The Little νeutral One

History and Overview
African School of Fundamental Physics and its Applications (ASP2021)

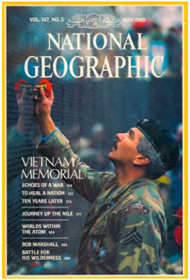
Mary Bishai
Brookhaven National Laboratory

July 22nd, 2021

Bio: Mary Bishai, Senior Physicist, BNL

- **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, USA**
- **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.**

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

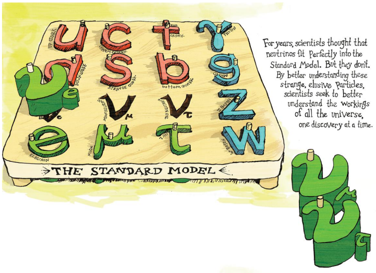


- **1998-2004: Postdoc on the Collider Detector at Fermilab (CDF) experiment. Worked on silicon detectors,** B **physics**
- **2004-now: Staff scientist at BNL working on neutrino projects: MINOS, LBNE (Project Scientist), DUNE (Executive Committee), MicroBooNE, Daya Bay**
- **2014: Elected Fellow of the American Physical Society**

Bio: Mary Bishai, Senior Physicist, BNL

NB: Scientists at Brookhaven National Lab do not directly supervise Ph.D. students. *Some limited support* **available for visiting scientists, MS and Ph.D. student interns through the US DOE and collaborative efforts with institutional partners and/or individual faculty members.**

About Neutrinos



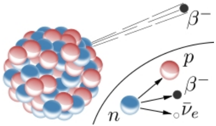
From Symmetry Magazine, Feb 2013

Cosmic Gall
by John Updike

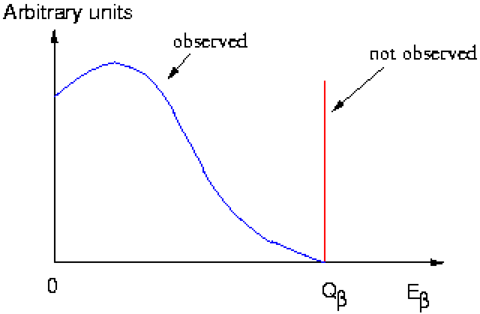
Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial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

