ECT Lecture 2

- Reactor Antineutrino Detection
- The Discovery of Neutrinos

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Discovering Neutrinos from Nuclear Explosion

- **Inverse Beta-decay Cross Section**
  - $\sigma_{IBD} < 10^{-37}$ cm^2 (H.R. Crane, 1948)
  - Theoretical prediction: $\sigma IBD = 10^{-44}$ cm^2
  - Experiment sensitivity: $\sigma_{IBD} > 10^{-40}$ cm^2

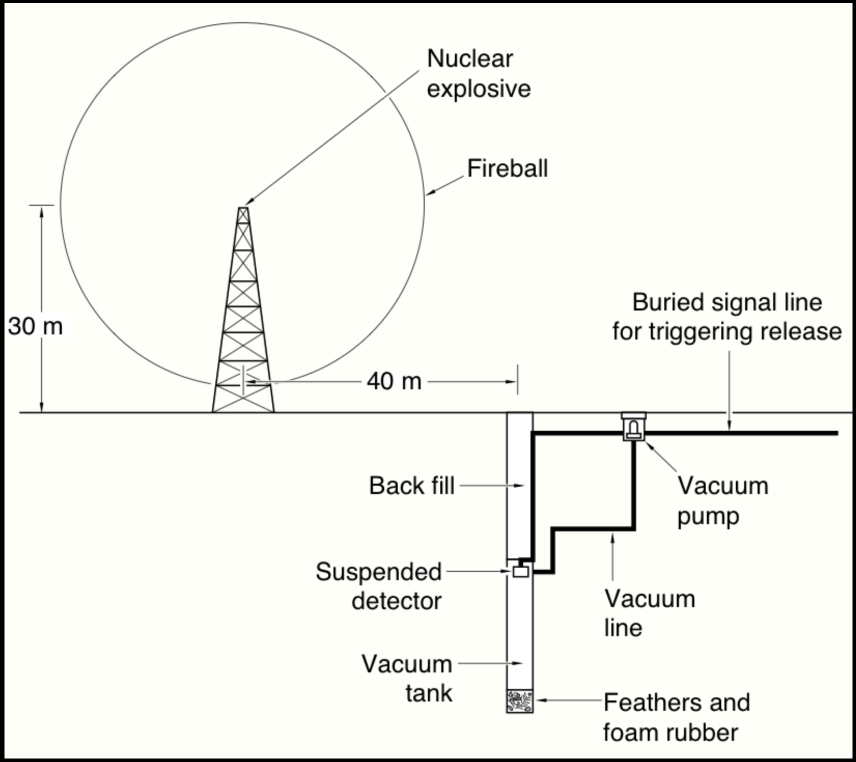
  → experiment approved!

- Pyramidal **ton scale toluene/teraphenyl liquid scintillator** coupled to 4 PMTs: 'a giant liquid scintillation device' called 'El Monstro'

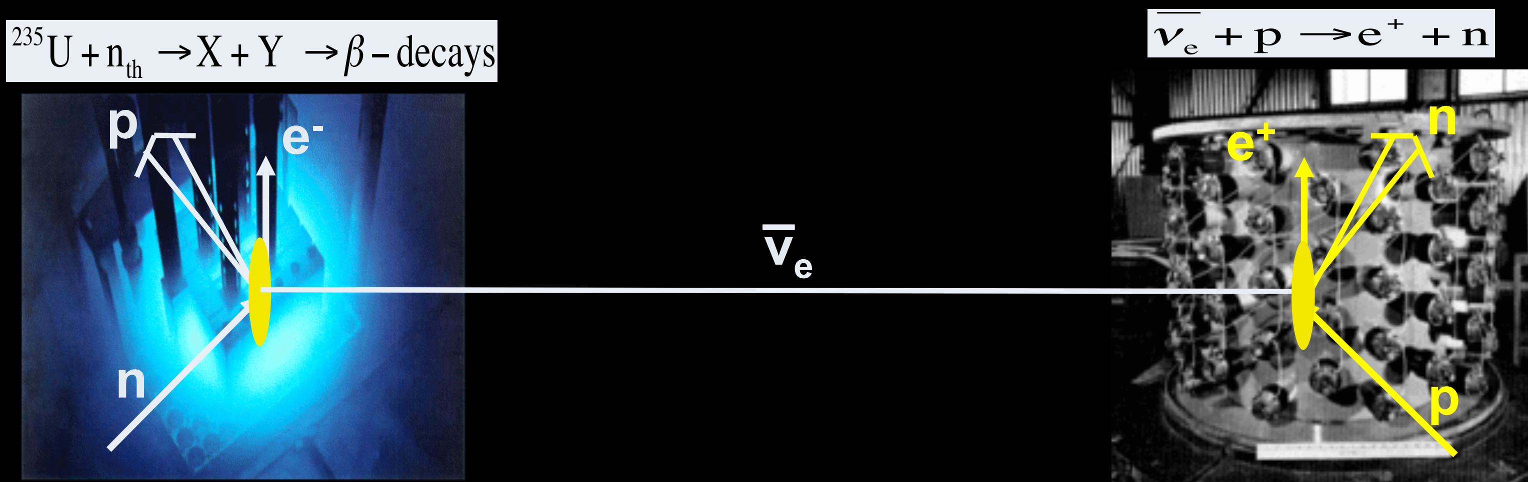
- 2 second free-fall in a vacuum shaft detector in coincidence with the nuclear blast → several interactions at 50 meters from the tower-based explosion of a 20-kiloton bomb

- But J. M. B. Keylogg pushed for an experiment close to a fission reactor & Reines & Cowan considered (e+,n) coincidence detection → **project canceled**

