70th Anniversary of the Neutrino

Karsten Heeger
Yale Wright Lab All-Hands Meeting

June 29, 2026

With slides from B. Svoboda at Neutrino2026 and others

Neutrinos and Beta Decay

1930, Pauli

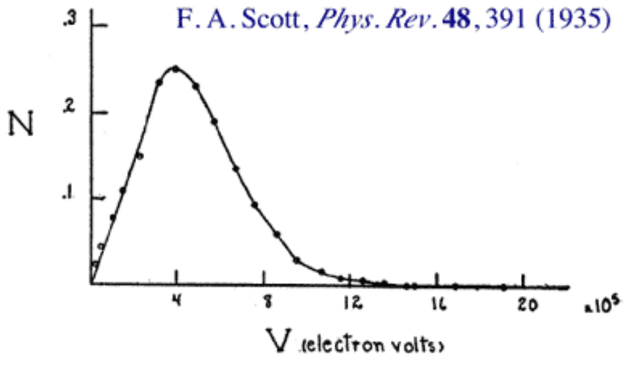
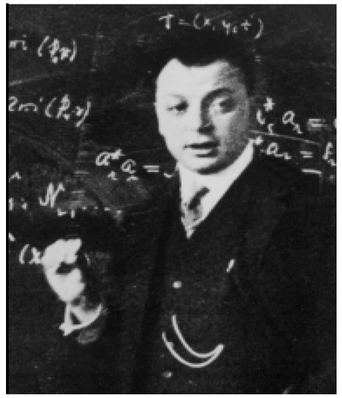
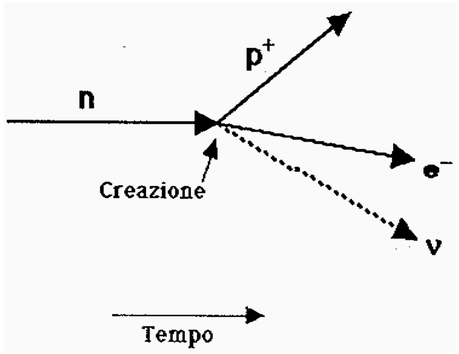
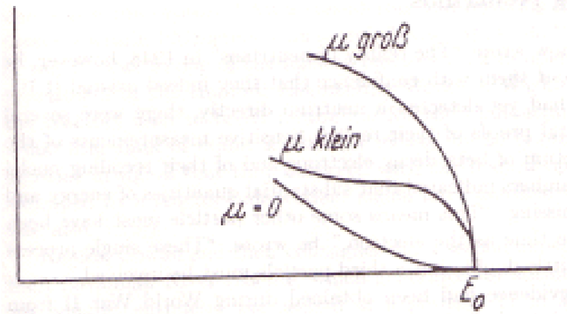


FIG. 5. Energy distribution curve of the beta-rays.

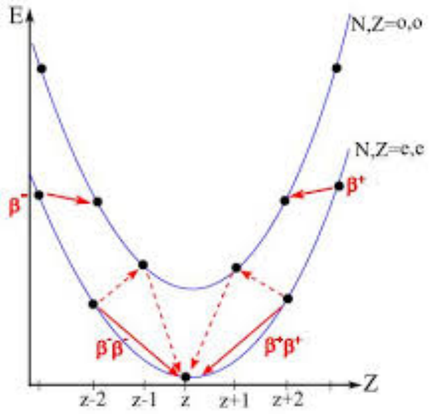


1932, Fermi

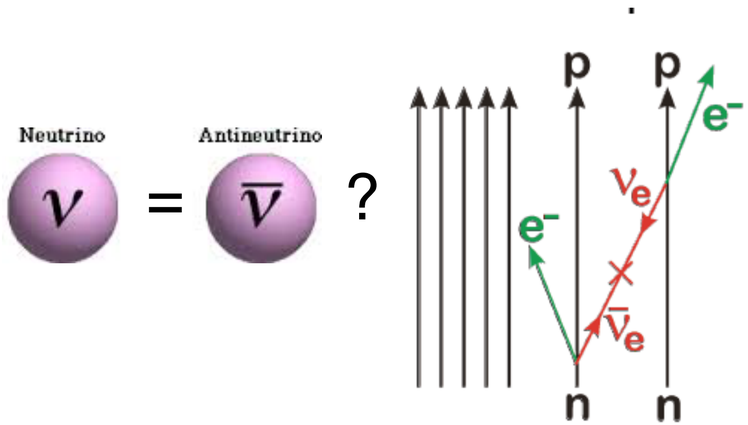




1935, Goeppert Mayer



1937, Majorana



Zürich

Physical Institute of the
Federal Institute of Technology (ETH)
Zürich

Dear radioactive ladies and gentlemen,

As the bearer of these lines, to whom I ask you to listen graciously, will explain more exactly, considering the 'false' statistics of N-14 and Li-6 nuclei, as well as the continuous β-spectrum, I have hit upon a desperate remedy to save the "exchange theorem"* of statistics and the energy theorem. Namely [there is] the possibility that there could exist in the nuclei electrically neutral particles that I wish to call neutrons,** which have spin 1/2 and obey the exclusion principle, and additionally differ from light quanta in that they do not travel with the velocity of light: The mass of the neutron must be of the same order of magnitude as the electron mass and, in any case, not larger than 0.01 proton mass. The continuous β-spectrum would then become understandable by the assumption that in β decay a neutron is emitted together with the electron, in such a way that the sum of the energies of neutron and electron is constant.

Now, the next question is what forces act upon the neutrons. The most likely model for the neutron seems to me to be, on wave mechanical grounds (more details are known by the bearer of these lines), that the neutron at rest is a magnetic dipole of a certain moment μ. Experiment probably required that the ionizing effect of such a neutron should not be larger than that of a γ ray, and thus μ should probably not be larger than $e.10^{-13}$ cm.

