

Where's

V?



70th Anniversary of the Neutrino Discovery



Robert Svoboda, Neutrino 2026



Where's
V?



70th Anniversary of the Neutrino Discovery

Savannah Team 1955



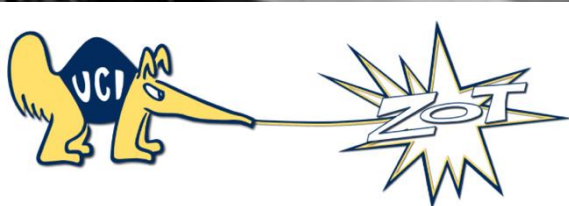
The Hanford Team: (on facing page, left to right, back row) F. Newton Hayes, Captain W. A. Walker, T. J. White, Fred Reines, E. C. Anderson, Clyde Cowan, Jr., and Robert Schuch (inset); not all team members are pictured.
The Savannah River Team: (clockwise, from lower left foreground) Clyde Cowan, Jr., F. B. Harrison, Austin McGuire, Fred Reines, and Martin Warren; (left to right, front row) Richard Jones, Forrest Rice, and Herald Kruse.

Reines and Cowan
Experiment 1956

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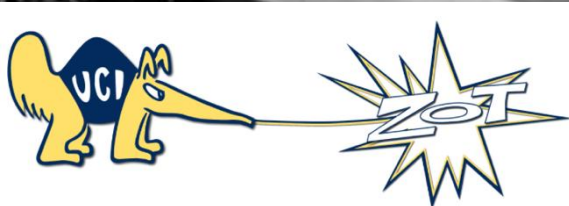
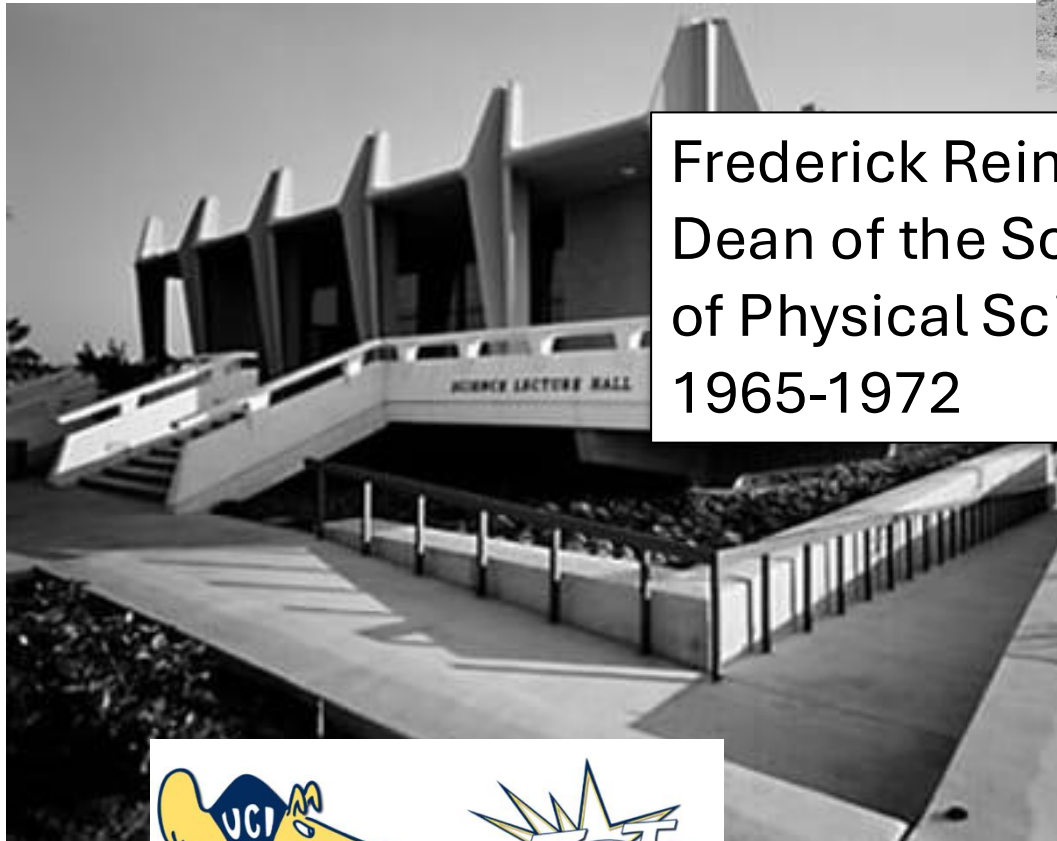
UC Irvine was founded
19 years later in 1965
...but there is a
connection!



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19 years later in 1965
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Frederick Reines, first
Dean of the School
of Physical Sciences
1965-1972



UC Irvine was founded
19 years later in 1965

a



Frederick Reines, first
Dean of the School
of Physical Sciences
1965-1972

I was a postdoc
in Fred's Neutrino
Group 1985-1989



1985-1989 was a heady time to be in the Neutrino Group at UCI



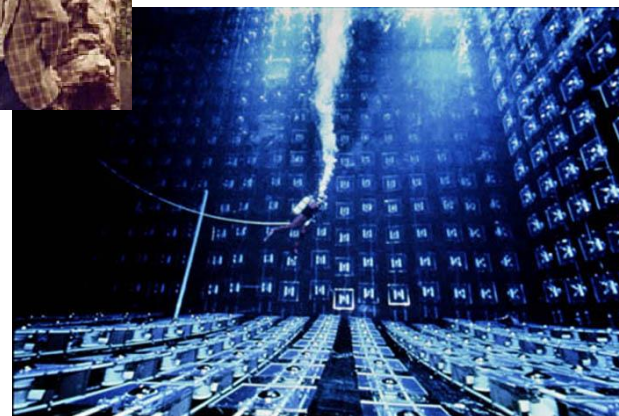
Herb Chen (working on idea for a heavy water neutrino experiment)



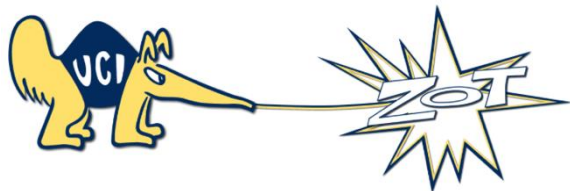
Mike Moe and Steve Elliott (first measurement of two-neutrino double beta decay)



The 8-kiloton Irvine-Michigan-Brookhaven Experiment



UCI: Wojciech Gajewski, Danka Kielczewska, Bill Kropp, Hank Sobel



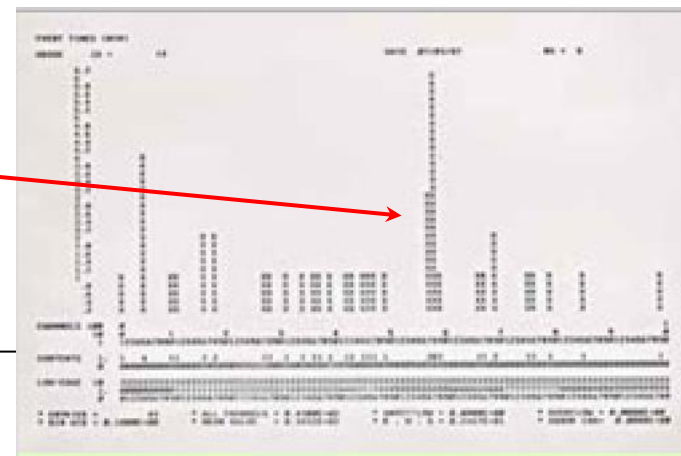
ABSTRACT

A six-second burst of eight neutrino events was recorded by the IMB proton decay detector roughly five hours before the SN1987A Type II supernova in the Large Magellanic Cloud. The events have energies in the range 20–40 MeV and are consistent with being inverse beta decay interactions of anti-electron neutrinos generated in a stellar core collapse preceding the supernova.

1987ESOC 26 2298



UT 23 February 7^h 35^m 41.37^s



Tape# D M YR H:M

2591	17	2	87	18:52	0	0	0	9:35	-2	-2	28	-2	-2	RCS	
2592	18	2	87	6:14	0	0	0	9:19	-2	-2	59	-2	-2	RCS	
2593	18	2	87	17:19	0	0	0	9:04	-2	-2	96	-2	-2	RCS	
2594	19	2	87	4:19	0	0	0	2:58	-2	-2	33	-2	-2	RCS	
2595	19	2	87	16:49	0	0	0	7:05	-2	-2	88	-2	-2	RCS	
2596	20	2	87	3:00	0	0	0	7:05	-2	-2	78	-2	-2	RCS	
2597	20	2	87	13:22	0	0	0	9:36	-2	-2	34	-2	-2	RCS	
2598	21	2	87	0:31	0	0	0	9:35	-2	-2	69	-2	-2	RCS	
2599	21	2	87	21:52	0	0	0	9:25	-2	-2	48	-2	-2	RCS	
2600	22	2	87	9:01	0	0	0	9:25	-2	-2	-2	-2	-2	RCS	
2601	22	2	87	20:11	0	0	4	3:30	-2	-2	-2	-2	-2	RCS	<Supernova SN1987A>BAD HOWIE
2602	0	0	00	0:00	0	0	0	0:00	-2	-2	-2	-2	-2	---	NO SUCH TAPE
2603	23	2	87	11:32	0	0	0	9:19	-2	-2	66	-2	-2	RCS	
2604	23	2	87	22:40	0	0	0	3:42	-2	-2	52	-2	-2	RCS	POWER FAILURE
2605	24	2	87	8:10	0	2	2	0:00	-2	-2	-2	-2	-2	---	CALFXD

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 $e \cdot 10^{-13}$ 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)

The “Neutrino”

1934 Article of Bethe and Peierls

[H. BETHE](#) & [R. PEIERLS](#)

[Nature](#) **133**, 532 (1934) | [Cite this article](#)

5305 Accesses | **97** Citations | **8** Altmetric | [Metrics](#)

Abstract

THE view has recently been put forward¹ that a neutral particle of about electronic mass, and spin $\frac{1}{2}h$ (where $h = h/2$) exists, and that this neutrino is emitted together with an electron in decay. This assumption allows the conservation laws for energy and angular momentum to hold in nuclear physics², Both the emitted electron and neutrino could be described either (*a*) as having existed before in the nucleus or (*b*) as being created at the time of emission. In a recent paper³ Fermi has proposed a model of disintegration using (*b*) which seems to be confirmed by experiment.

The “Neutrino”

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“-one can conclude that there is no practically possible way of observing the neutrino.”