The Theory of Weak Interactions

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

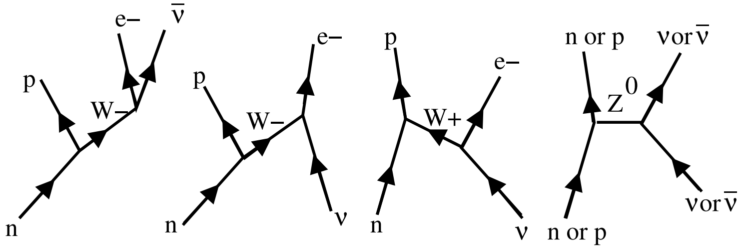
Charged current interactions

Decay of neutron

Neutrino interacts with neutron

Neutral current interactions

n or p interacts with neutrino or antineutrino



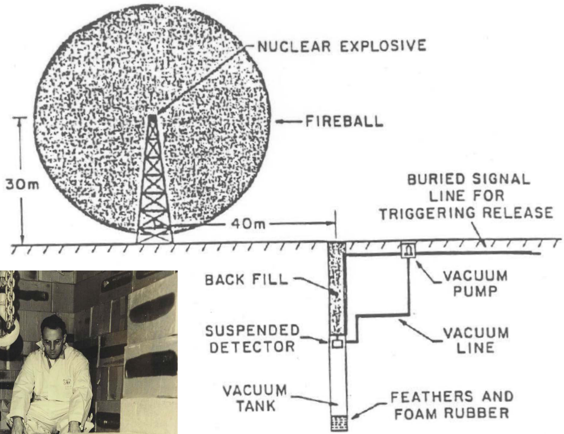
$n \rightarrow p + e^- + \bar{\nu}$

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

NEUTRINO DISCOVERY: NUCLEAR REACTORS

Finding Neutrinos.... 1st attempt

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

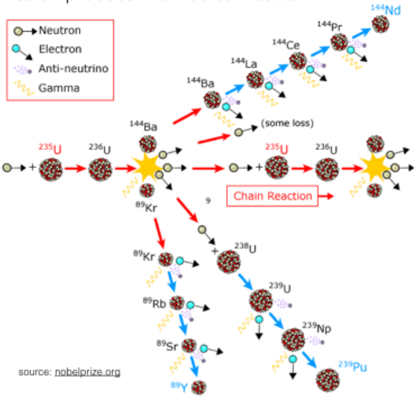


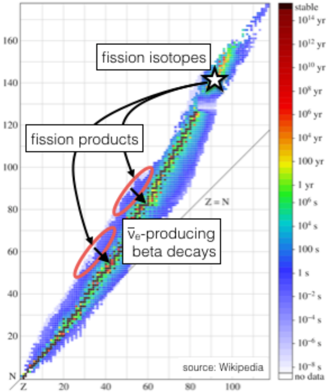
NOT APPROVED !

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

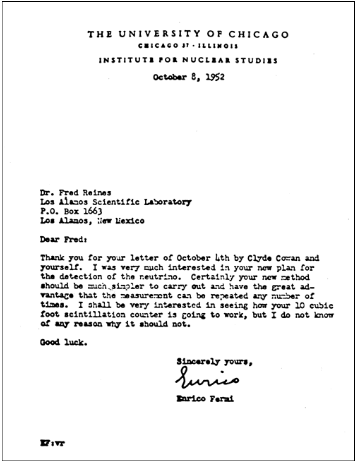
fission process in a nuclear reactor





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,

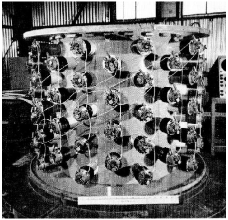
Enrico

Enrico Fermi

EF:vr

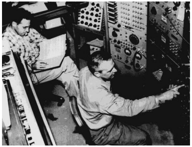
Finding Neutrinos.... 2nd attempt

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 $\sigma \sim 10^{-43}\mathrm{cm}^2$ 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)

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)

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

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

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)

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

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

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

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

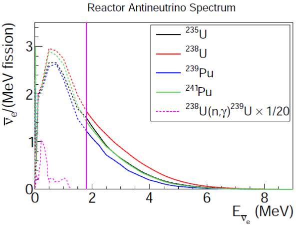
Reactor power and neutrinos

ν Exercise:

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

Fission fragment	Energy (MeV)
Fission products	**175**
⟨2.44⟩ **neutrons**	**5**
γ **from fission**	**7**
γ**s and** β**s from** beta **decay**	**13**
⟨6⟩ **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?

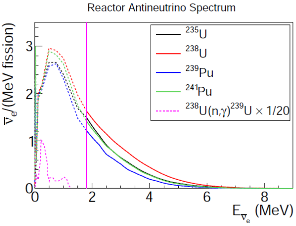
Reactor power and neutrinos

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?

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

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 $\sigma = 10^{-43}\text{cm}^2$/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)

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)

 # 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 ($\bar{\nu}_e + p \rightarrow e^+ + n$) 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

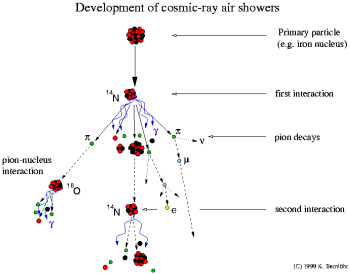
 # interactions/day = 118

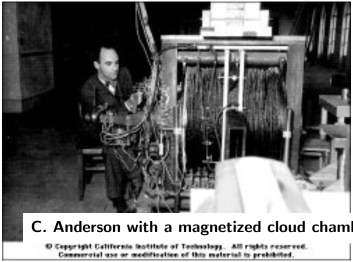
Precision ν expt: need 1 GW nuclear reactor ($1B) + 100's tons