But I don't feel secure enough to publish anything about this idea, so I first turn confidently to you, dear radioactives, with a question as to the situation concerning experimental proof of such a neutron, if it has something like about 10 times the penetrating capacity of a γ ray.

I admit that my remedy may appear to have a small *a priori* probability because neutrons, if they exist, would probably have long ago been seen. However, only those who wager can win, and the seriousness of the situation of the continuous β-spectrum can be made clear by the saying of my honored predecessor in office, Mr. Debye, who told me a short while ago in Brussels, "One does best not to think about that at all, like the new taxes." Thus one should earnestly discuss every way of salvation.—So, dear radioactives, put it to test and set it right.—Unfortunately, I cannot personally appear in Tübingen, since I am indispensable here on account of a ball taking place in Zürich in the night from 6 to 7 of December.—With many greetings to you, also to Mr. Back, your devoted servant,

W. Pauli

Pauli's famous 1930 Letter

- "false" statistics of N-14, Li-6
- conserve energy in the continuous β decay spectrum
- mass same order of magnitude as the electron
- small interaction coupling (maybe magnetic moment?)

(Note: Neutron discovery in 1932)

Neutrino Physics is (almost) Impossible

532 NATURE April 7, 1934

Bethe

Peierls

The "Neutrino"

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

(Inverse beta decay)

For an energy of $2 \cdot 3 \times 10^{6}$ volts, t is 3 minutes and therefore $\sigma < 10^{-44}$ cm.^{2} (corresponding to a penetrating power of 10^{16} km. in solid matter). It is

of the neutrino in nuclear transformations—one can conclude that there is no practically possible way of observing the neutrino.

H. Bethe.
R. Peierls.

What is practical in 1946 is different than 1934…

Bruno Pontecorvo

Inverse β Process

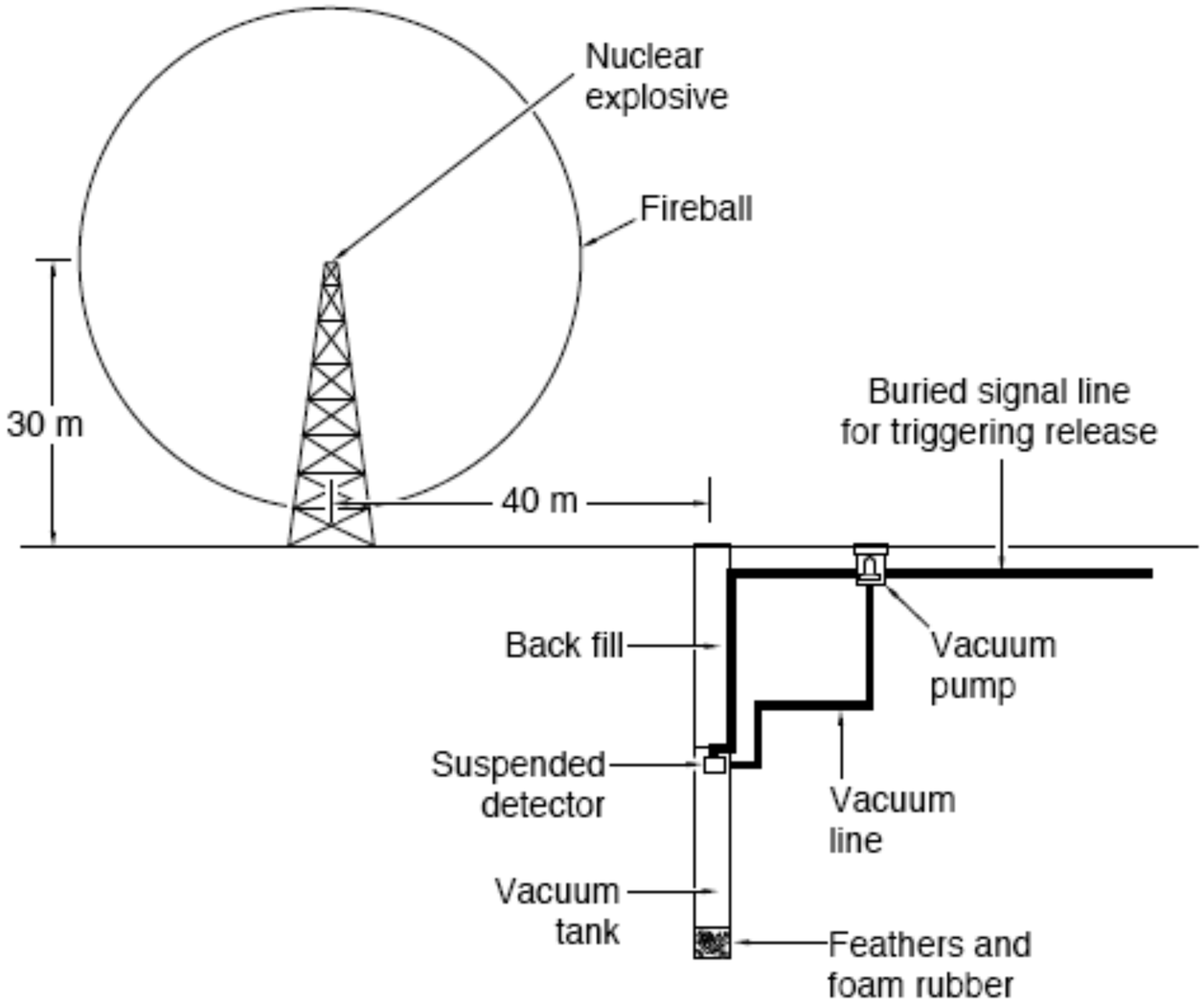
(National Reserach Council of Canada, Division of Atomic Energy. Chalk River, 1946, Report PD-205.
This version was kindly provided by Prof. W.F.Davidson).