Approved experiment (early 1950's)
Reines & Cowan's Group



Towards Neutrino Discovery



Production

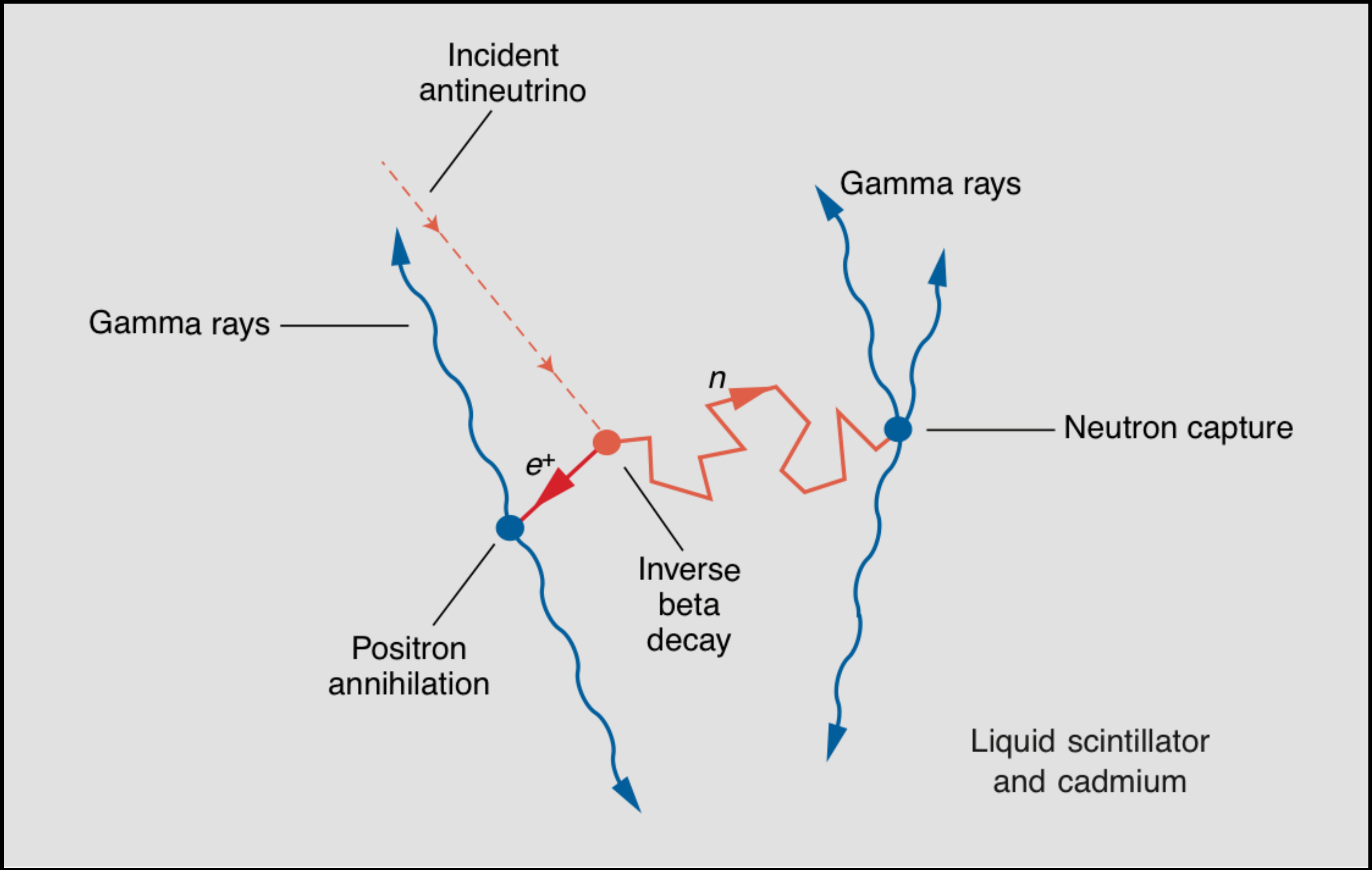
Detection

$t_{creation}$ → $t_{detection}$

Time (Neutrino Proper Time)

The Poltergest Project

Electron antineutrino detection



Positron Detection

- **Positron:**
  - m_n = 0.511 MeV, +1 electric charge
- **Energy Loss**
  - Collision/Scattering with nuclei
    - Bethe-Bloch dE/dx formula
    - multiple-scattering complicated the analytical computation → MC
  - Bremsstrahlung
    - Emission of atomic radiation as e^+ scatter in the electric field of the nucleus
    - A few % of the total loss for MeV e^+
  - **Total dE/dx = $(dE/dx)_{coll} + (dE/dx)_{rad}$**
  - Mean free path is on the mm to cm scale
- **Annihilation**
  - Positron looses its kinetic energy and start diffusing
  - Annihilation with electron : $e^+ + e^- \rightarrow \gamma + \gamma$
    - Prompt signal
    - Gamma energy : E_g=1.022 MeV
    - Back-to-back gammas (momentum conservation)
    - Attenuation length in oil is about 10 cm at 511 keV

Neutron Physics Basics

- **Neutron:**
  - m_n = 938.27 MeV
  - no electric charge, main interaction through strong interaction
  - Must path close to nucleus to interact (10^{-11} cm) → penetrating particle

- **Interactions**
  - Elastic scattering (main): A + n → A + n'
  - Inelastic scattering (main): A + n → A^* + n ; A + n → B + n' + n''
  - Radiative neutron capture: n + (Z,A) → (Z,A+1) + γ
    - cross section ∞ 1/v ; resonances
  - Others: (n,p), (n,d), (n,α), …

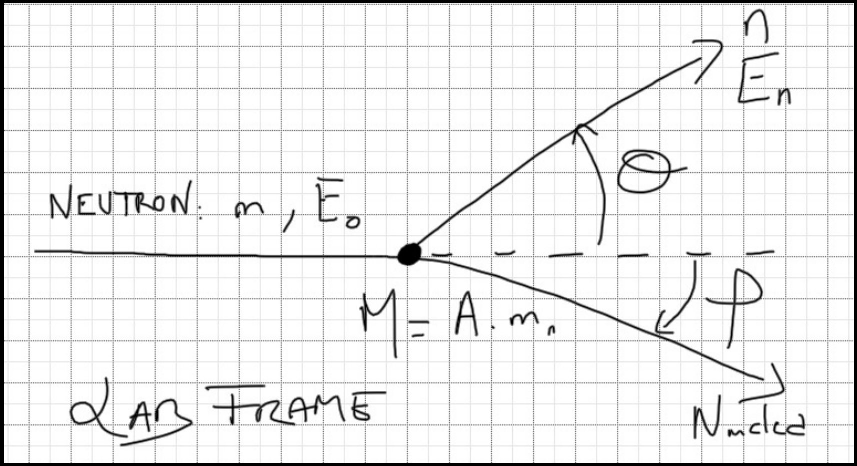
- **Energy & terminology**
  - Fast n: E > 100 keV - ten's of MeV — Epithermal n: E = 1 eV - 100 keV
  - Slow n: E = 0.025 eV - 1 eV — Thermal n: E = 0.025 eV