NEUTRINOS FROM COSMIC RAYS

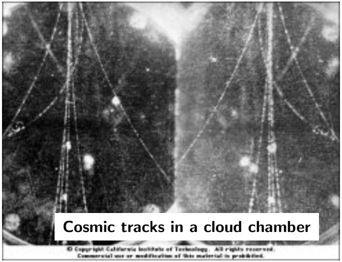
Discovery of the Muon (μ)

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

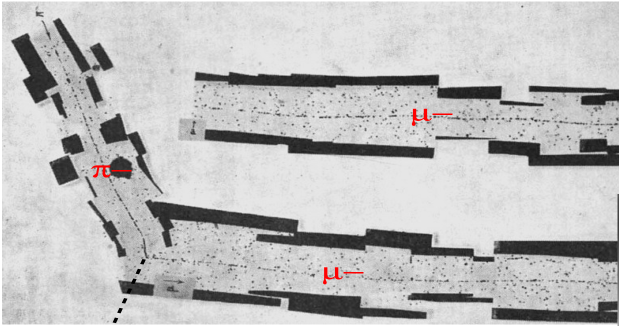
The muon and the electron are *different "flavors" of the same family of elementary particles called leptons*.

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:



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

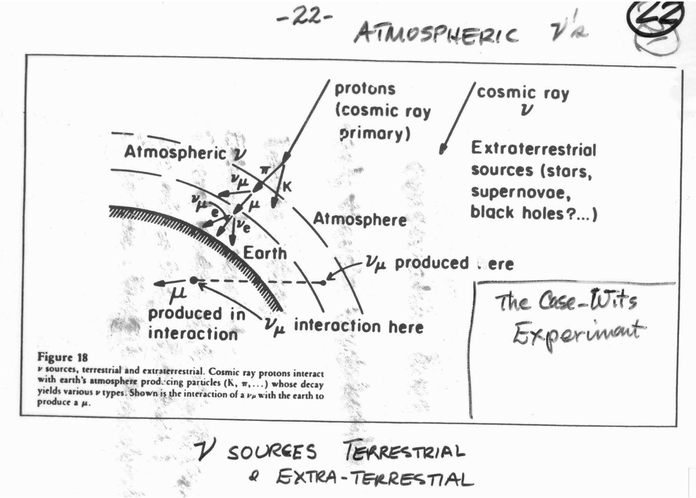
Pions are composed of $q\bar{q}'$ pairs. Weak decays produce neutrinos like in beta decay.

1950 Nobel prize for Powell

Cecil Powell

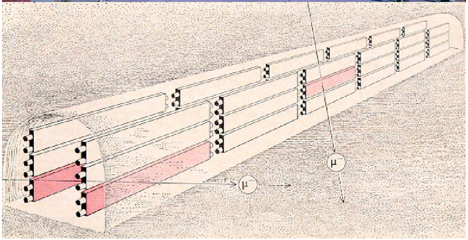
Proposal to find Atmospheric Neutrinos

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



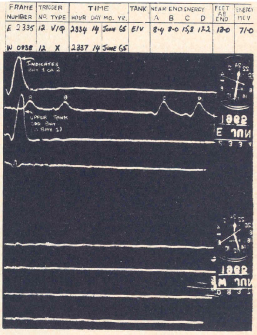
The CWI-SAND Experiment

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

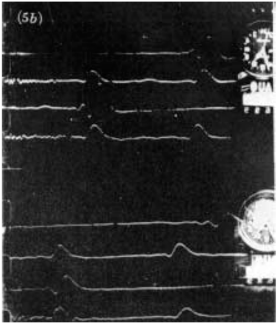


The CWI-SAND Experiment

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



Downward-going Muon (background)



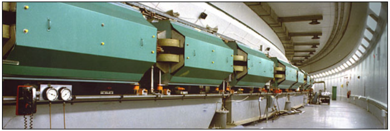
Horizontal Muon (neutrino signal)

Detection of the first neutrino in nature!