Inverse β Process

It is clear that inverse β transformations produced by neutrinos are processes of this type and certainly can be produced by neutrinos, if neutrinos exist at all. They consist of the concomitant absorption of a neutrino and emission of a β particle (positron or negatron) by a nucleus. It is obvious, on thermodynamical grounds, that such process must have an extreme low yield since their inverse, the β process, is so unlikely. It has been currently stated in the literature that an inverse process produced by neutrinos cannot be observed, due to the low yield. As it will be shown below, this statement seems to be too drastic. The object of this note is to show that the experimental observation of an inverse β process produced by neutrinos is not out of the question with the modern experimental facilities, and to suggest a method which might make an experimental observation feasible.

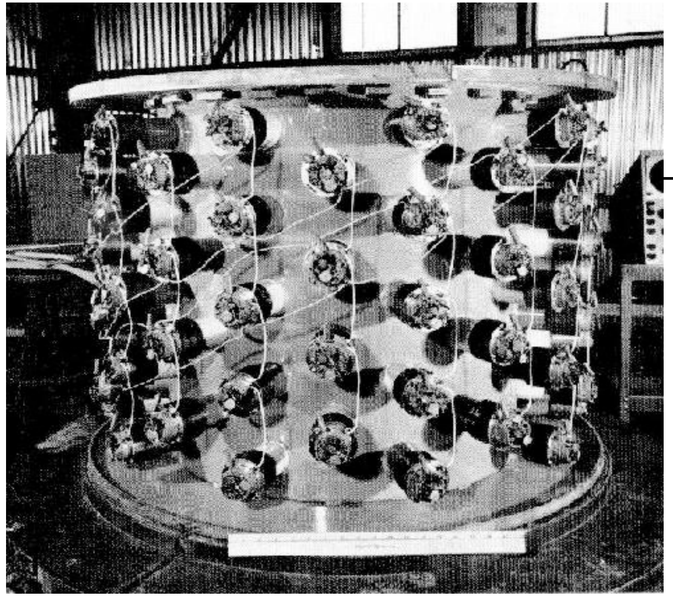
…goes on to discuss a possible Chlorine-based radiochemical experiment