- **Mean free path length**
  - $1/\lambda$ (cm^{-1}) = n (cm^{-3}) . σ (cm^2)
  - collimated n beam : $N=N_0 \exp(-x/\lambda)$

Neutron Physics Basics

- **Moderation:**
  - Fast neutrons scatter loosing their energy until thermal equilibrium
  - Then neutrons diffuse until they are captured

- **Elastic scattering**



- **Energy of the scattered neutron**
  - $(A-1)^2/(A+1)^2 E_0 < E_n < E$

- **Implication for neutron shielding**
  - The lighter the target nucleus, the more recoil energy is absorbed by the neutron
  - Low-Z material are being used to slow down neutrons
    - Water
    - Paraffin (CH_2)
    - Oil

Neutron Moderation

- **How many collisions before thermalization?**
  - Depends on the target material atomic number

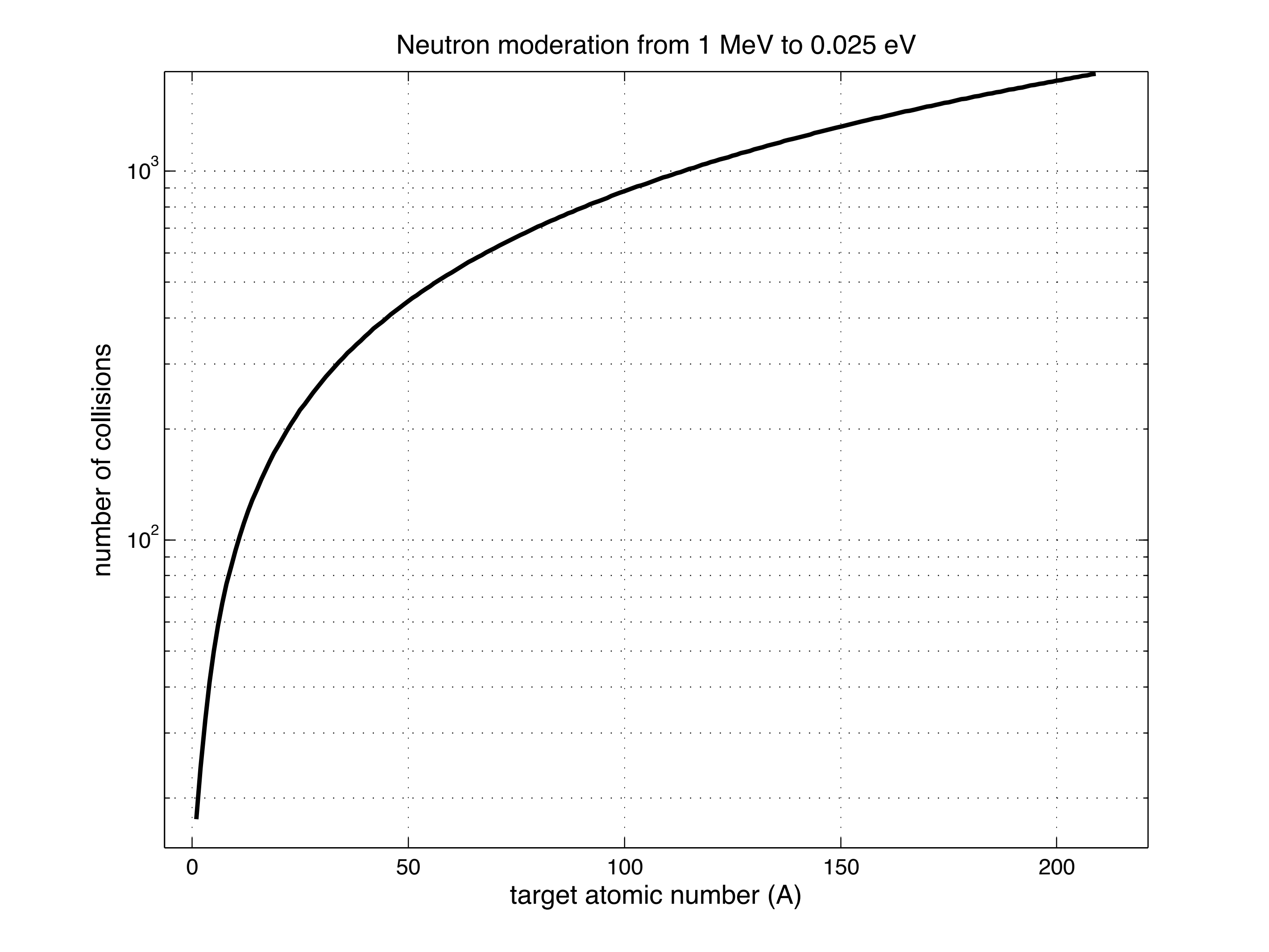
- **Lethargy change**
  - Neutron initial energy : Ei
  - Neutron final energy : Ef
  - u = ln (Ei/Ef)
  - $Ef/Ei = (A^2+1+2A\cos\theta)/(A+1)^2$ (center of mass)

  - Average lethargy change by collision :
    - $\xi = 1 + (A-1)^2/2A \ln (A-1)(1+1) = cte(A)$
    - independent of the initial energy

- **Number of collisions before thermalization**
  - $N_c = \ln (Ei/Ef) / \xi$

- **Application**
  - A=1 (hydrogen): 18 collisions
  - A=12 (carbon): 111 collisions
  - A=207 (lead) : 1818 collisions