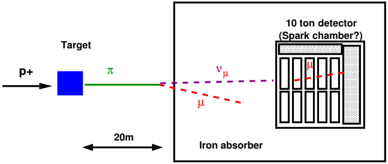
DISCOVERY OF NEUTRINO FLAVOR

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 $\pi \rightarrow \mu\nu_x$

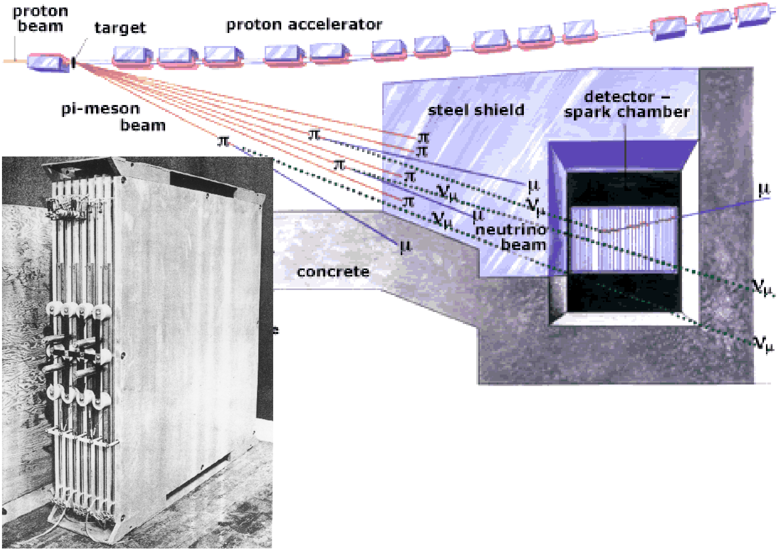


The AGS

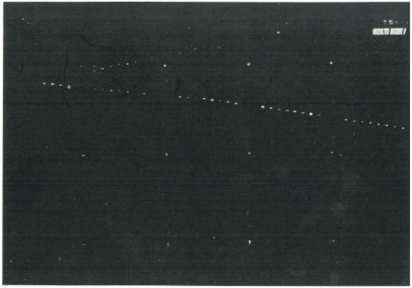


Making ν's

The Two-Neutrino Experiment

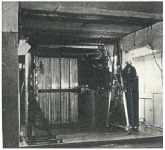


The Two-Neutrino Experiment



NEUTRINO EVENT

COLUMBIA (NEVIS)



BNL

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.

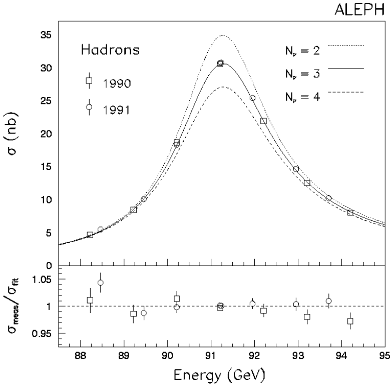
1988 NOBEL PRIZE

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.

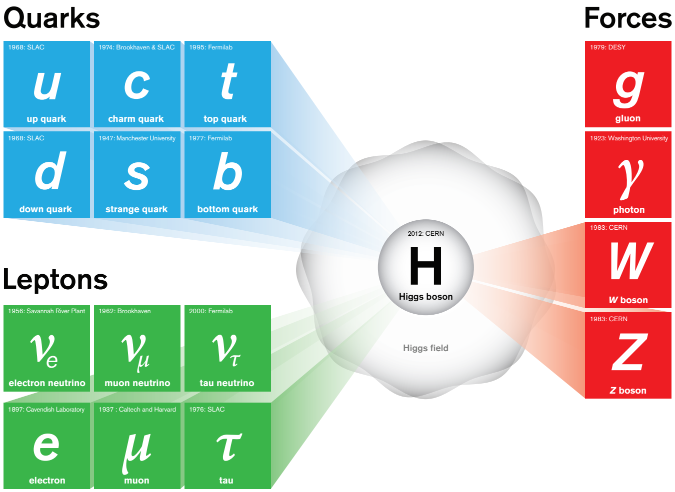
The LEP e^+e^- collider at CERN, Switzerland