Thinking out of the box…

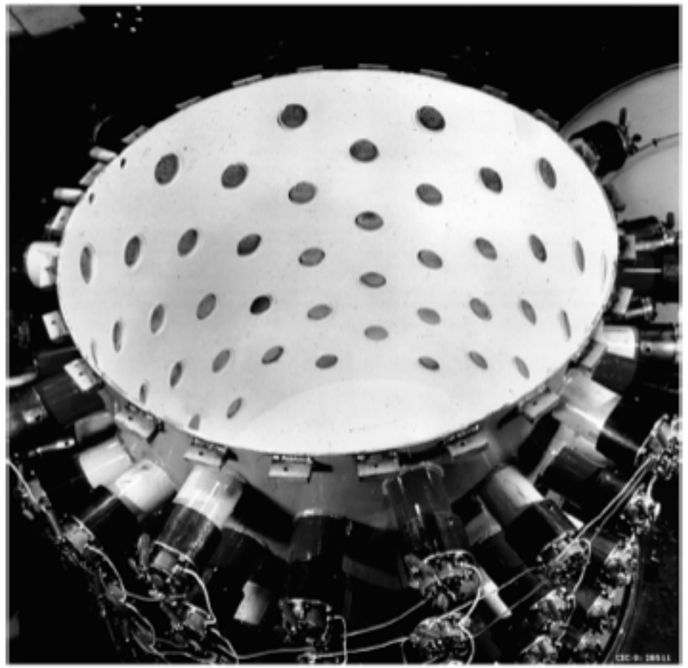


Reines

Hanford Experiment

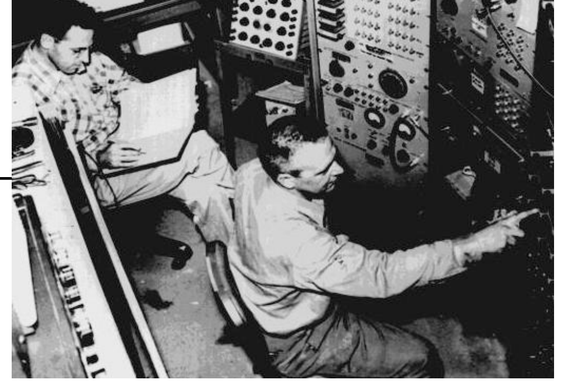


300 liters of liquid scintillator loaded with cadmium

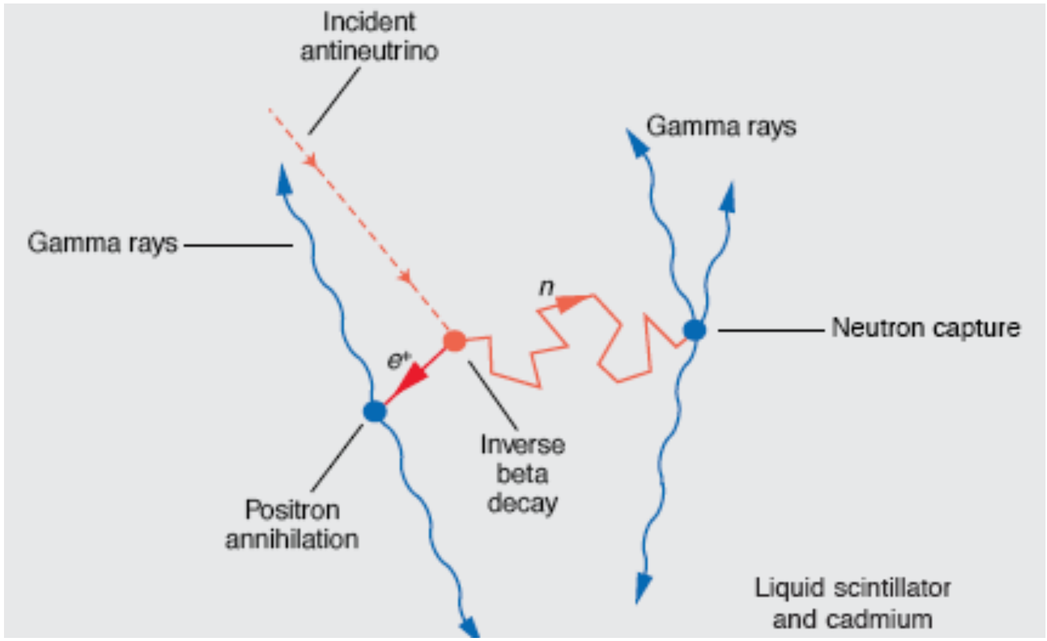


inverse beta decay

$\overline{\nu}_e + p \rightarrow e^+ + n$



Reines, Cowan



0.41+/- 0.20 events/minute

high background (S/N ~ 1/20) made the experiment inconclusive

1953: Project Poltergeist

Experiment at Hanford

Detection of the Free Neutrino*

F. Reines and C. L. Cowan, Jr.
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

(Received July 9, 1953; revised manuscript received September 14, 1953)

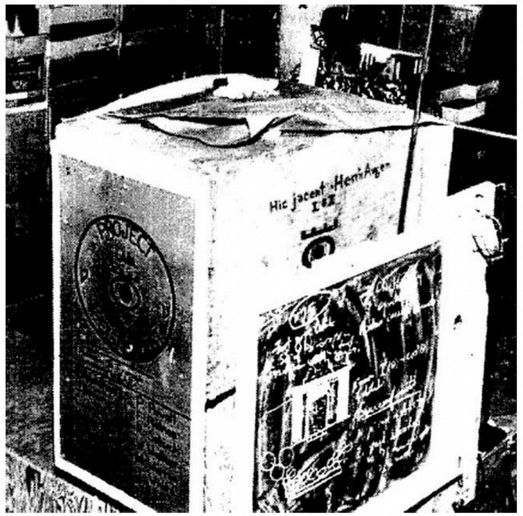
AN experiment[1] has been performed to detect the free neutrino. It appears probable that this aim has been accomplished although further confirmatory work is in progress. The cross section for the reaction employed,

$$\nu_- + p \rightarrow n + \beta^+, \qquad (1)$$

F. Newton Hayes, W.A. Walker, T.J. White
F. Reines, E.C. Anderson, C.L. Cowan

TABLE I. Listing of data.

Run	Pile status	Length of run (seconds)	Net delayed pair rate counts/min	Accidental background rate counts/min
1	up	4000	2.56	0.84
2	up	2000	2.46	3.54
3	up	4000	2.58	3.11
4	down	3000	2.20	0.45
5	down	2000	2.02	0.15
6	down	1000	2.19	0.13



Reactor ON: 2.55 +/- 0.15 count/min
Reactor OFF: 2.14 +/- 0.13 count/min

→ 0.41 +/- 0.20 count/min

(roughly consistent with the 0.2 counts/min expected)

The Savannah River Detector

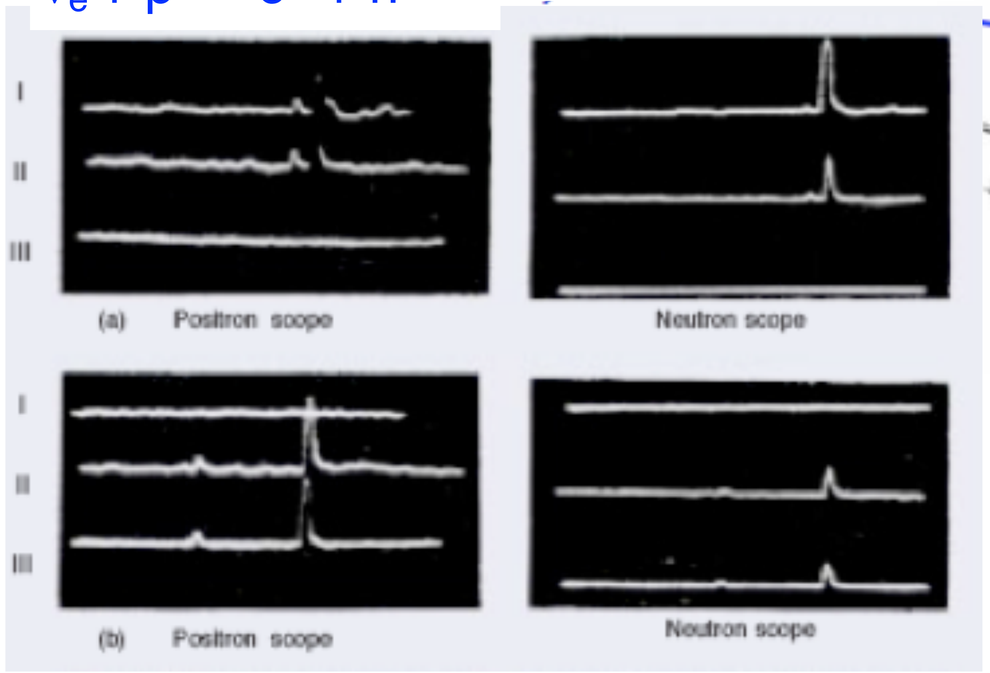
A new design (1959)