Neutron Moderation

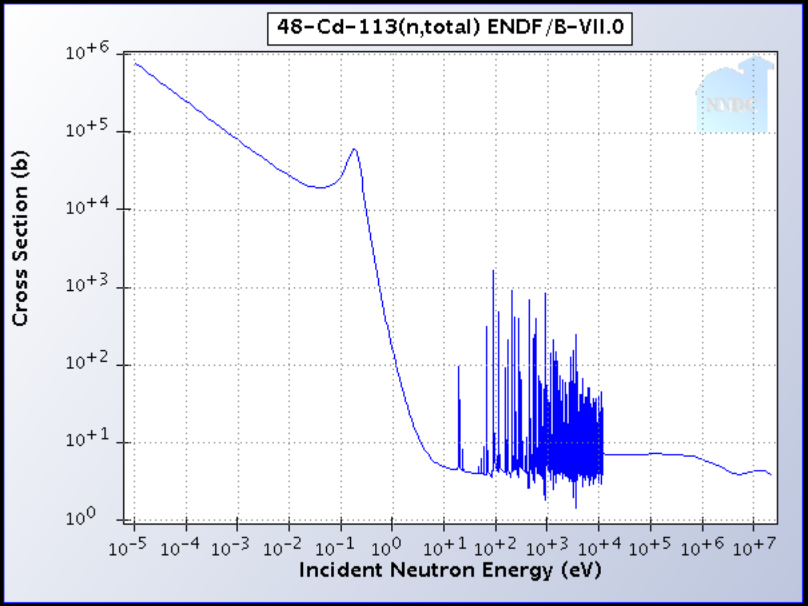


Detecting the neutron capture

- **Few tens of keV neutrons emitted in inverse beta decay**

- **Toluene acts as a moderator**
  - neutron collides with hydrogen nuclei
  - ½ of its energy lost at each collision
  - Takes about 20 collisions to thermalize

- **Cadmium enhancing neutron capture**
  - 12.2% of ^{113}Cd
  - $^{113}Cd+n \rightarrow {}^{114}Cd \rightarrow {}^{114}Cd+\gamma$'s
  - ^{113}Cd, high neutron capture cross section of $>10^4$ barns for E<0.5 eV
  - Emission 9.21 MeV gamma's on average, well above any natural radioactive gamma ray emission



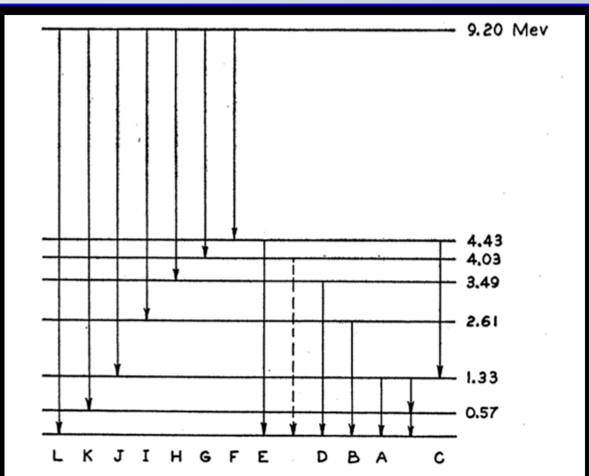
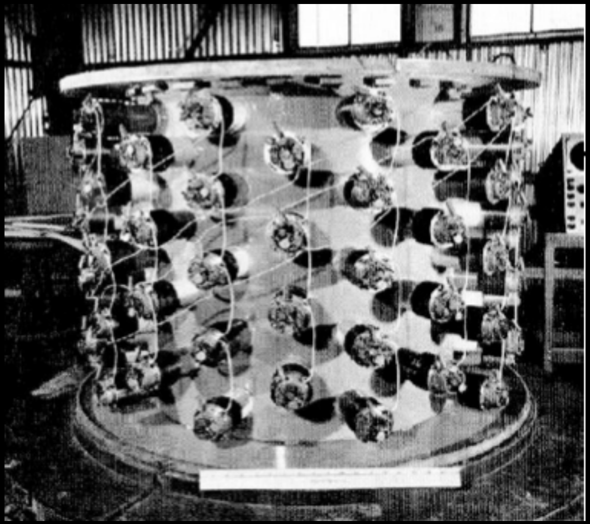
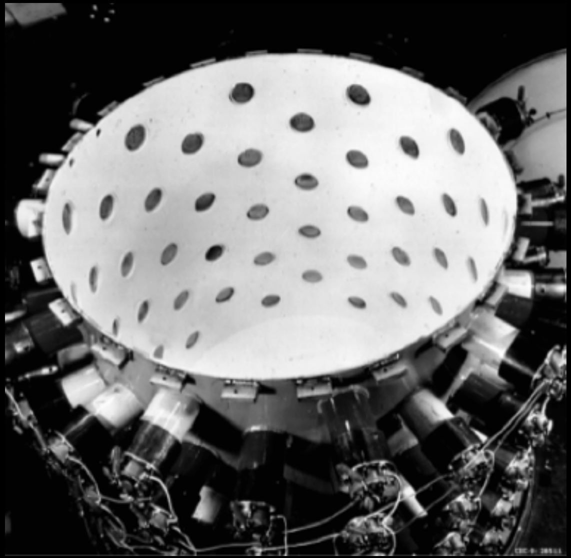


FIG. 2. Level scheme for Cd114 proposed on the basis of the Fig. 1 results.

The Hanford Experiment (1953)