Abstract

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hold in nuclear physics², Both the em as having existed before in the nucleu recent paper³ Fermi has proposed a n confirmed by experiment.

If, therefore, the neutrino has no interaction with other particles besides the processes of creation and annihilation mentioned—and it is not necessary to assume interaction in order to explain the function of the neutrino in nuclear transformations—one can conclude that there is no practically possible way of observing the neutrino.

Physical Laboratory,
University,
Manchester.
Feb. 20.

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

Hanford Nuclear Reactor Complex - 1944



P-338

UNIVERSITY OF CALIFORNIA

Radiation Laboratory

**Alvarez article of 1947
proposes to use the
37-Cl method to find
the neutrino...**

emission of an electron. (According to one theory of β -decay, the distinction between neutrinos and anti-neutrinos could be of importance, since anti-neutrinos would be required to reverse an electron capture process, while a pile emits ordinary neutrinos. Reasons for believing that pile neutrinos will be capable of reversing an electron capture reaction are given in Appendix I.)

UNCLASSIFIED

A PROPOSED EXPERIMENTAL TEST OF THE NEUTRINO THEORY

Luis W. Alvarez

April 18, 1949

UNIVERSITY OF CALIFORNIA

Radiation Laboratory

**Alvarez article of 1947
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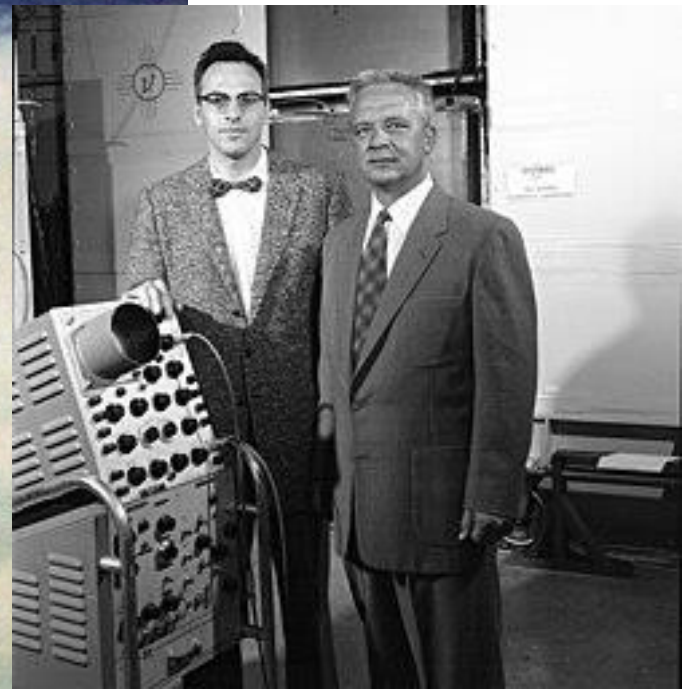
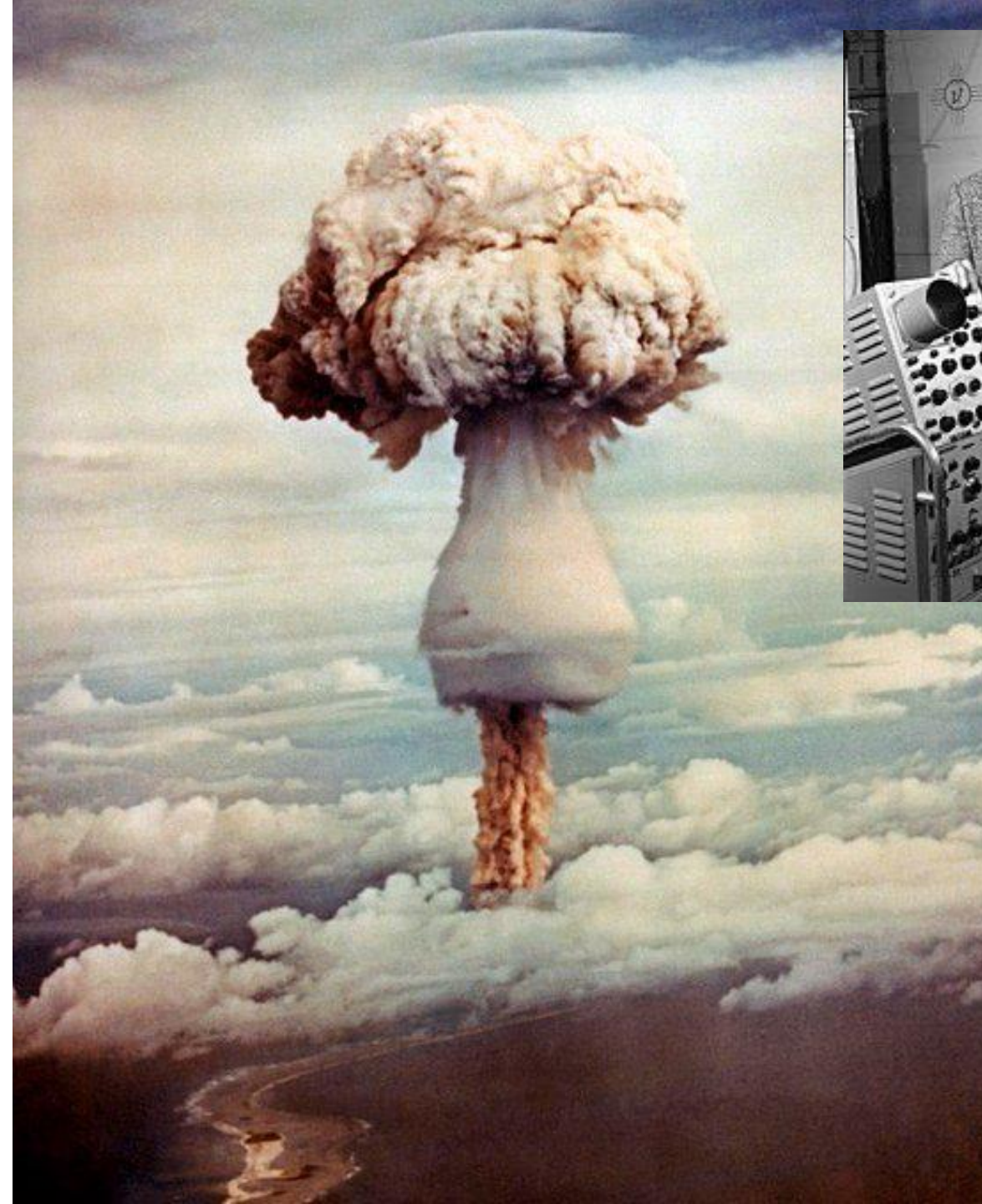
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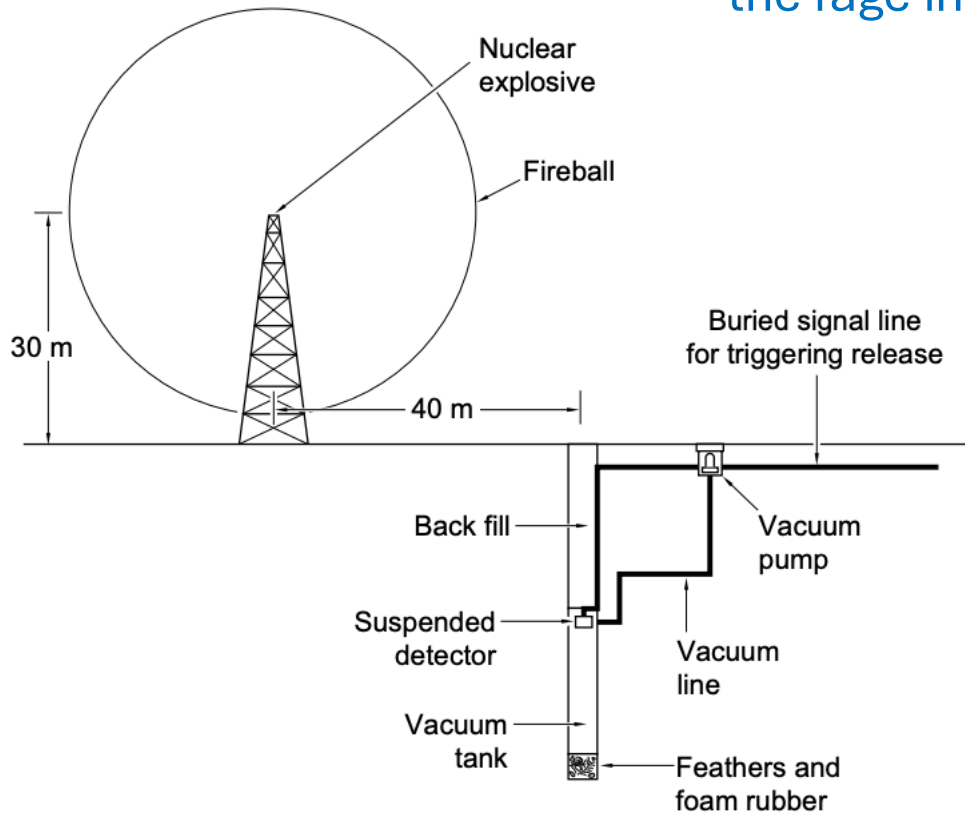
**Proposed a 37-Cl experiment
with a nuclear reactor. Assumes
that neutrino and antineutrino
may not be different in reality (but
also acknowledges that they might be)**



Reine and Cowan
realizes there is
another possible
source of neutrinos

1951

Above ground nuclear testing was all the rage in 1951



“Our crude knowledge of the expected energy spectrum of neutrinos from a fission bomb suggested that the inverse beta decay reaction would occur several times in a several-ton detector located about 50 meters from the tower-based explosion of a 20-kiloton bomb.