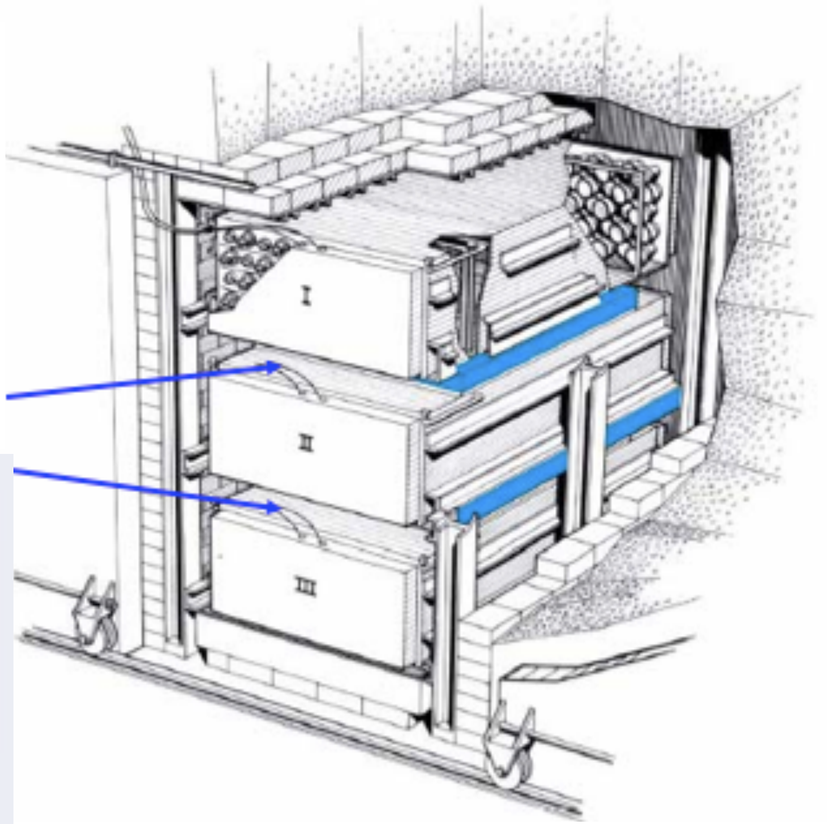
tanks I, II, and III were filled with liquid scintillator and instrumented with 5” PMTs

target tanks (blue) were filled with water+cadmium chloride

inverse beta decay

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





inverse beta decay would produce prompt and delayed signal in neighboring tanks

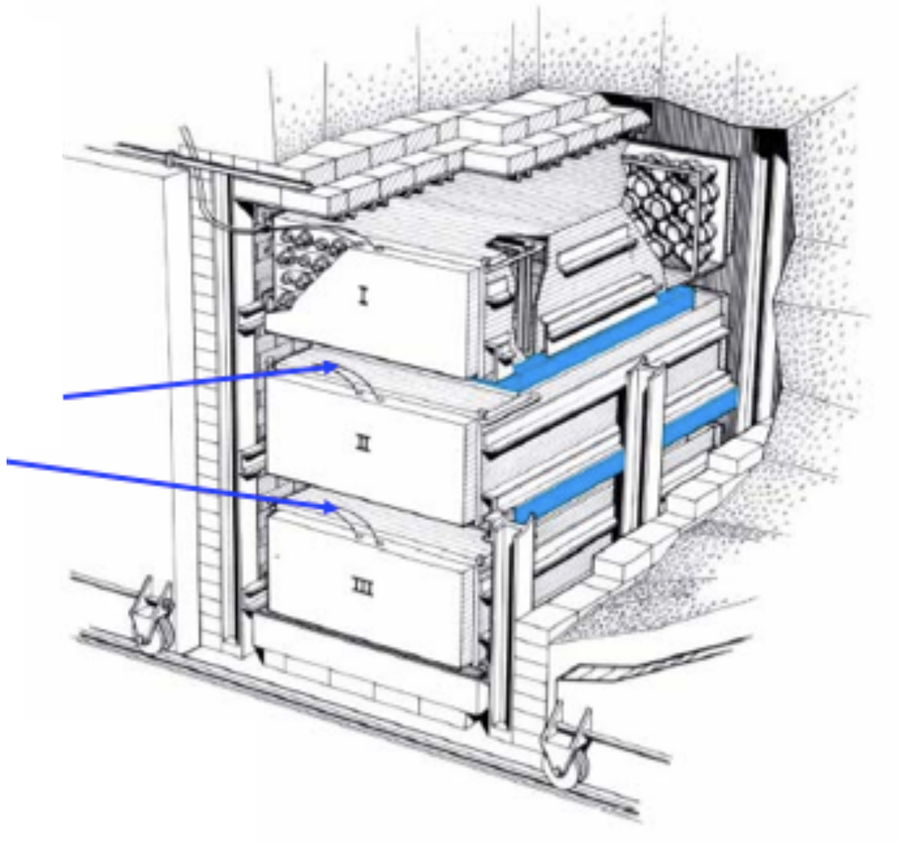
The Savannah River Detector

A new design (1959)

tanks I, II, and III were filled with liquid scintillator and instrumented with 5” PMTs

target tanks (blue) were filled with water+cadmium chloride

Shielding: 4 ft of soaked sawdust

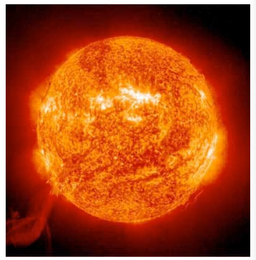


shielding and background reduction is important!