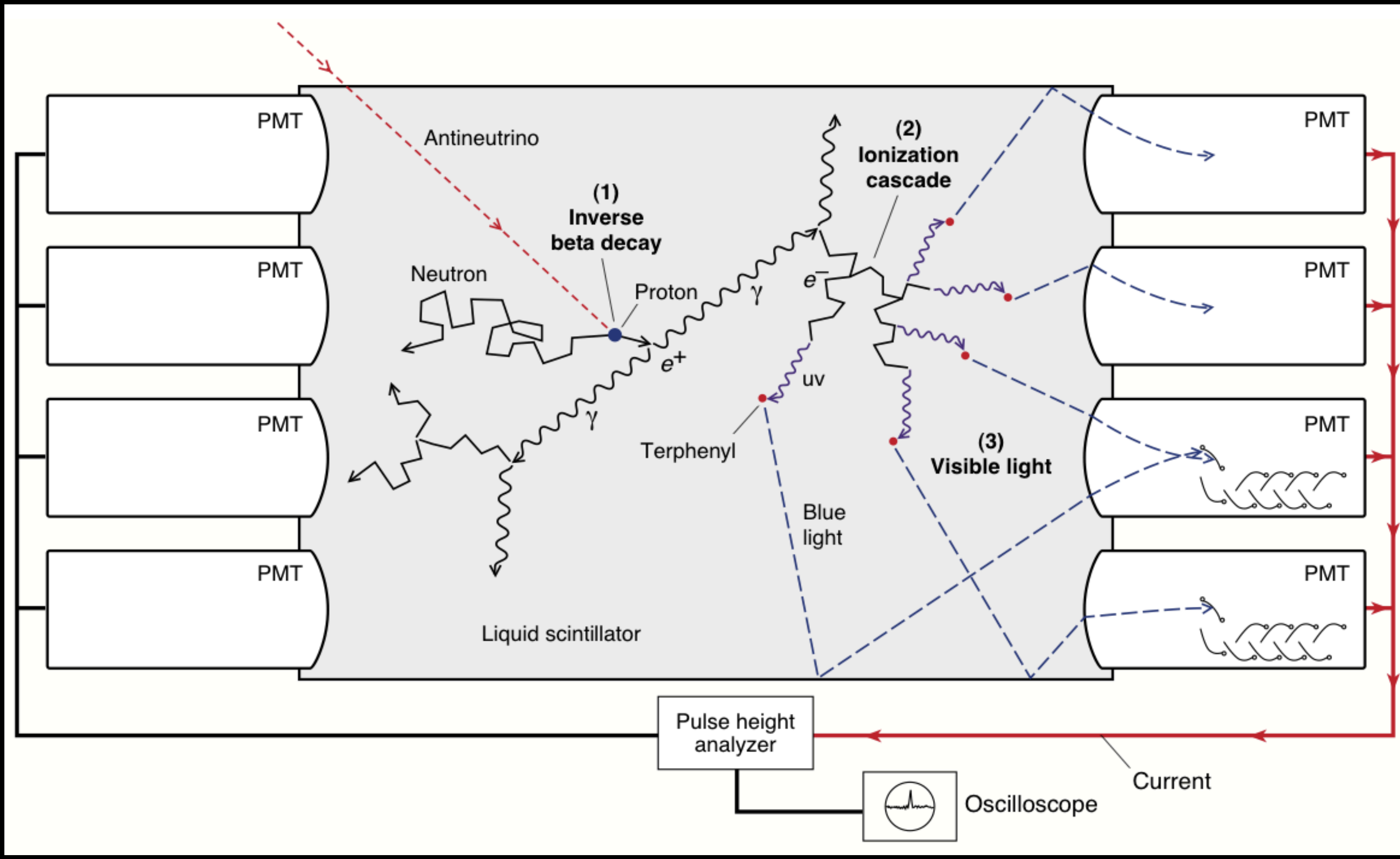
- **'Herr Auge' Detector**
  - 283 liter of toluene based liquid scintillator (largest detector at that time)
  - 90 PMTs (two inches)
- Deployed at to the Hanford plutonium producing reactor
- **Electronics & DAQ**
  - Two gates accepting prompt-like & delayed-like signals
  - < 9 μs coincidence gate
- **Backgrounds not know at that time**
  - **Surface detector**
  - 1.2-1.8 m boron-paraffin shielding (neutrons)
  - 10-20 cm lead (gammas)
- No neutrino detection, but background…
  - Expected rate: 0.1-0.3 counts per minute
  - Measured rate: 5 counts per minute…





The Hanford experiment concept

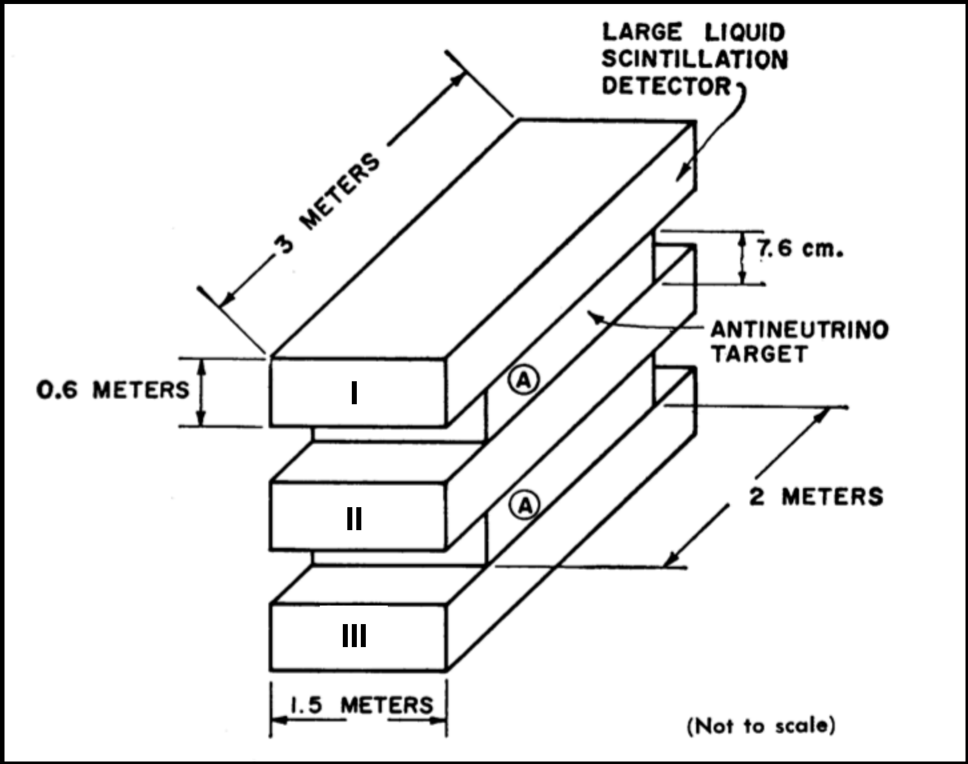
- Target protons transparent medium : toluene liquid scintillator
- Terphenyl+PPO as the wavelenght shifter
- Cadmium phopionate mixed with methanol as neutron eater