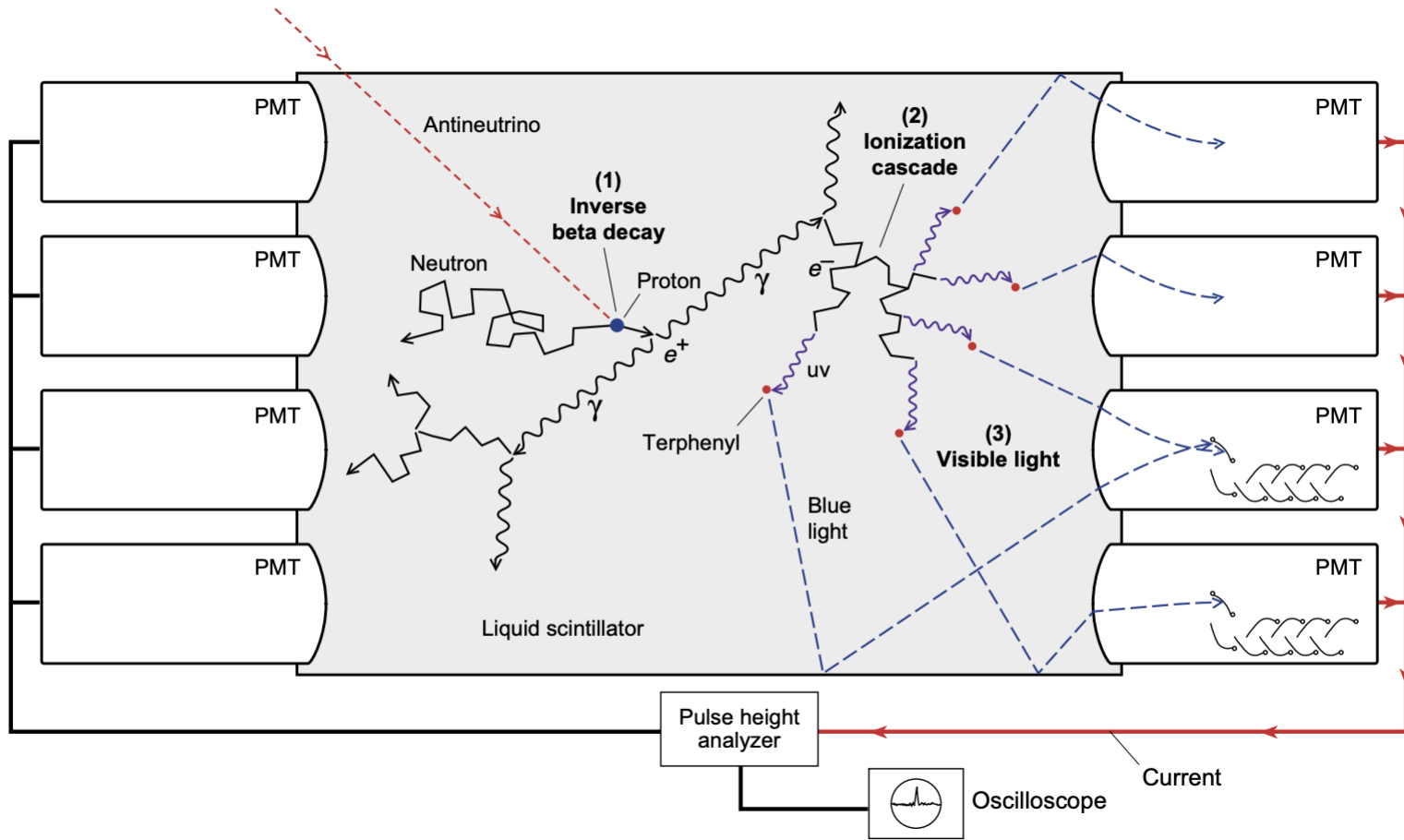
(Anyone untutored in the effects of nuclear explosions would be deterred by the challenge of conducting an experiment so close to the bomb, but we knew otherwise from experience and pressed on). The detector we dreamed up was a giant liquid scintillation device, which we dubbed ‘El Monstro.’ This was a daring extrap-

Figure 1. Detecting Neutrinos from a Nuclear Explosion

(Reines, 1997)

Antineutrinos from the fireball of a nuclear device would impinge on a liquid scintillation detector suspended in the hole dug below ground at a distance of about 40 meters from the 30-meter-high tower. In the original scheme of Reines and Cowan, the antineutrinos would induce inverse beta decay, and the detector would record the positrons produced in that process. This figure was redrawn courtesy of Smithsonian

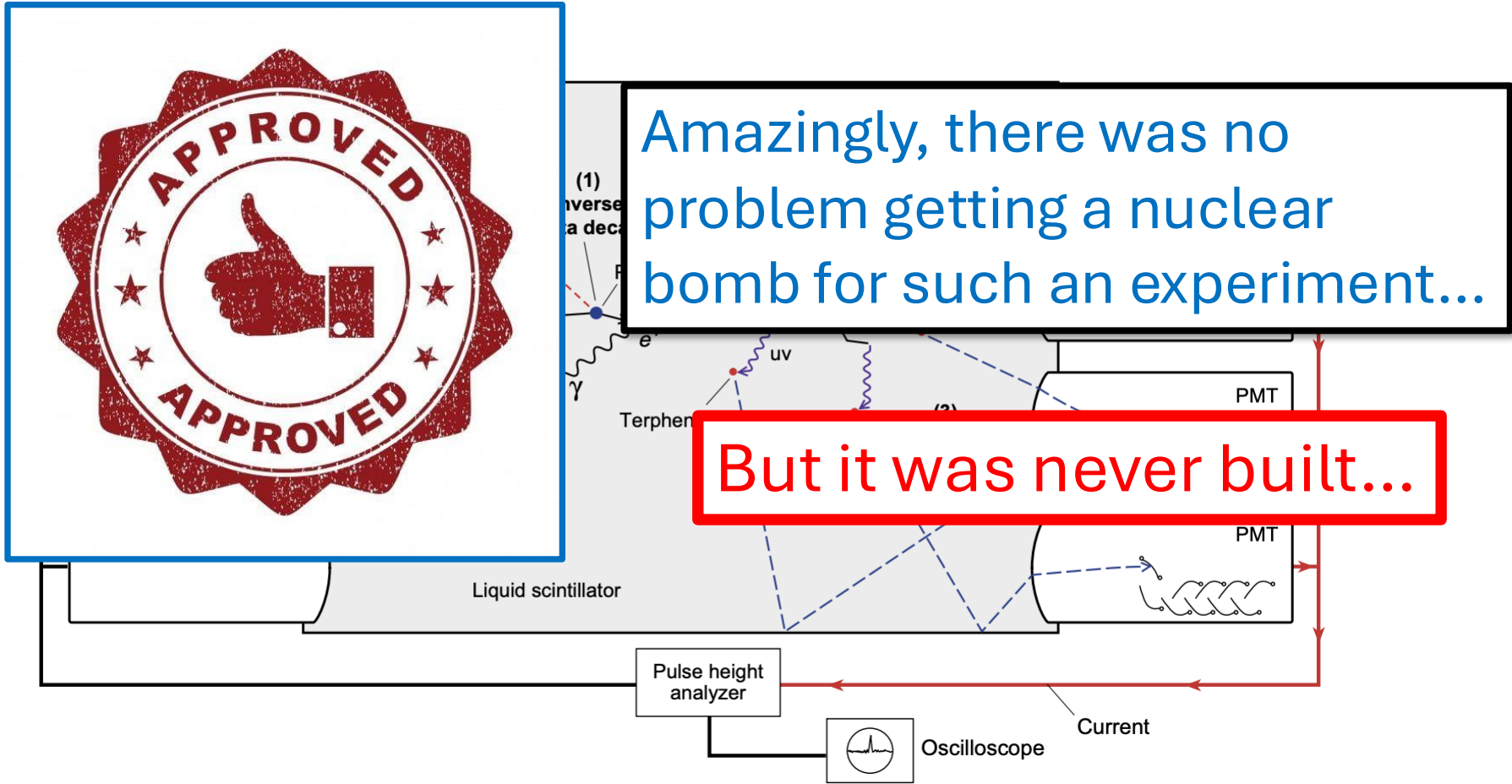
El Monstro (1951)



Proposed ~ 1 ton neutrino detector with LS and eight PMTs.
The “run” would last 2 seconds.

Liquid scintillator made from toluene + terphenyl fluor

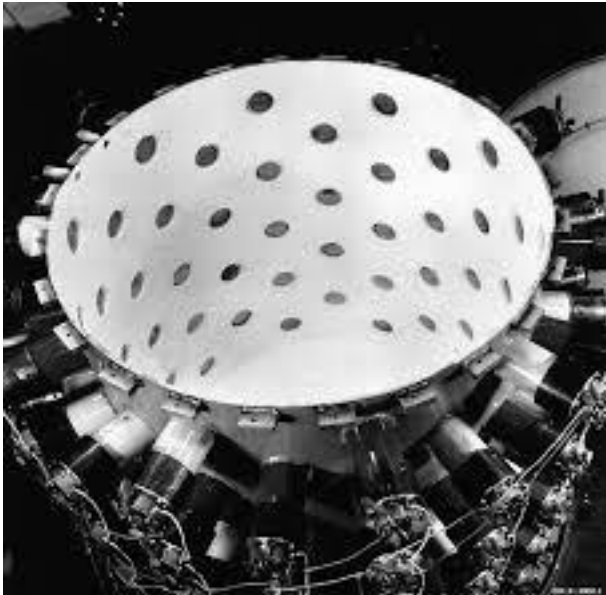
El Monstro (1951)



Proposed ~1 ton neutrino detector with LS and eight PMTs.
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Hanford Detector (1953)



- 300 L of LS doped with cadmium (9 MeV of capture γ s)
- Two arrays of 45 2-in. PMTs and a **coincidence circuit** for positron and neutron like pulses.
- One bank also measured pulse height of positron signal
- **18-channel 9 μ s delay time analyzer electronics**

4 days of Hanford 250 MW reactor produce as many neutrinos as a 20 kT nuclear bomb - but have to deal with **BACKGROUNDS**

We built a cylindrical well into one of the detectors and proceeded to put quantities of steel, liquids, wax, and other materials into it for testing. We found that brass and aluminum were quite radioactive compared to iron and steel, and that the potassium in the glass envelopes of our photomultiplier tubes would contribute to the detector backgrounds

C. Cowan (1964)

They worried about internal backgrounds from detector materials and instituted large scale screening



Reactor backgrounds required extensive lead and borated wax shielding

An active veto and passive water shield were also later added on top to shield cosmic rays

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 experiment¹ 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,



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

TABLE I. Listing of data.