Neutrino as a Probe of Other Physics

1938 Bethe & Critchfield

$p + p \rightarrow {}^2H + e^+ + \nu_e$



1947 Pontecorvo, 1949 Alvarez propose neutrino detection through

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

1960's Ray Davis builds chlorine detector. John Bahcall, generates first solar model calculations and ν flux predictions.

Light Element Fusion Reactions

$p + p \rightarrow {}^2H + e^+ + \nu_e$ (99.75%)

$p + e^- + p \rightarrow {}^2H + \nu_e$ (0.25%)

$^2H + p \rightarrow {}^3He + \gamma$

85%: $^3He + {}^3He \rightarrow {}^4He + 2p$

~15%: $^3He + {}^4He \rightarrow {}^7Be + \gamma$

~10^{-5}%: $^3He + p \rightarrow {}^4He + e^+ + \nu_e$

15.07%: $^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e$

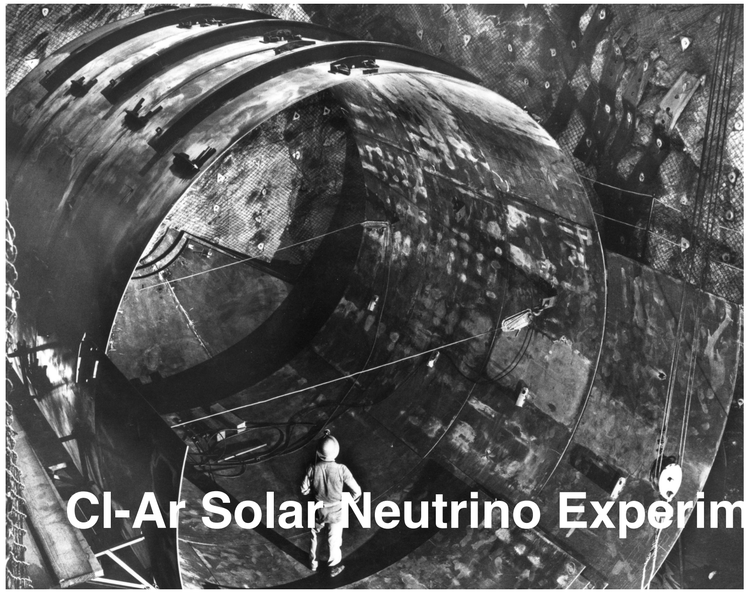
$^7Li + p \rightarrow \alpha + \alpha$

0.02%: $^7Be + p \rightarrow {}^8B + \gamma$

$^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

"…to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars..." (Bahcall, 1964)