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



$N_\nu = 2.984 \pm 0.008$

The Particle Zoo



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?**

Neutrinos from Accelerators

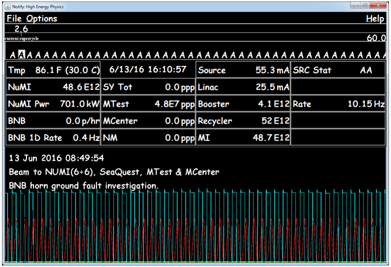
To produce neutrinos from accelerators

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

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?**

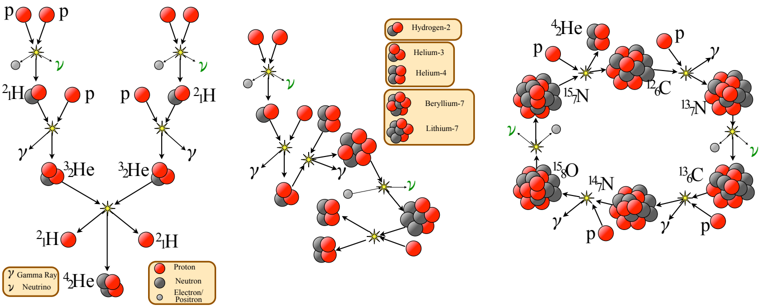
Power = 120 GeV $\times$ 4.86 10^{13} protons $\times$ 1.6 10^{-10} Joules/GeV $\times$ 1/1.33s = 702 kW



THE SOLAR NEUTRINO QUESTION

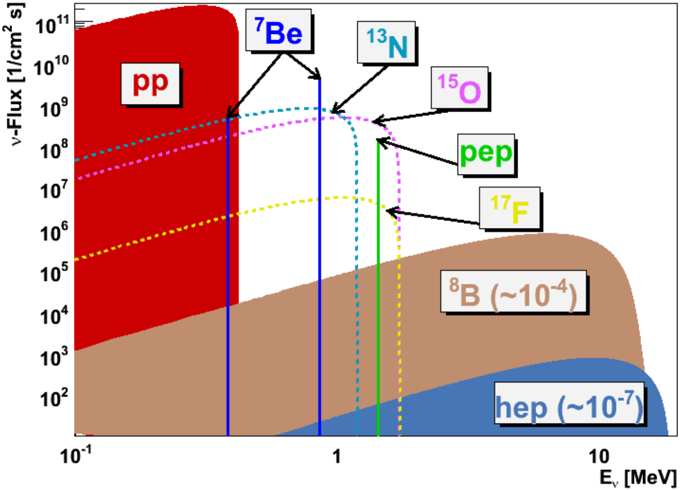
Solar Neutrinos

Fusion of nuclei in the Sun produces solar energy and neutrinos



Solar Neutrinos

Fusion of nuclei in the Sun produces solar energy and neutrinos

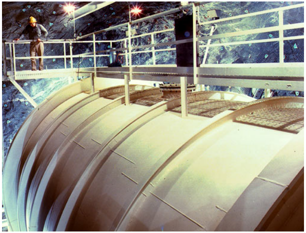


The Homestake Experiment

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

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

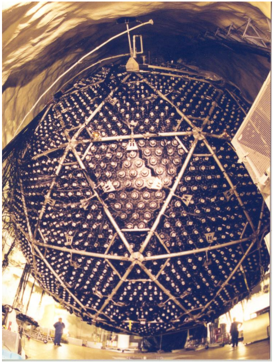


Results: 1969 - 1993 Measured 2.5 $\pm$ 0.2 SNU (1 SNU = 1 neutrino interaction per second for 10^{36} target atoms) while theory predicts 8 SNU. This is a ν_e^{sun} deficit of 69%.