The Savannah River Experiment

- **Identification of the cosmic rays as major source of background**

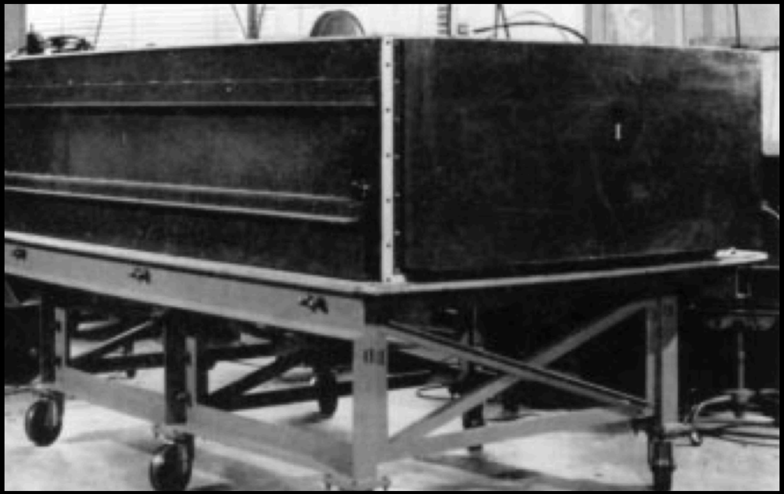
- **New detector (ready by 1955)**
  - Two large 200 l plastic tanks filled with water acting as target H medium (A & B)
  - Cadmium salt dissolved in water
  - I, II, III large 1,400 l purified triethylbenzene solution of terphenyland POPOP liquid scintillator
  - each tanki is viewed by 110 PMTs
  - Scintillator tank coated with epoxy inside to preserve the scintillator purity
  - 10 tons detector (without the shieldings)
  - Whole detector wrapped with fiberglass insulating material for temperature control



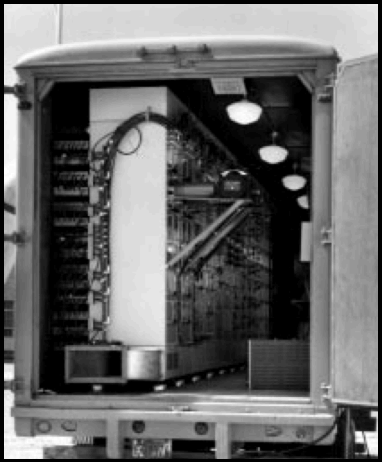
- **New site:** Savahnnah River Plant (SC, US)
  - Basement of the reactor building
  - 11 meters of concrete from the core
  - 12 meter overburden to shield from cosmic rays
  - ON-OFF cycles

The Savannah River Experiment

liquid scintillator tank (I, II, III)

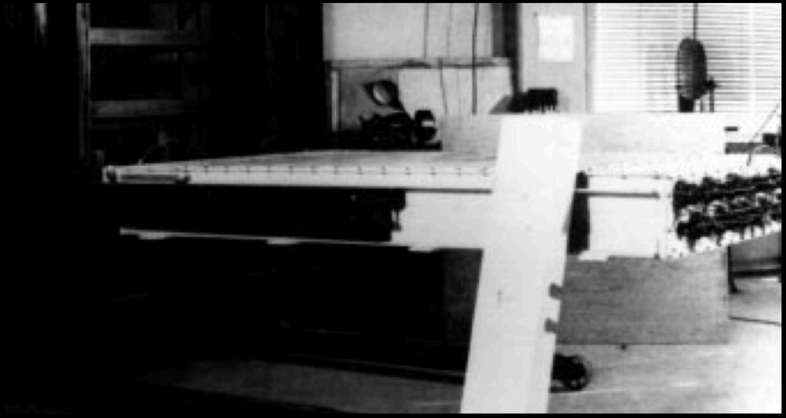


electronics truck

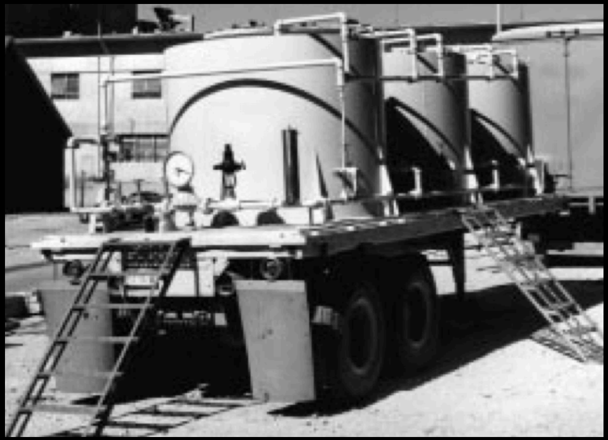


water soaked sawdust (d=0.5)

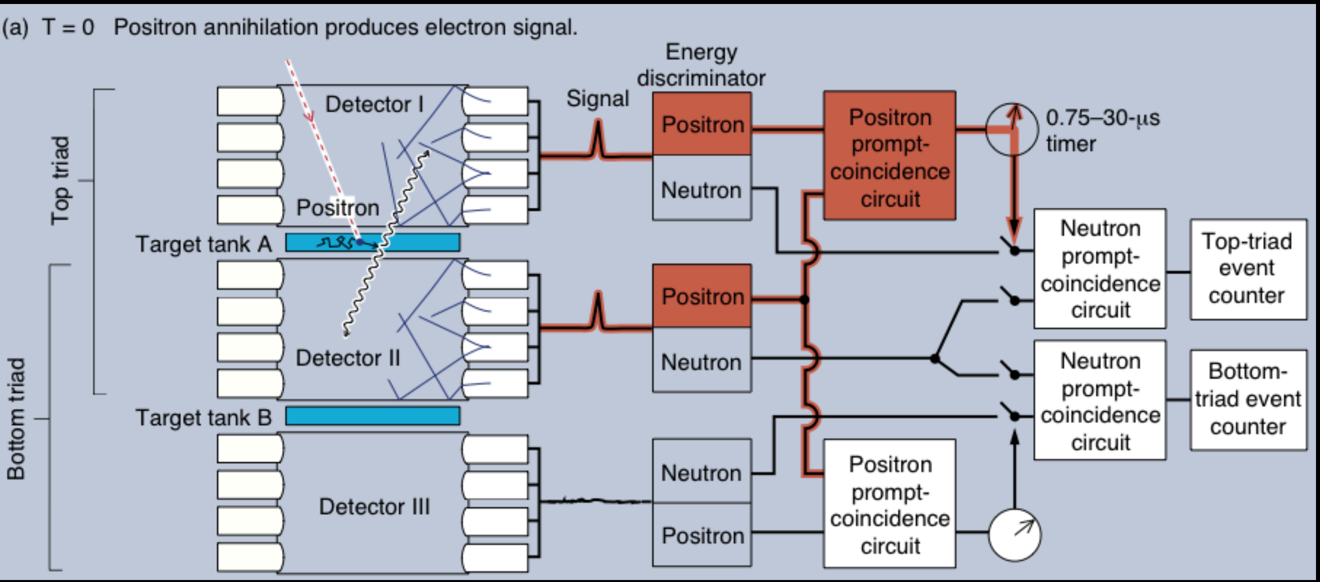
cadmium doped water tank (A, B)