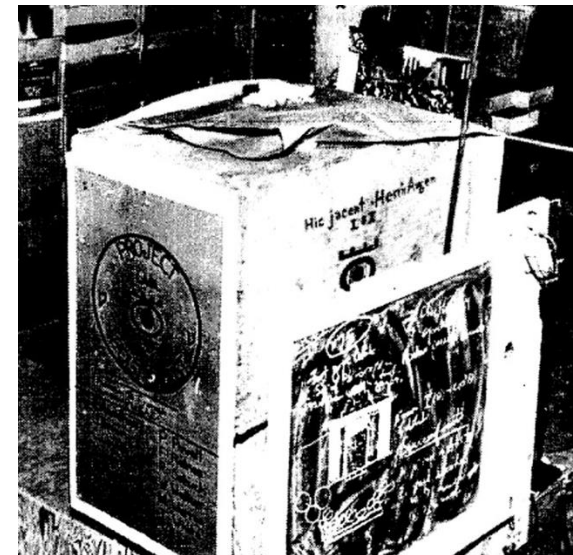
Run	Pile status	Length of run (seconds)	Net delayed pair rate counts/min	Accidental background rate counts/min
1	up	4000	2.56	0.84
2	up	2000	2.46	3.54
3	up	4000	2.58	3.11
4	down	3000	2.20	0.45
5	down	2000	2.02	0.15
6	down	1000	2.19	0.13

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)



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TEXTSTUDIO

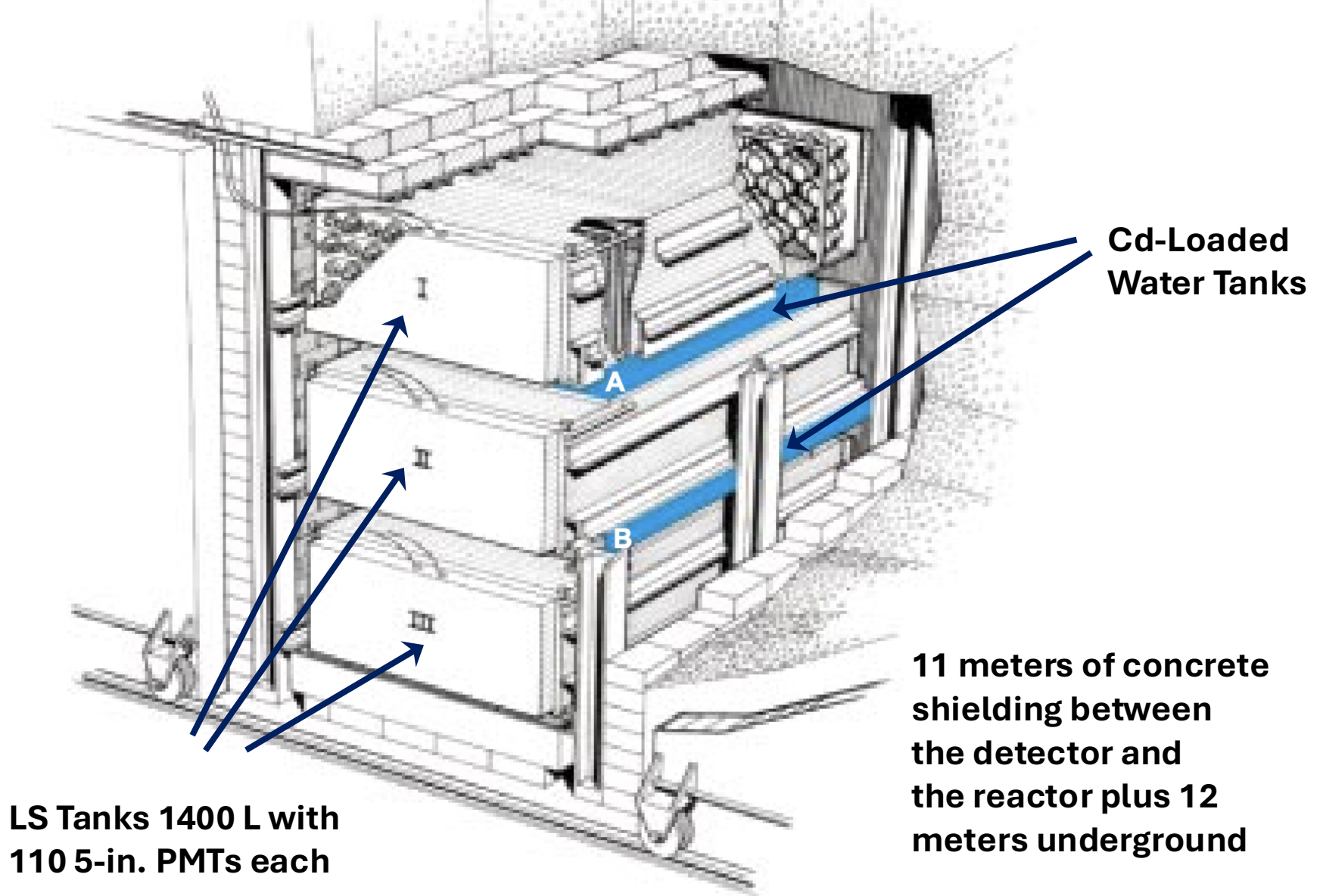
What's Needed?

- Better Shielding
- Better Electronics
- More powerful reactor
- Longer run time

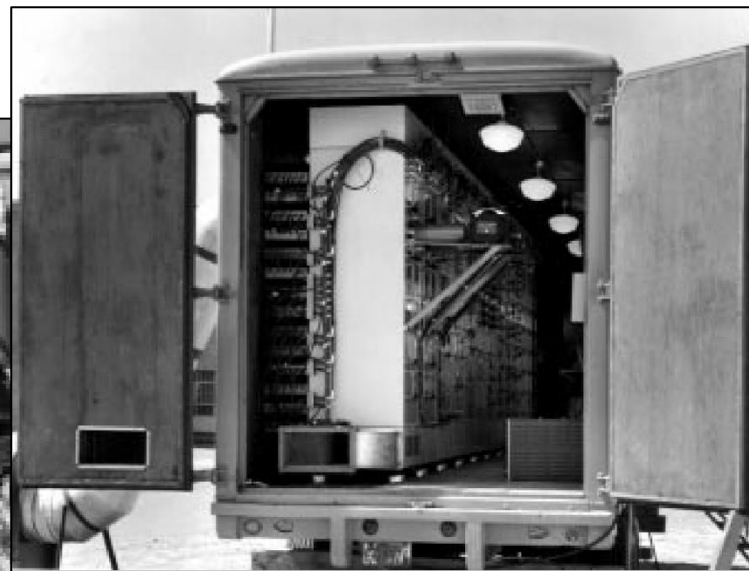
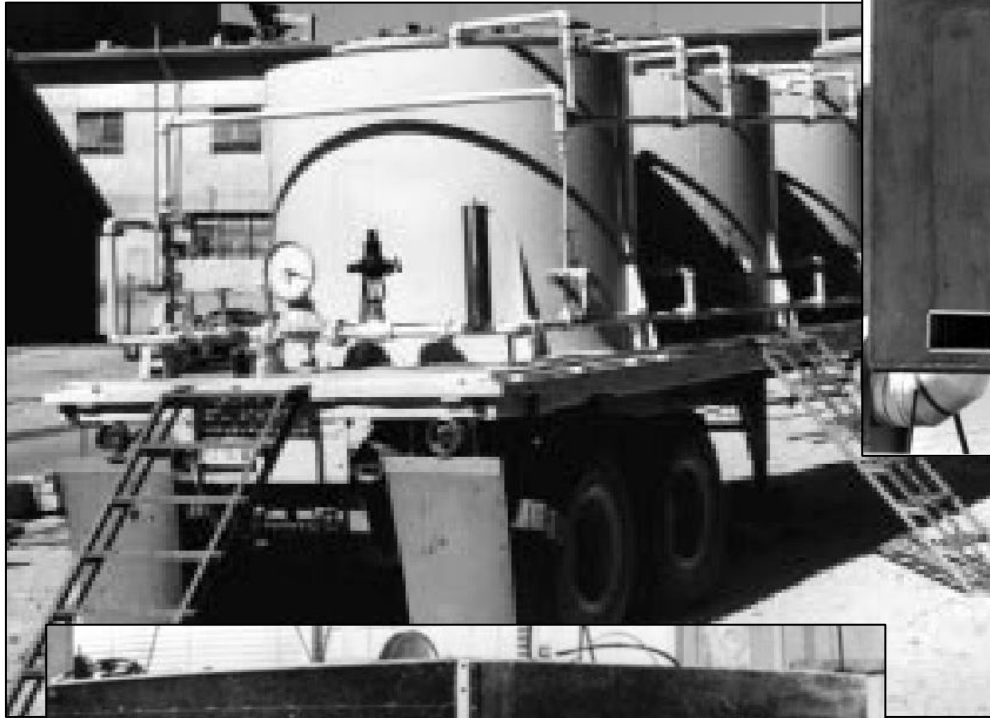