Where did the suns ν_e's go?

RAY DAVIS SHARES 2002 NOBEL PRIZE

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) $\nu_e + d \to e^- + p + p$ **(CC).**
2) $\nu_x + d \to p + n + \nu_x$ **(NC).**
3) $\nu_x + e^- \to e^- + \nu_x$ **(ES).**

SNO measured:

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

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

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

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

2015 Nobel Prize

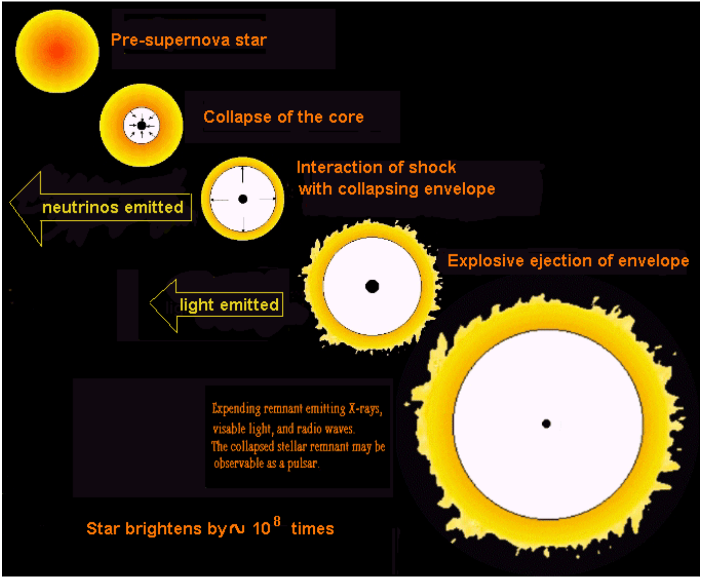
Takaaki Kajita
University of Tokyo, Japan
(SuperKamiokande)