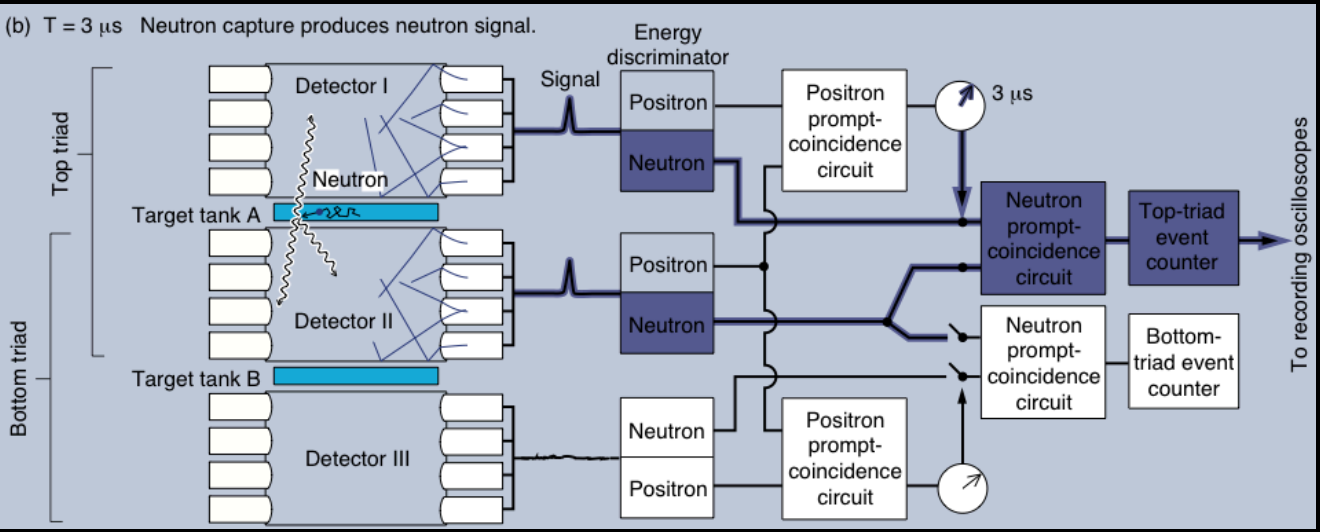
fluid handling system (4,500 l steel tanks)



Delayed Coincidence Signal Tagging

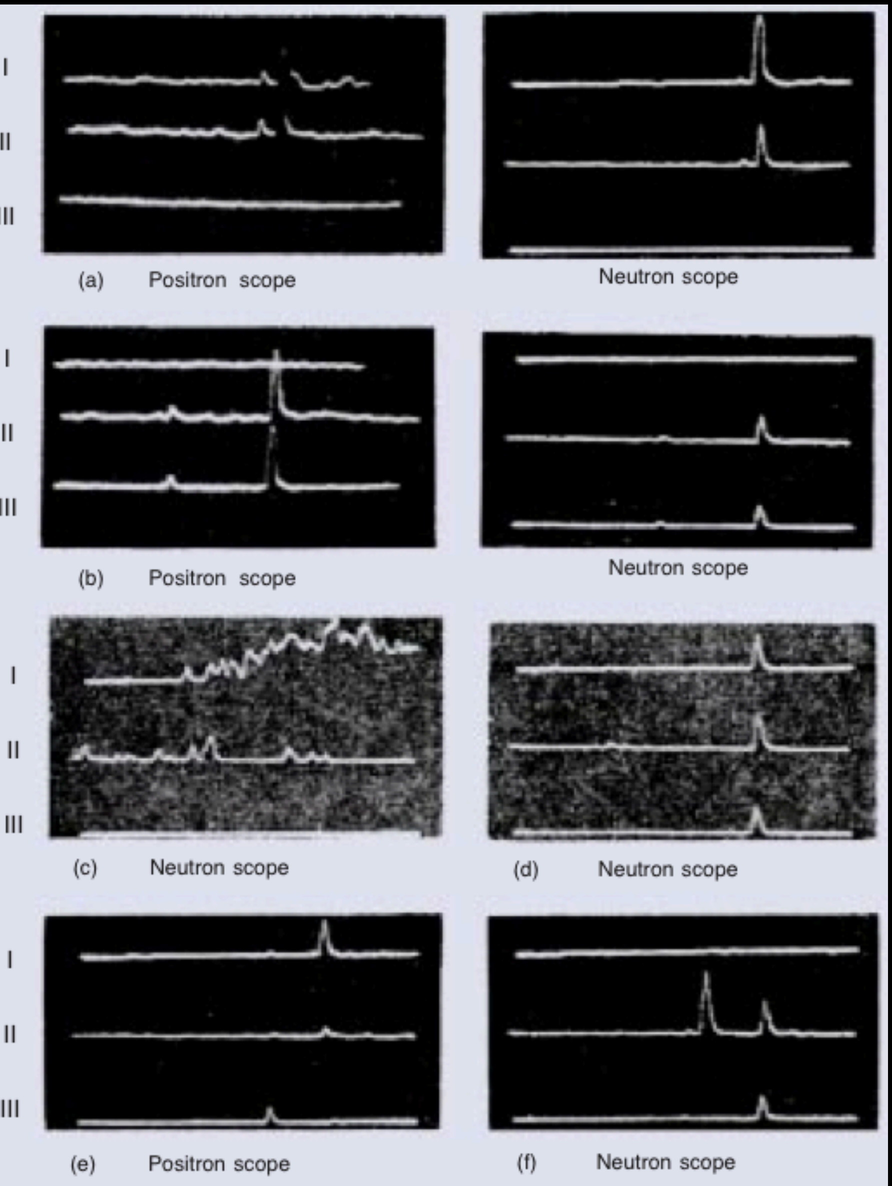


- **Positron-like**
- Two energy depositions in I,II or II,III
- No energy deposition in the farthest tank
- 0.2 < E < 0.6 MeV, each
- Within 200 ns
- Start neutron-prompt coincidence timer



