approx \sin^2\theta_{atmospheric}$

3 quantum states interfering $\Rightarrow$ phase δ

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.

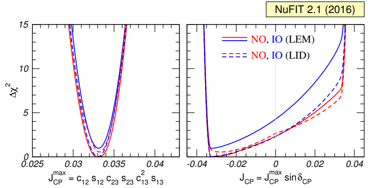
A violation of CP $\Rightarrow$ matter/anti-matter asymmetry.



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

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

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



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

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

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

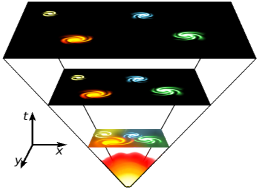
For CKM (mixing among the 3 quark generations):

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

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

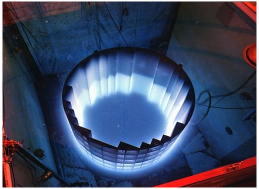
Sources of Neutrinos (Summary)

Big Bang



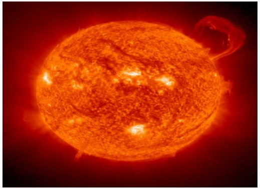
10^{-4} eV
$56/\text{cm}^3$

Reactors



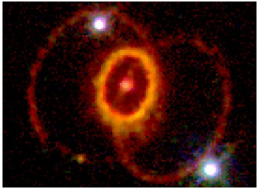
few MeV
10^{21}/**GW**$_{\text{th}}$/**s**

Sun



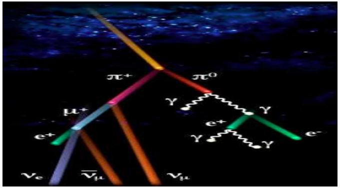
0.1-14 MeVg
10^{10}/**cm**^{2}/**s**

SuperNova



$\sim$ 10 **MeV**
10^9/**cm**^{2}/**s**

Atmosphere

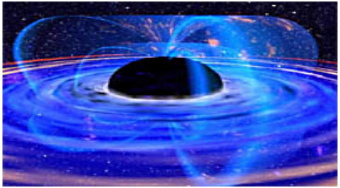


$\sim$ 1 **GeV**
few/cm^2/s

Accelerators

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

Extragalactic



TeV-PeV
varies

BREAK ... NEUTRINO RAP

Click for Neutrino rap!!