Savannah River P-Reactor **2250 MW** by 1956

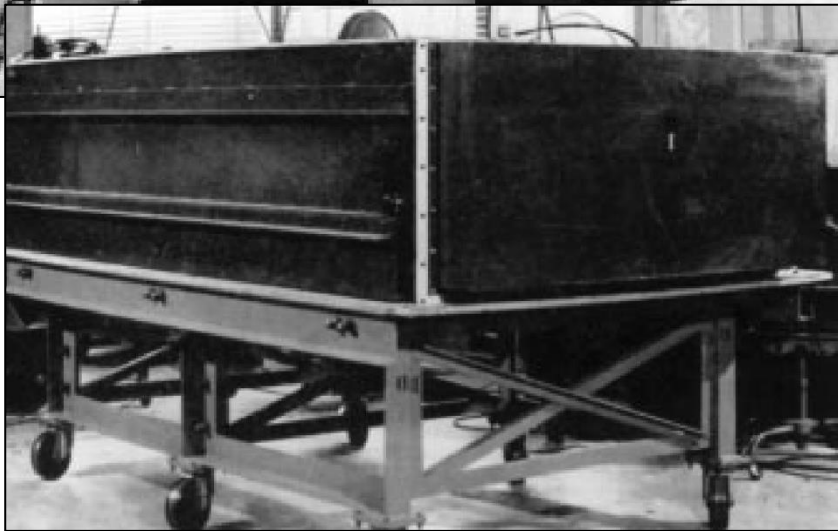
Savannah River Detector: 1956



LS mixing plant



Electronics truck

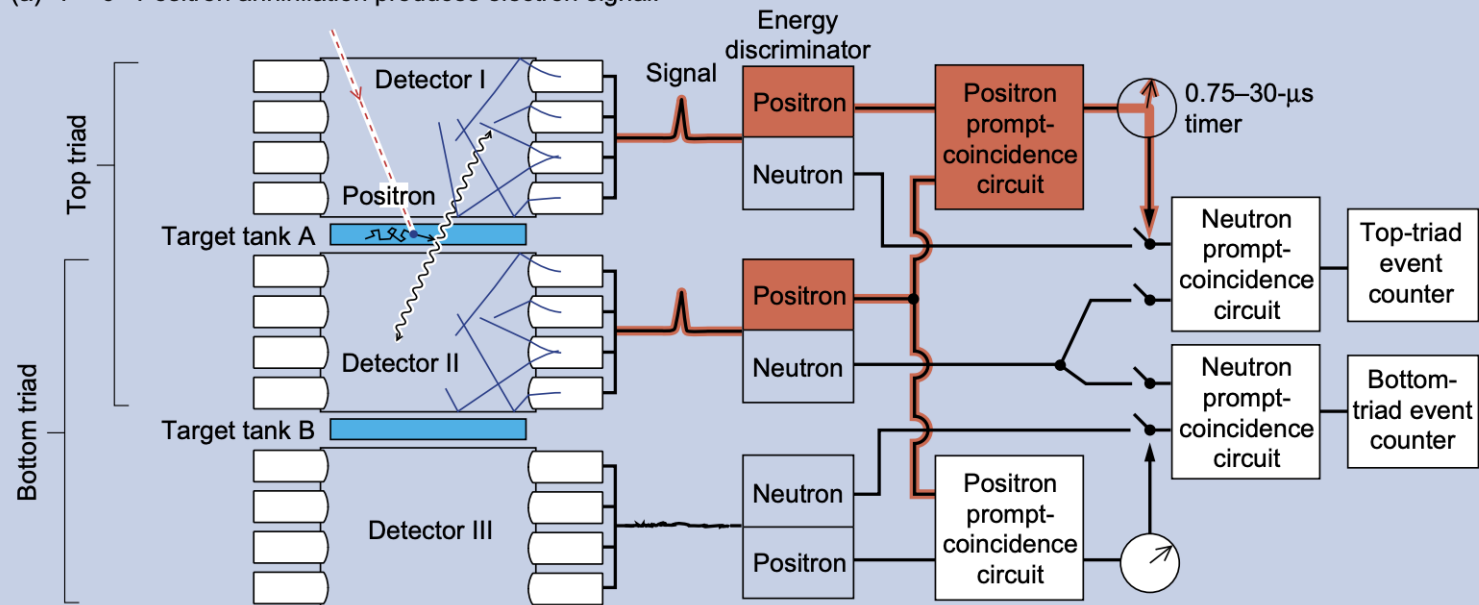


Cadmium-loaded water tank

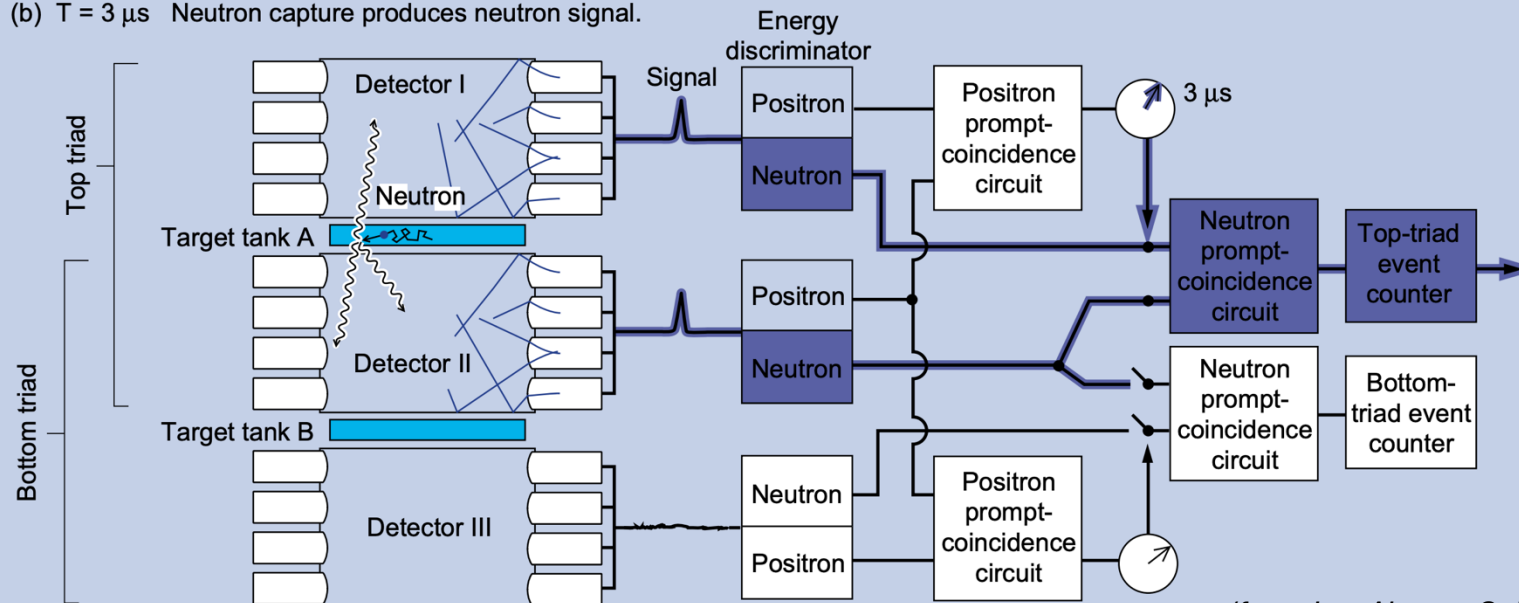


Wet sawdust shielding

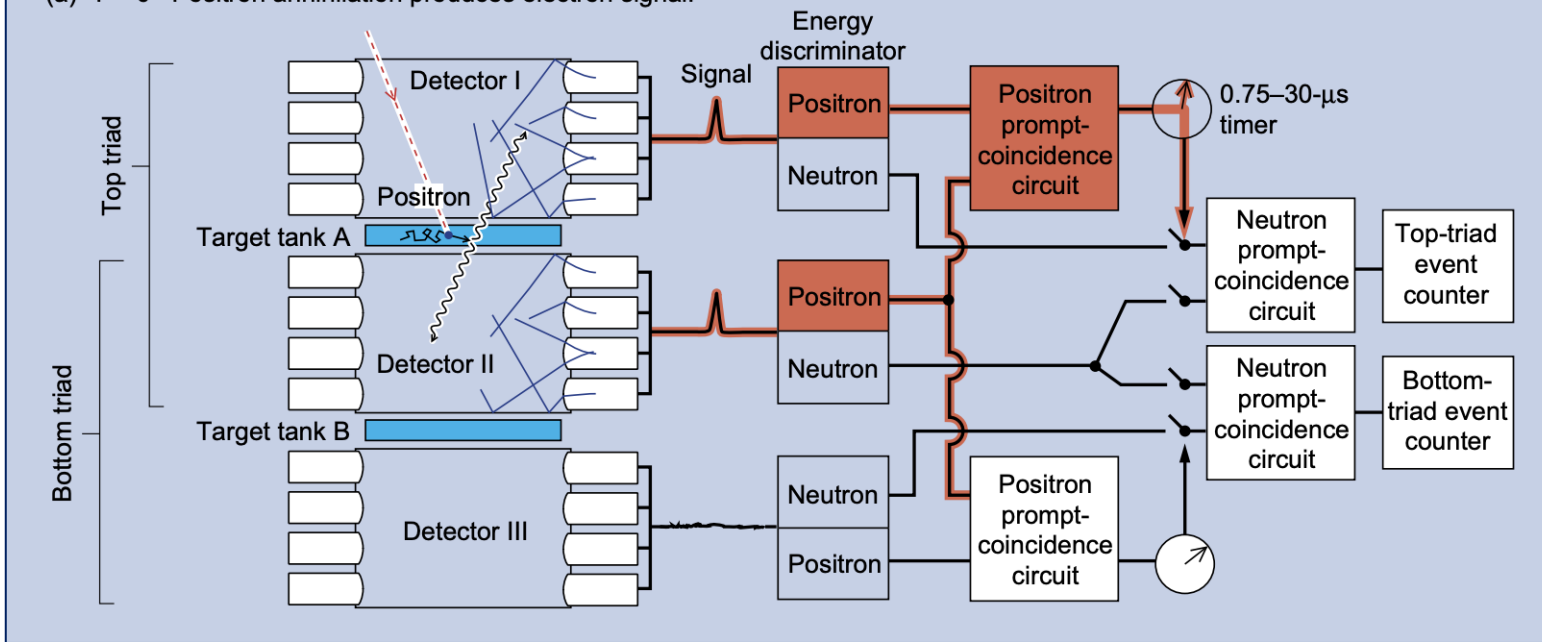
(a) $T = 0$ Positron annihilation produces electron signal.



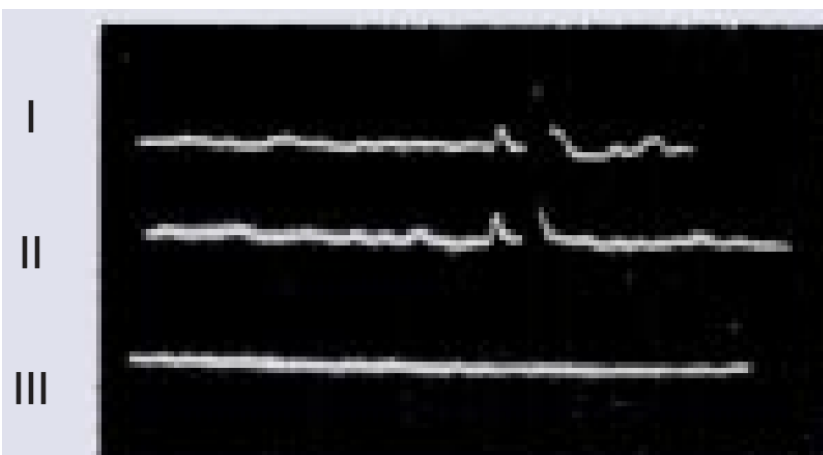
(b) $T = 3 \mu\text{s}$ Neutron capture produces neutron signal.



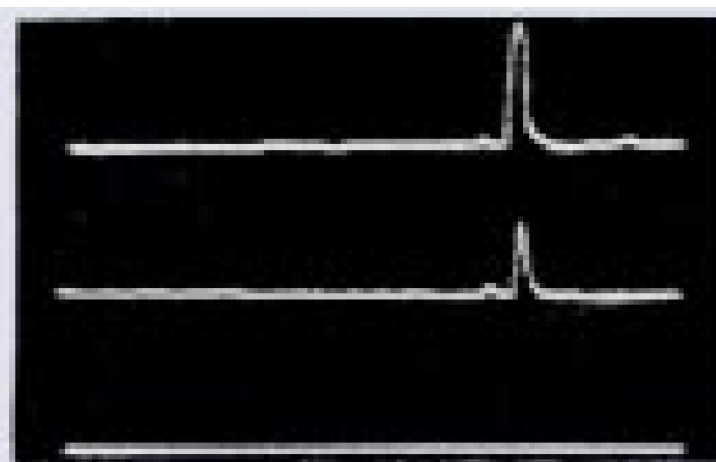
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A Neutrino Candidate!