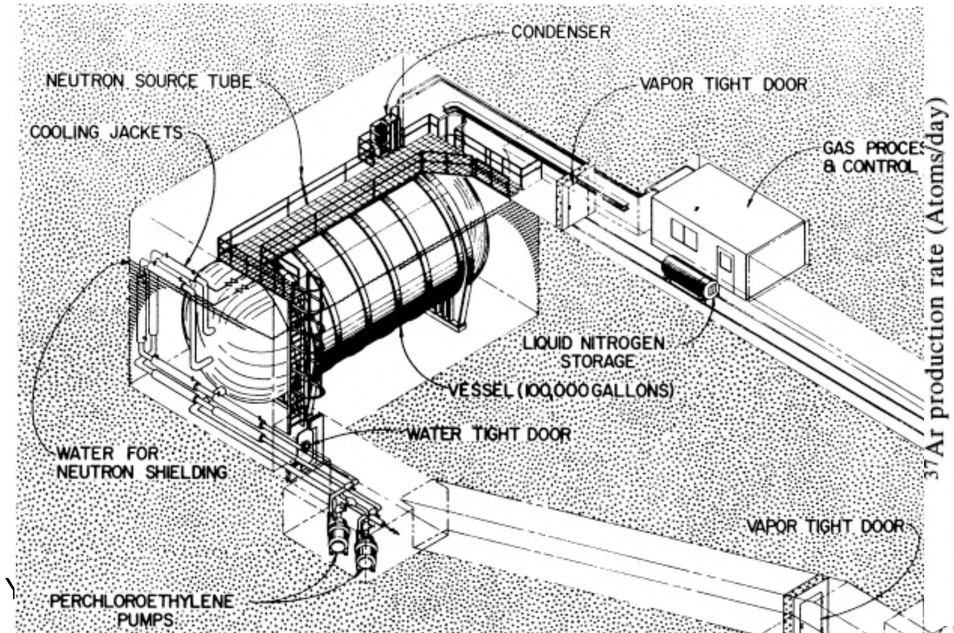
Pioneering Experiments

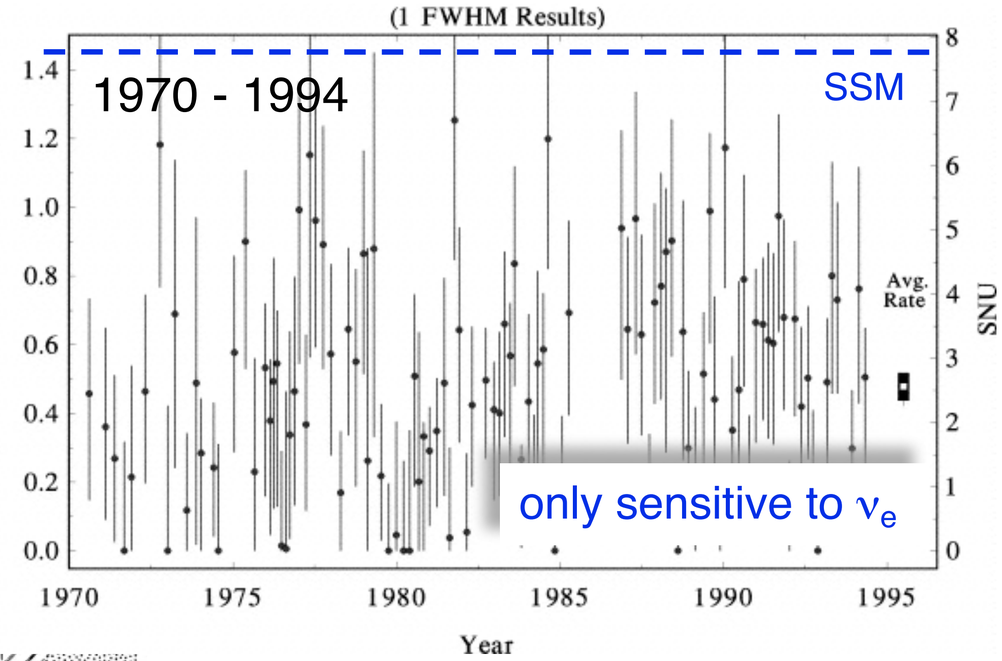


Ray Davis

experimental talent
patience
persistence

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





Discovery of Neutrino Flavor Change and Oscillation

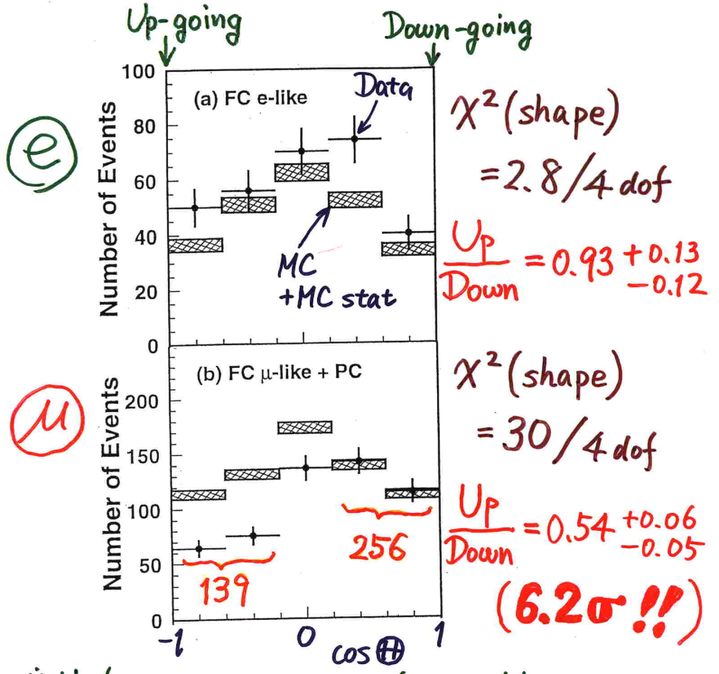
Neutrino 98

ν98, @Takayam
June 1998

Atmospheric neutrino results
from Super-Kamiokande & Kamiokand
— Evidence for ν_μ oscillations —

T. Kajita
Kamioka observatory, Univ. of Tokyo
for the {Kamiokande / Super-Kamiokande} Collaborations

Zenith angle dependence (Multi-GeV)

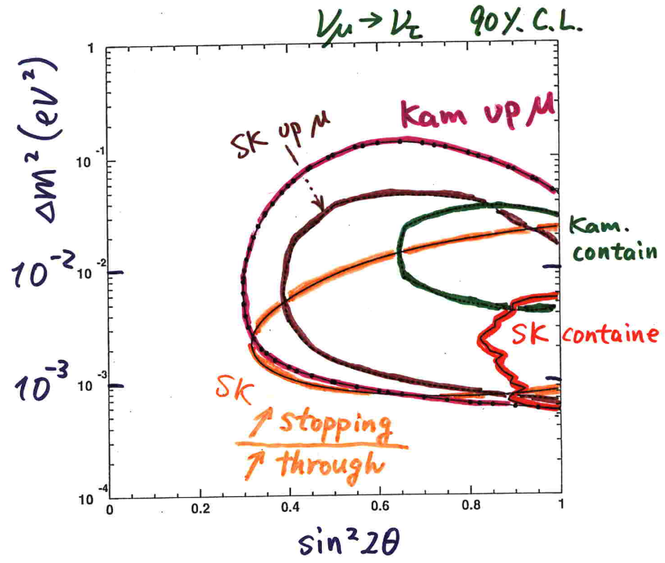


e: χ^2(shape) = 2.8/4 dof
$\frac{Up}{Down} = 0.93^{+0.13}_{-0.12}$

μ: χ^2(shape) = 30/4 dof
$\frac{Up}{Down} = 0.54^{+0.06}_{-0.05}$
(6.2σ !!)

※ Up/Down syst. error for μ-like
Prediction (flux calculation ····· ≲1%; 1km rock above SK ···· 1.5%) 1.8%
Data (Energy calib. for ↑↓ ···· 0.7%; Non ν Background ·····< 2%) 2.1%