- **Neutron-like**
- Two energy depositions in I,II or II,III
- No energy deposition in the farthest tank
- E > 0.2 MeV each
- 3< E_{tot} < 11 MeV
- within 200 ns
- less than 30 microsecond after the prompt signal trigger

True Signals (from Reines, Cowan, Harisson, et al. 1960)



▪ a) neutrino-like signal

- e^+ scope (I,II): E_I=0.3 MeV, E_{II}=0.35 MeV, $\Delta t<0.2$ μs
- n scope (I,II): E_I=5.8 MeV, E_{II}=3.3 MeV, $\Delta t<0.2$ μs
- 2.5 μs coincidence time

▪ b) neutrino-like signal

- e^+ scope (II,III): E_{II}=0.3 MeV, E_{III}=0.35 MeV, $\Delta t<0.2$ μs
- n scope (II,III): E_I=2.0 MeV, E_{II}=1.7 MeV, $\Delta t<0.2$ μs
- 13.5 μs coincidence time

▪ c) electrical noise signal

- e^+ scope (I,II): strange non physical pulse shape
- n scope (I,II,II): cosmic ray induced event

▪ d) background signal

- e^+ scope (I,II,III): cosmic ray event
- n scope (I,II): ? but rejected since extra-pulse in II

Announcement of the discovery

- **Signal**

- Reactor-power dependent
- 1371 hours running time
- 2.88+/-0.22 events per hours

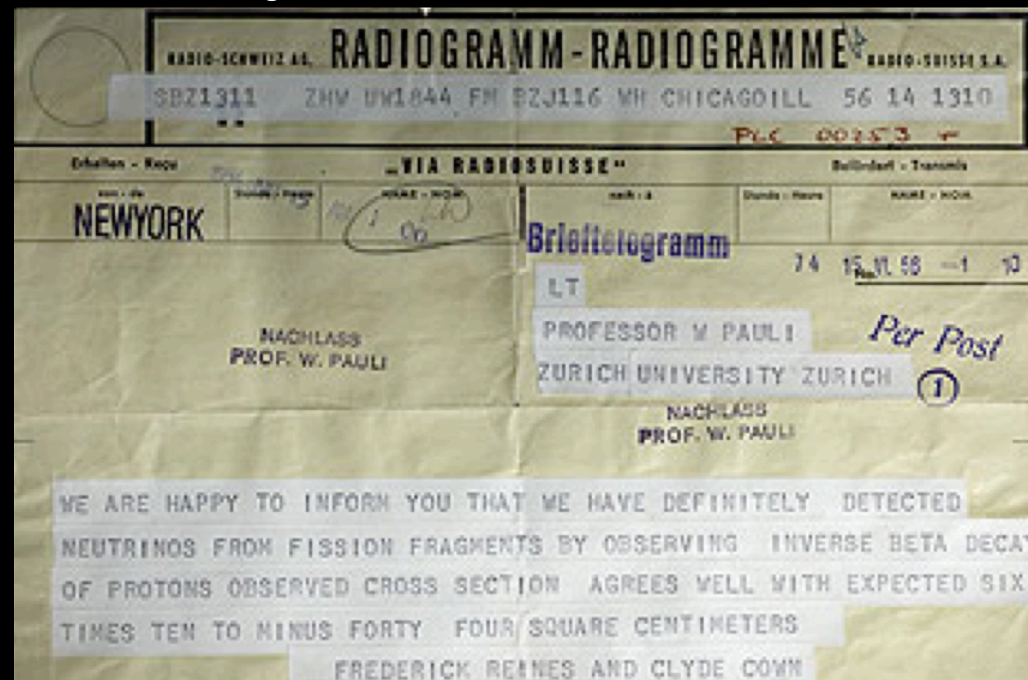
- **Backgrounds**

- Signal to background ratio : 3 /1
- Reactor induced background : 1/20 of the signal
- check with reactor on-off periods

- **Consistency checks**

- ½ dilution with D_2O to reduce the target proton density
- proton signal calibrated using ^{64}Cu 0.3 MeV source dissolved in water`
- neutron detection efficiency measured with a plutonium-beryllium source
- Doubling of the cadmium concentration
- Increase of the 'neutron' shield

telegram send to Pauli on June 14^{th} 1956


RADIOGRAMM - RADIOGRAMME

SBZ1311 ZHW UW1844 FM BZJ116 WH CHICAGOILL 56 14 1310

VIA RADIOSUISSE

NEWYORK

Brieftelegramm

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWAN

IDB Cross Section

- **Measured neutrino rates depends on:**
  - Neutrino flux ($10^{13}/cm^2/sec$ at the Savannah River experiment site)
  - Target Proton number (10^{28} for the Savannah River detector)
  - IDB cross section (parity non-conservation no yet discovered in 1956)
  - Cross section per fission (>25% uncertainty on reactor neutrino spectrum in 1956)
  - Detector efficiency

- **Savannah River Cross Section per fission, 1956**
  - Predicted: 6.3+/-1.6 10^{-44} cm^2
  - Reines et al. article in Science (20 July 1956, Volume 124, Number 3212) reported a cross section in agreement with the predicted value, within 5%

- **Parity non-conservation was found soon after neutrino discovery**
  - Two component neutrino (instread of four). Predicted increased by a factor of 2

- **Savannah River Cross Section per fission revisited, 1960**
  - Reines et al. in Physical Review 117 (159) 1960 reported 12^{+7}_{-4} 10^{-44} cm^2

- **In 1995 Reines was awarded by the Nobel price for the neutrino discovery**