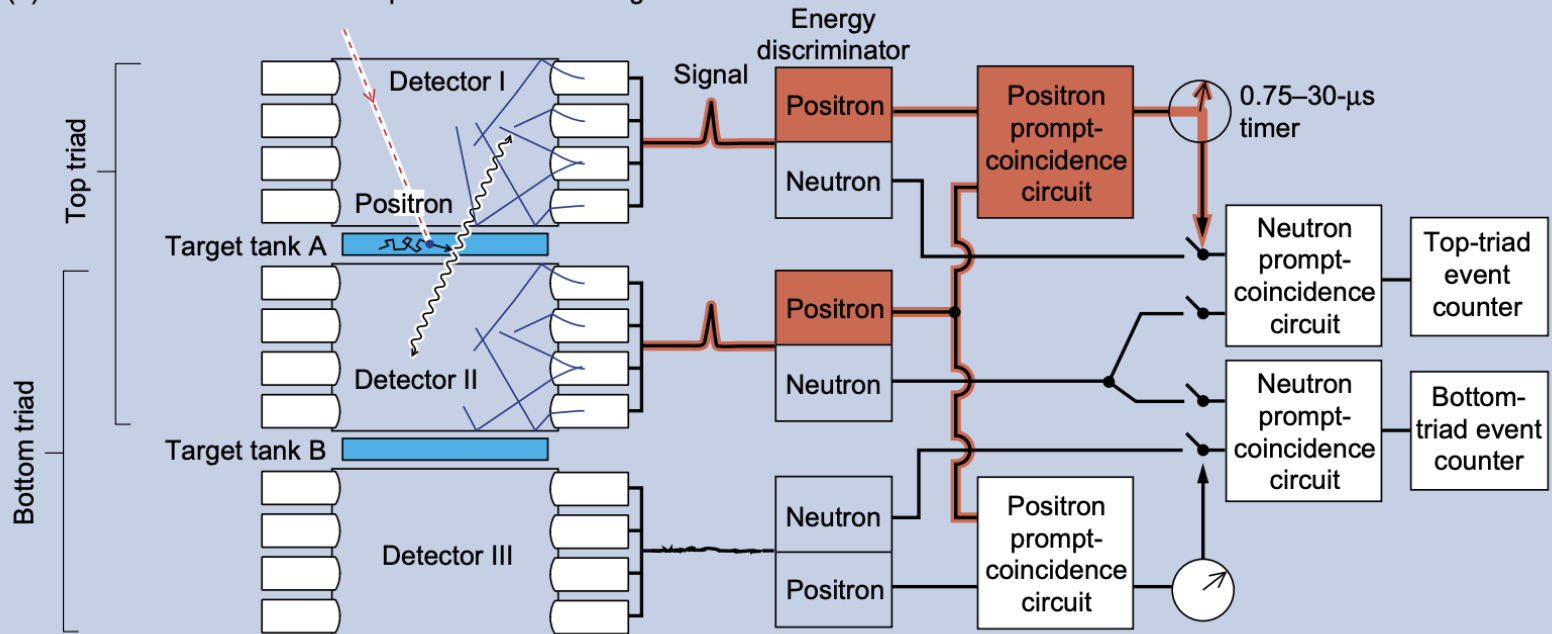


(a) Positron scope

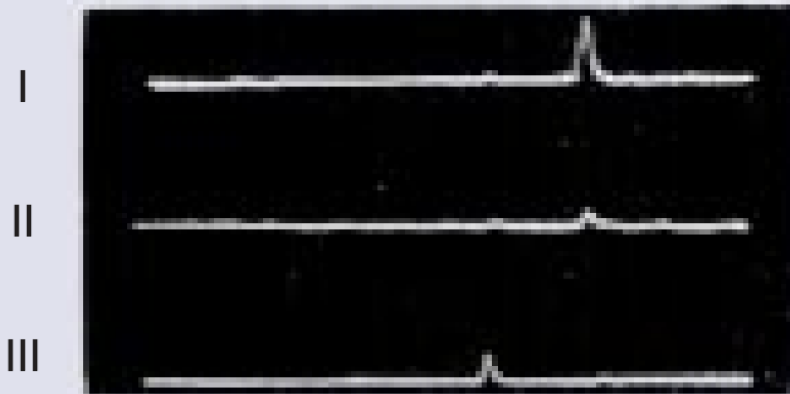


Neutron scope

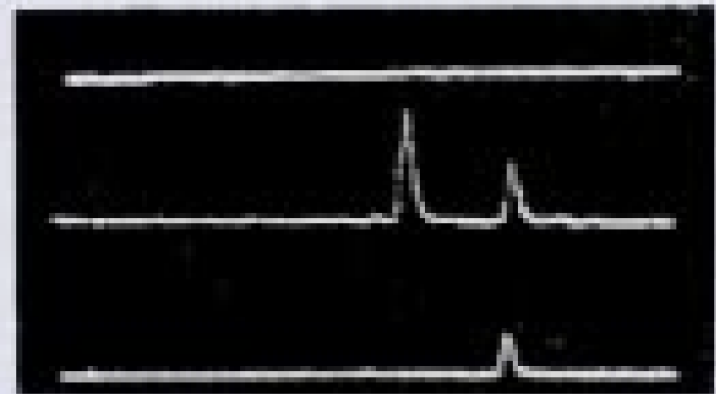
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Background...



(e) Positron scope



(f) Neutron scope

THE NEUTRINO

By DR. FREDERICK REINES and DR. CLYDE L. COWAN, jun.
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico

Savannah Team 1955



The Hanford Team: (on facing page, left to right, back row) F. Newton Hayes, Captain W. A. Walker, T. J. White, Fred Reines, E. C. Anderson, Clyde Cowan, Jr., and Robert Schuch (Inset); not all team members are pictured.

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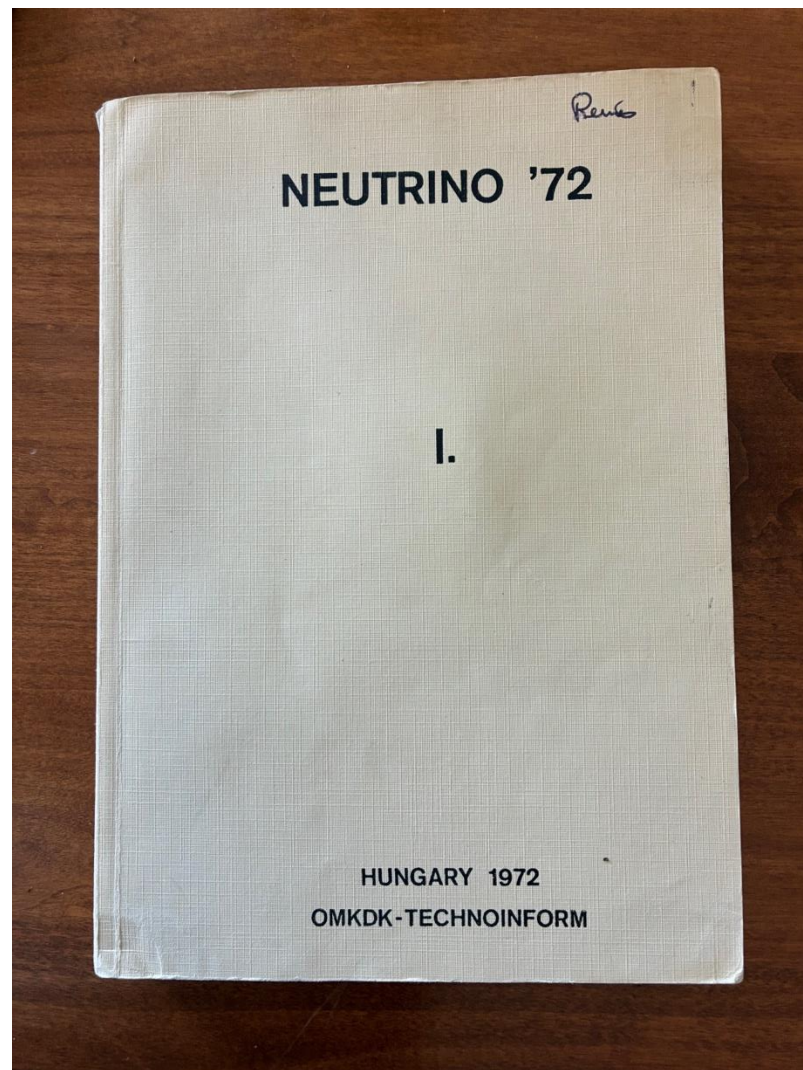
(1) A signal dependent upon reactor-power, 2.88 ± 0.22 counts/hr. in agreement with the predicted²⁰ cross-section (6×10^{-44} cm.²), was measured with a signal-to-reactor associated accidental background in excess of 20/1. The signal-to-reactor independent background ratio was 3/1.



...and it worked!

VOLUME I	page
Neutrino'72 /OPENING ADDRESS/ <i>G. Marx</i>	1
Report on the Brookhaven Solar Neutrino Experiment <i>R. Davis Jr., J.C. Evans, V. Radeka and L.C. Rogers</i>	5
Are the solar neutrino-experiments suggestive of the existence of a resonance in the $He^3 + He^3$ system? /discussion remark/ <i>V.N. Fetisov and Y.S. Kopysov</i>	23
Solar neutrinos: Theory <i>J.N. Bahcall</i>	29
The background effects in solar neutrino experiments <i>R. Davis, A.W. Wolfendale and E.C.M. Young</i>	77
The investigation of the background in the solar neutrino proportional counters /discussion remark/ <i>I.R. Barabanov and A.A. Pomansky</i>	85
New approaches to the solar neutrino puzzle <i>K. Lande, G. Bozóki, C.L. Lee and E. Fenyves</i>	87
Double beta decay <i>E. Fiorini</i>	99
Note on University of California, Irvine double-beta-decay experiment <i>M. Moe, D. Lowenthal and F. Reines</i>	121
Lepton charge conservation <i>G. Marx</i>	123
Note on electron stability and the Pauli principle /discussion remark/ <i>F. Reines and H.W. Sobel</i>	135
Remark on stability of $\bar{\nu}_e$ /discussion remark/ <i>F. Reines</i>	137
Neutrino excitation of nuclear levels in ^{12}C <i>H. Uberall, B.A. Lamers, J.B. Langworthy and F.J. Kelly</i>	139
Antineutrino-electron scattering <i>H.S. Gurr, F. Reines and H.W. Sobel</i>	147
The Lepton era of the Big Bang <i>T. de Graaf</i>	167
Cosmological limit on neutretto mass /discussion remark/ <i>G. Marx and A.S. Szalay</i>	191
Field-particle aspects of the cosmological neutrino problem /discussion remark/ <i>B. Kuchowicz</i>	197
Review of the experimental situation on neutral currents <i>C. Baltay</i>	199
Discussion	227

While looking around in my books I realized I borrowed this but forgot to return it...