Summary
Evidence for ν_μ oscillations



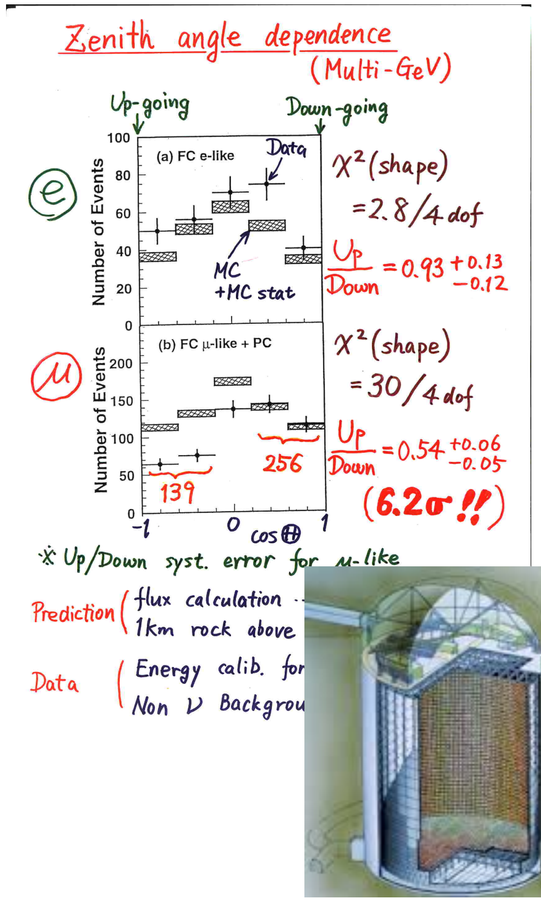
- $\begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$

(• $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$?)

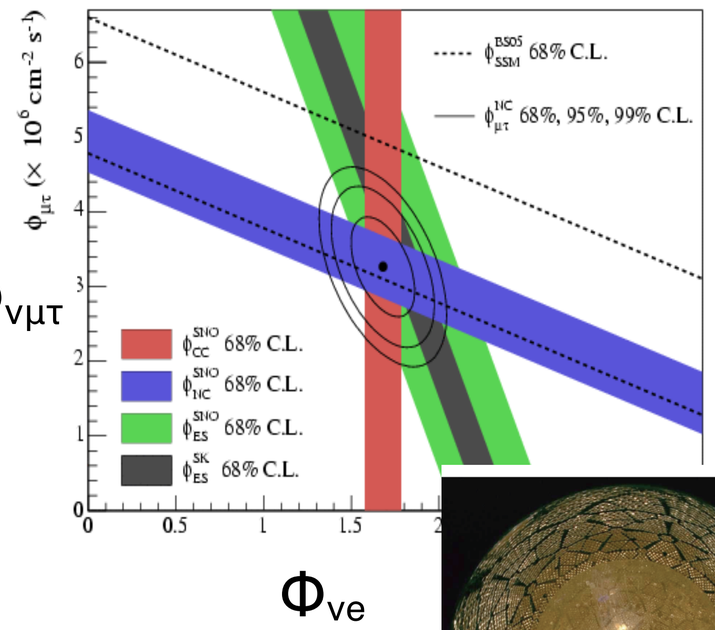
Evidence for atmospheric neutrino oscillation.

Discovery of Neutrino Flavor Change and Oscillation

Atrmospheric ν — Super-K

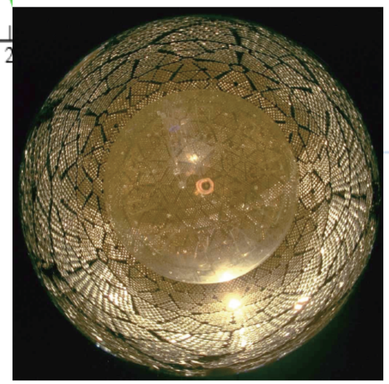


Solar ν_e — SNO

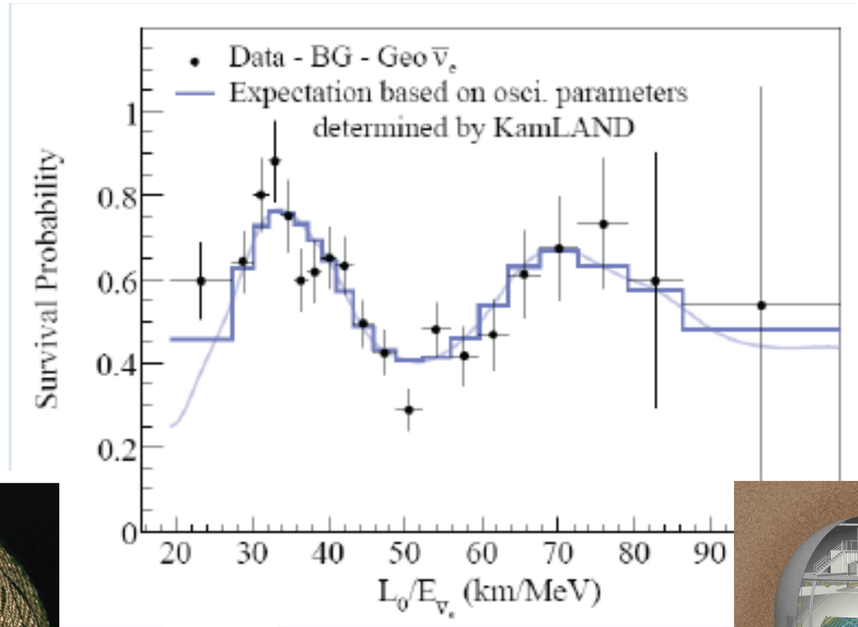


$\Phi_{\nu\mu\tau}$

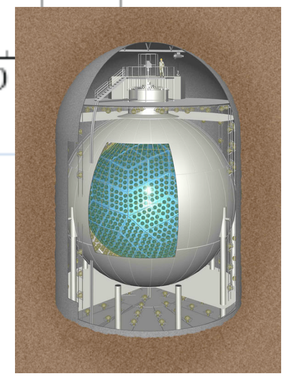
Φ_{ve}



Reactor $\overline{\nu}_e$ — KamLAND



L/E



Neutrino oscillations imply that neutrinos have mass and mix.
Indication of new physics beyond the Standard Model.