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"*

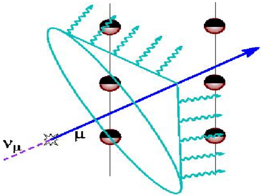
NEUTRINOS FROM SUPERNOVA

Supernova Neutrinos

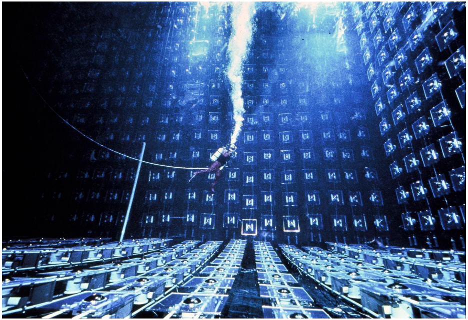


The Irvine-Michigan-Brookhaven (IMB) Detector

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

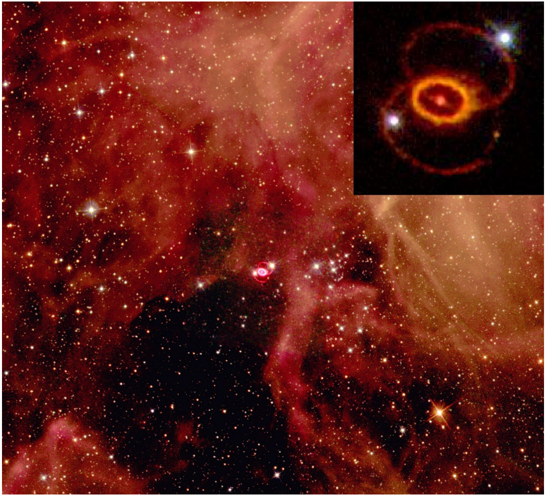


The Irvine-Michigan-Brookhaven Detector



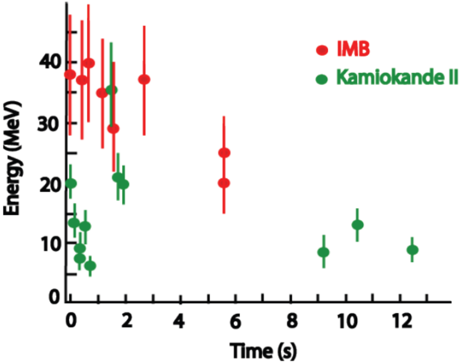
IMB consisted of a roughly cubical tank about 17 × 17.5 × 23 meters, filled with 2.5 million gallons of ultrapure water in Morton Salt Fariport Mine, Ohio. Tank surrounded by 2,048 photomultiplier tubes. IMB detected fast moving particles produced by proton decay or neutrino interactions

IMB/Kamioka Detect First Supernova Neutrinos!



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

IMB/Kamioka Detect First Supernova Neutrinos!



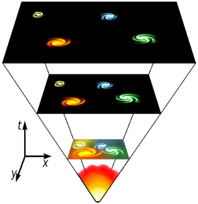
2-3 hrs earlier: IMB detects 8 neutrinos

AND Kamioka detector (Japan) detects 11 neutrinos

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

Sources of Neutrinos (Summary)

Big Bang

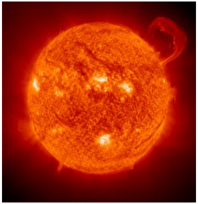


10^{-4} **eV**
56/cm^3

Reactors

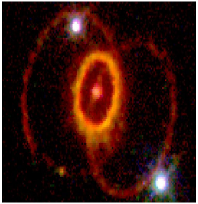
few MeV
10^{21}/**GW$_{th}$/s**

Sun



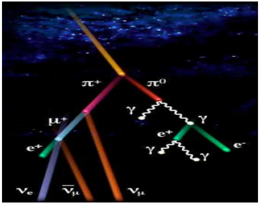
0.1-14 MeV
10^{10}/**cm^2/s**

SuperNova



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

Atmosphere

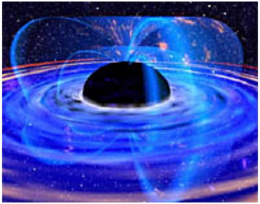


$\sim$ 1 **GeV**
few/cm^2/s

Accelerators

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

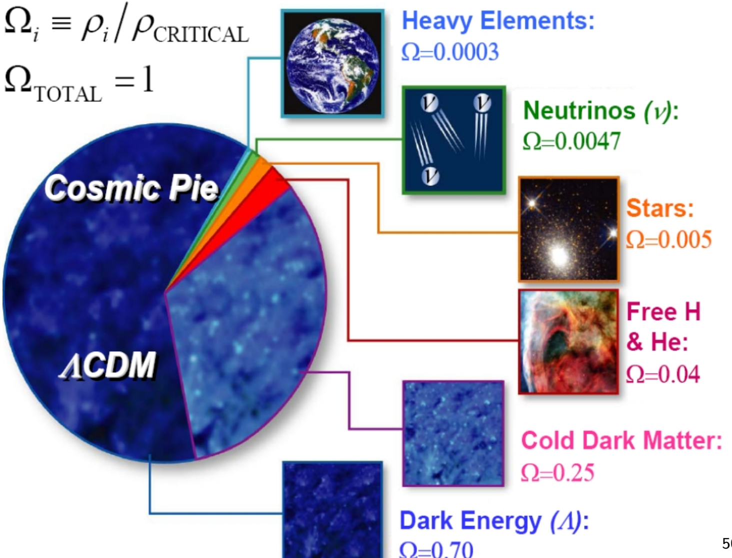
Extragalactic



TeV-PeV
varies

Neutrinos and Todays Universe

Neutrino mass $<$ 1 eV (beta-decay limits)



THANK YOU

Click for Neutrino rap!!