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Antineutrino-electron scattering <i>H.S. Gurr, F. Reines and H.W. Sobel</i>	147
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Cosmological limit on neutretto mass /discussion remark/ <i>G. Marx and A.S. Szalay</i>	191
Field-particle aspects of the cosmological neutrino problem /discussion remark/ <i>B. Kuchowicz</i>	197
Review of the experimental situation on neutral currents <i>C. Baltay</i>	199
Discussion	227

Ray Davis reports initial results from his new Cl-37 solar neutrino experiment in Homestake Mine

He measured 0.18 ± 0.10 cnt/day, consistent with background, setting an upper limit on the solar neutrino flux of 1 SNU^* well below the 9 SNU predicted by theory.

* $1 \text{ SNU} = 10^{-36}$ neutrino captures per target nucleus

Neutrino'72 /OPENING ADDRESS/ <i>G.Marr</i>	1
Report on the Brookhaven Solar Neutrino Experiment <i>R.Davis Jr., J.C.Evans, V.Radeka and L.C.Rogers</i>	5
Are the solar neutrino-experiments suggestive of the existence of a resonance in the $\text{He}^3 + \text{He}^3$ system? /discussion remark/ <i>V.N.Batistov and V.S.Kopysov</i>	23
Solar neutrinos: Theory <i>J.N.Bahcall</i>	29
The background effects in solar neutrino experiments <i>R.Davis, A.W.Wolfendale and E.C.M.Young</i>	77
The investigation of the background in the solar neutrino proportional counters /discussion remark/ <i>I.R.Barabanov and A.A.Pomansky</i>	85
New approaches to the solar neutrino puzzle <i>K.Lande, G.Bozóki, C.L.Lee and E.Fenyves</i>	87
Double beta decay <i>E.Fiorini</i>	99
Note on University of California, Irvine double-beta-decay experiment <i>M.Moe, D.Lowenthal and F.Reines</i>	121
Lepton charge conservation <i>G.Marr</i>	123
Note on electron stability and the Pauli principle /discussion remark/ <i>F.Reines and H.W.Sobel</i>	135
Remark on stability of $\bar{\nu}_e$ /discussion remark/ <i>F.Reines</i>	137
Neutrino excitation of nuclear levels in ^{12}C <i>H.Uberall, B.A.Lamers, J.B.Langworthy and F.J.Kelly</i>	139
Antineutrino-electron scattering <i>H.S.Gurr, F.Reines and H.W.Sobel</i>	147
The Lepton era of the Big Bang <i>T. de Graaf</i>	167
Cosmological limit on neutretto mass /discussion remark/ <i>G.Marr and A.S.Szalay</i>	191
Field-particle aspects of the cosmological neutrino problem /discussion remark/ <i>B.Kuchowicz</i>	197
Review of the experimental situation on neutral currents <i>C.Baltay</i>	199
Discussion	227

Ray Davis reports initial results from his new Cl-37 solar neutrino experiment in Homestake Mine

He measured 0.18 ± 0.10 cnt/day, consistent with background, setting an upper limit on the solar neutrino flux of 1 SNU^* well below the 9 SNU predicted by theory (Bahcall et al.).

John Bahcall updates his calculation using new LANL nuclear opacity data. Now predicts 6 SNU

* $1 \text{ SNU} = 10^{-36}$ neutrino captures per target nucleus

VOLUME I	page
Neutrino'72 /OPENING ADDRESS/ <i>G. Marx</i>	1
Report on the Brookhaven Solar Neutrino Experiment <i>R. Davis Jr., J.C. Evans, V. Radeka and L.C. Rogers</i>	5
Are the solar neutrino-experiments suggestive of the existence of a resonance in the $\text{He}^3 + \text{He}^3$ system? /discussion remark/ <i>V.N. Fetisov and Y.S. Kopysov</i>	23
Solar neutrinos: Theory <i>J.N. Bahcall</i>	29
The background effects in solar neutrino experiments <i>R. Davis, A.W. Wolfendale and E.C.M. Young</i>	77
The investigation of the background in the solar neutrino proportional counters /discussion remark/ <i>I.F. Barabanov and A.A. Pomansky</i>	85
New approaches to the solar neutrino puzzle <i>K. Lande, G. Bozoki, C.L. Lee and E. Fenyes</i>	87
Double beta decay <i>E. Fiorini</i>	99
Note on University of California, Irvine double-beta-decay experiment <i>M. Moe, D. Lowenthal and F. Reines</i>	121
Lepton charge conservation <i>G. Marx</i>	123
Note on electron stability and the Pauli principle /discussion remark/ <i>F. Reines and H.W. Sobel</i>	135
Remark on stability of $\bar{\nu}_e$ /discussion remark/ <i>F. Reines</i>	137
Neutrino excitation of nuclear levels in ^{12}C <i>H. Uberall, B.A. Lamers, J.B. Langworthy and F.J. Kelly</i>	139
Antineutrino-electron scattering <i>H.S. Gurr, F. Reines and H.W. Sobel</i>	147
The Lepton era of the Big Bang <i>T. de Graaf</i>	167
Cosmological limit on neutretto mass /discussion remark/ <i>G. Marx and A.S. Szalay</i>	191
Field-particle aspects of the cosmological neutrino problem /discussion remark/ <i>B. Kuchowicz</i>	197
Review of the experimental situation on neutral currents <i>C. Baltay</i>	199
Discussion	227

Mike Moe (from UCI) sets an upper limit on double beta decay for Ge-76 of 2.8×10^{21} years

(Note: very close to the $2.022 \pm 0.018(\text{stat}) \pm 0.038(\text{sys})$ measured by GERDA*)

* Phys. Rev. Lett. **131**, 142501 (2023)

VOLUME I	page
Neutrino'72 /OPENING ADDRESS/ <i>G. Marx</i>	1
Report on the Brookhaven Solar Neutrino Experiment <i>R. Davis Jr., J.C. Evans, V. Radeka and L.C. Rogers</i>	5
Are the solar neutrino-experiments suggestive of the existence of a resonance in the $\text{He}^3 + \text{He}^3$ system? /discussion remark/ <i>V.N. Fatisov and Y.S. Kopysov</i>	23
Solar neutrinos: Theory <i>J.N. Bahcall</i>	29
The background effects in solar neutrino experiments <i>R. Davis, A.W. Wolfendale and E.C.M. Young</i>	77
The investigation of the background in the solar neutrino proportional counters /discussion remark/ <i>I.F. Barabanov and A.A. Pomansky</i>	85
New approaches to the solar neutrino puzzle <i>K. Lande, G. Bozoki, C.L. Lee and E. Fenyeves</i>	87
Double beta decay <i>E. Fiorini</i>	99
Note on University of California, Irvine double-beta-decay experiment <i>M. Moe, D. Lowenthal and F. Reines</i>	121
Lepton charge conservation <i>G. Marx</i>	123
Note on electron stability and the Pauli principle /discussion remark/ <i>F. Reines and H.W. Sobel</i>	135
Remark on stability of $\bar{\nu}_e$ /discussion remark/ <i>F. Reines</i>	137
Neutrino excitation of nuclear levels in ^{12}C <i>H. Uberall, B.A. Lamers, J.B. Langworthy and F.J. Kelly</i>	139
Antineutrino-electron scattering <i>H.S. Gurr, F. Reines and H.W. Sobel</i>	147
The Lepton era of the Big Bang <i>T. de Graaf</i>	167
Cosmological limit on neutretto mass /discussion remark/ <i>G. Marx and A.S. Szalay</i>	191
Field-particle aspects of the cosmological neutrino problem /discussion remark/ <i>B. Kuchowicz</i>	197
Review of the experimental situation on neutral currents <i>C. Baltay</i>	199
Discussion	227

Fred Reines and Hank Sobel set a limit on the electron antineutrino decay length of 10^5 AU, ruling this out as a cause of the solar neutrino problem.

Neutrino'72 /OPENING ADDRESS/ <i>G. Marx</i>	1
Report on the Brookhaven Solar Neutrino Experiment <i>R. Davis Jr., J.C. Evans, V. Radeka and L.C. Rogers</i>	5
Are the solar neutrino-experiments suggestive of the existence of a resonance in the $\text{He}^3 + \text{He}^3$ system? /discussion remark/ <i>V.N. Fatisov and Y.S. Kopysov</i>	23
Solar neutrinos: Theory <i>J.N. Bahcall</i>	29
The background effects in solar neutrino experiments <i>R. Davis, A.W. Wolfendale and E.C.M. Young</i>	77
The investigation of the background in the solar neutrino proportional counters /discussion remark/ <i>I.F. Barabanov and A.A. Pomansky</i>	85
New approaches to the solar neutrino puzzle <i>K. Lande, G. Bozóki, C.L. Lee and E. Fenyves</i>	87
Double beta decay <i>E. Fiorini</i>	99
Note on University of California, Irvine double-beta-decay experiment <i>M. Moe, D. Lowenthal and F. Reines</i>	121
Lepton charge conservation <i>G. Marx</i>	123
Note on electron stability and the Pauli principle /discussion remark/ <i>F. Reines and H.W. Sobel</i>	135
Remark on stability of $\bar{\nu}_e$ /discussion remark/ <i>F. Reines</i>	137
Neutrino excitation of nuclear levels in ^{12}C <i>H. Uberall, B.A. Lamers, J.B. Lanaworthu and E.J. Kelly</i>	139
Antineutrino-electron scattering <i>H.S. Gurr, F. Reines and H.W. Sobel</i>	147
The Lepton Era of the Big Bang <i>T. de Graaf</i>	167
Cosmological limit on neutretto mass /discussion remark/ <i>G. Marx and A.S. Szalay</i>	191
Field-particle aspects of the cosmological neutrino problem /discussion remark/ <i>B. Kuchowicz</i>	197
Review of the experimental situation on neutral currents <i>C. Baltay</i>	199
Discussion	227

They also set a limit on the Weinberg Angle using reactor antineutrino-electron scattering



DEPARTMENT OF PHYSICS

IRVINE, CALIFORNIA 92717

August 24, 1989
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 Tel: (714) 856-7036

Dr. Taiji Yamanouchi
 Director's Office
 Fermilab
 P.O. Box 500,
 Mail Station 105
 Batavia, IL 60510

Dear Dr. Yamanouchi:

Enclosed is a letter of intent for: "A long baseline oscillation experiment using the high intensity neutrino beam from the Fermilab main injector and the IMB water cerenkov detector."

The contact person for this experiment is:

Wojciech Gajewski
 Physics Department
 University of California, Irvine
 Irvine, CA 92717
 Bitnet: WGAJEWSK@UCIVMSA
 Tel: (714) 856-6403

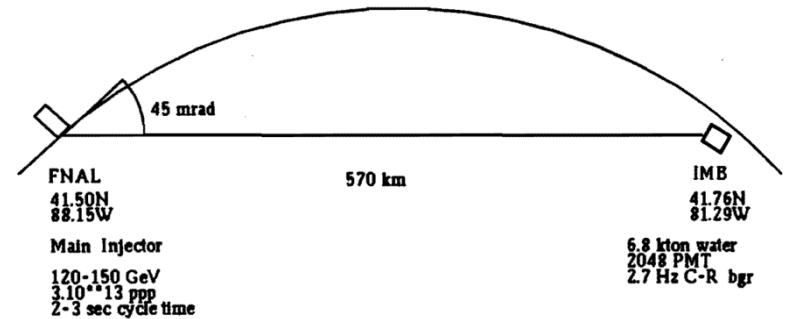
Sincerely,

Frederick Reines
 Spokesman for IMB Collaboration

FR:deo

**Last proposal from Fred was to
 Fermilab to build a long-baseline
 neutrino experiment in 1989**

805



THE LETTER OF INTENT FOR A LONG BASELINE OSCILLATION EXPERIMENT USING THE HIGH INTENSITY NEUTRINO BEAM FROM THE FERMILAB MAIN INJECTOR AND THE IMB WATER CERENKOV DETECTOR.

R. Becker-Szendy, C.B. Bratton, R. Cady, D. Casper, S.T. Dye, W. Gajewski, M. Goldhaber, T.J. Haines, P. Halverson, T.W. Jones, D. Kielczewska, W.R. Kropp, J. Learned, J.M. LoSecco, S. Matsuno, C. McGrew, L. R. Price, F. Reines, J. Schultz, H.W. Sobel, L.R. Sulak, R. Svoboda, F. Wittel.

The University of California, Irvine
 Boston University
 Brookhaven National Laboratory
 Louisiana State University
 Cleveland State University
 The University of Hawaii, Manoa
 University College, London
 Warsaw University
 The University of Notre Dame
 The University of Maryland

ABSTRACT

We propose to study muon neutrino oscillations by detecting neutrinos produced by the Fermilab Main Injector in the IMB detector, some 581 km distant. Interactions span the energy range 1-50 GeV. We are able to detect muon neutrino disappearance of more than a few percent down to a mass range of $\delta m^2 \sim 10^{-3} \text{ (eV)}^2$, a

Near Future*

- Definitive measurement of the neutrino mass ordering
- CP violation search/discovery
- More sensitive neutrinoless double beta decay searches - discovery?
- More UHE neutrinos detected?
- Diffuse SN Background (DSNB) neutrinos?

* “It’s tough to make predictions, especially about the future” - Y.Berra

The Future Future*

- Definitive measurement of the DSNB that would be able to get information on the fraction of SN that collapse to black holes
- New and larger neutrino telescopes yield more clues as to the origin of UHE neutrinos
- A galactic SN will happen, and the results will not be exactly what we expected
- A Neutrinoless Double beta Decay experiment will be built that can explore well below the inverted ordering band.
- Precision measurements of oscillation parameters by the new generation of experiments yield clues as to the origin of families.

* “It’s tough to make predictions, especially about the future future” - R.Svoboda

VOLUME I

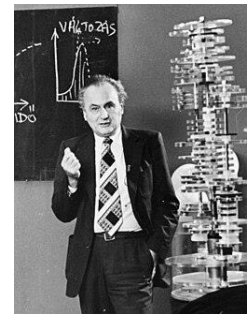
	page
Neutrino '72 /OPENING ADDRESS/ <i>G. Marx</i>	1
Report on the Brookhaven Solar Neutrino Experiment <i>R. Davis Jr., J.C. Evans, V. Radeka and L.C. Rogers</i>	5
Are the solar neutrino-experiments suggestive of the existence of a resonance in the $\text{He}^3 + \text{He}^3$ system? /discussion remark/ <i>V.N. Fatisov and Y.S. Kopysov</i>	23
Solar neutrinos: Theory <i>J.N. Bahcall</i>	29
The background effects in solar neutrino experiments <i>R. Davis, A.W. Wolfendale and E.C.M. Young</i>	77
The investigation of the background in the solar neutrino proportional counters /discussion remark/ <i>I.R. Barabanov and A.A. Pomansky</i>	85
New approaches to the solar neutrino puzzle <i>K. Lande, G. Bozoki, C.L. Lee and E. Fenyeves</i>	87
Double beta decay <i>E. Fiorini</i>	99
Note on University of California, Irvine double-beta-decay experiment <i>M. Moe, D. Lowenthal and F. Reines</i>	121
Lepton charge conservation <i>G. Marx</i>	123
Note on electron stability and the Pauli principle /discussion remark/ <i>F. Reines and H.W. Sobel</i>	135
Remark on stability of $\bar{\nu}_e$ /discussion remark/ <i>F. Reines</i>	137
Neutrino excitation of nuclear levels in ^{12}C <i>H. Uberall, B.A. Lamers, J.B. Langworthy and F.J. Kelly</i>	139
Antineutrino-electron scattering <i>H.S. Gurr, F. Reines and H.W. Sobel</i>	147
The Lepton era of the Big Bang <i>T. de Graaf</i>	167
Cosmological limit on neutretto mass /discussion remark/ <i>G. Marx and A.S. Szalay</i>	191
Field-particle aspects of the cosmological neutrino problem /discussion remark/ <i>B. Kuchowicz</i>	191
Review of the experimental situation on neutral currents <i>C. Baltay</i>	197
Discussion	199
	227

“We may now celebrate the 40th anniversary of the discovery of the neutrino.”

“Doing fundamental research is a hard job in our age. For tremendous efforts Nature pays only with very faint and very provisional results.”

“We have these tricky problems because we asked Nature in the sophisticated language offered by the modern experimental technique.... **There are good hopes that the tiny neutrinos may show the way to the pioneers in these virgin lands.**”

G. Marx



Enjoy the Meeting!



Enjoy the Meeting!



FNAL-IMB exclusion region

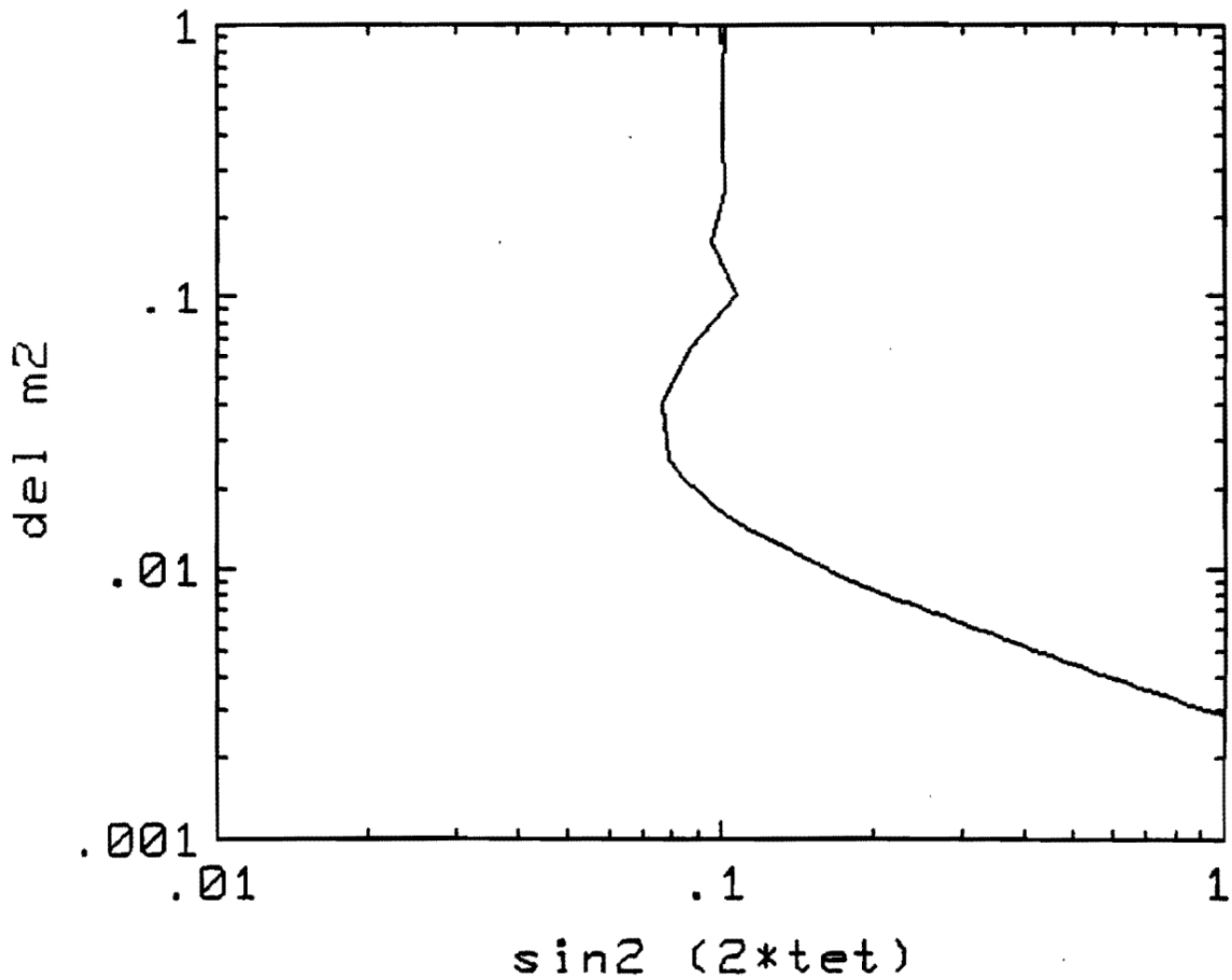


Fig. 10. $\theta_{12} = 33^\circ$, $\delta = 200^\circ$, $\delta m_{21}^2 = 2.5 \times 10^{-5} \text{ eV}^2$, $\delta m_{31}^2 = 2.5 \times 10^{-3} \text{ eV}^2$.