Weak interactions: Experimental evidence for the neutrino

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Beta decay

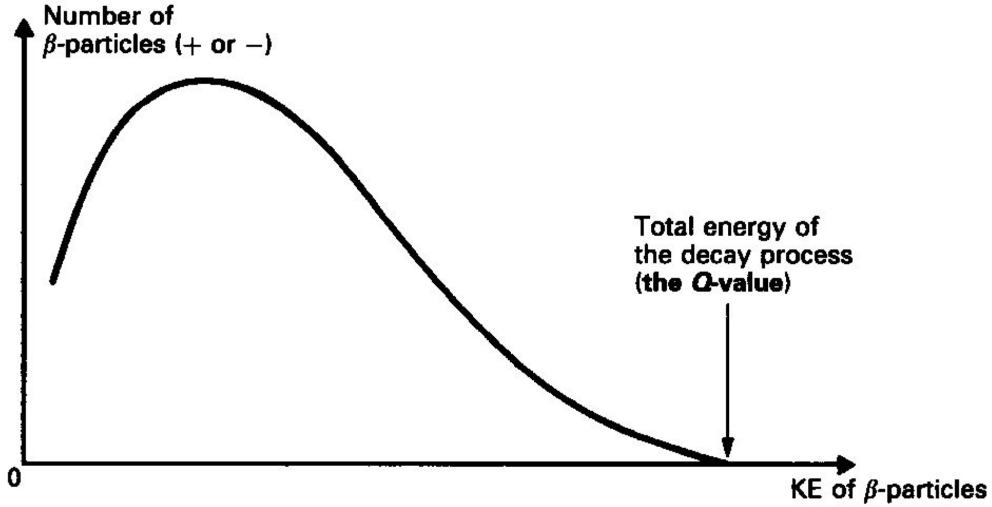
- Original picture of beta (minus) decay:

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-} $$

- Conversion of neutron to proton by emission of beta minus particle (energetic electron)
- Conversion of proton to neutron by emission of beta plus particle (energetic positron)

Missing energy

- Electron had a continuous energy spectrum - as the only product emitted other than the nucleus in the decay, **it was expected to have a particular, well defined value**, equal to the difference between the initial and final energies of the nucleus
- Broad distribution suggested **energy was lost** in the process



Pauli's hypothesis

- Bohr concluded that momentum, energy and spin must not be conserved in beta decay

- Pauli postulated the existence of the a small neutral particle, which he called a "neutron", to explain the continuous distribution of energy of the electrons emitted in beta decay **(1930)**

- **Inclusion of this third particle allowed conservation laws to be obeyed**

Wolfgang Pauli

Fermi's theory of beta decay

- Fermi renamed the particle a "neutrino" ("little neutral one") after Chadwick discovered the neutron in 1932

- Fermi developed a theory of beta decay to include the neutrino **(1934)**

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-} + \bar{\nu}_e $$

Reines and Cowan: 1953 (Hanford)

- In **1951** F. Reines decided that setting off a nuclear bomb as a neutrino source would be a great idea (and Fermi agreed)

- In **Feb 1953**, F. Reines and C. Cowan published a paper proposing how they would detect the neutrino (minus the bomb)

- In **July 1953**, they published a paper saying they believed they'd detected the neutrino but more work was needed

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$$\hookrightarrow + \ e^{-} \rightarrow \gamma + \gamma$$

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- Positron annihilates with electron, **producing two γ rays** with combined energy 1.02 MeV

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$e^{+} + e^{-} \rightarrow \gamma + \gamma$

$n + Cd \rightarrow Cd^{*} \rightarrow Cd + \gamma\text{'s}$

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- **Neutron will be captured by Cd** creating an excited isotope of Cd
- De-excites by the **emission of multiple γ rays** which can be detected

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- **“Delayed coincidence”**- the positron annihilates quickly, but it takes longer for the neutron to be captured and produce γ rays
- Mean neutron capture time of 5 microseconds

Reines and Cowan: 1953 (Hanford)

- Liquid scintillator counter in the shape of a cylinder

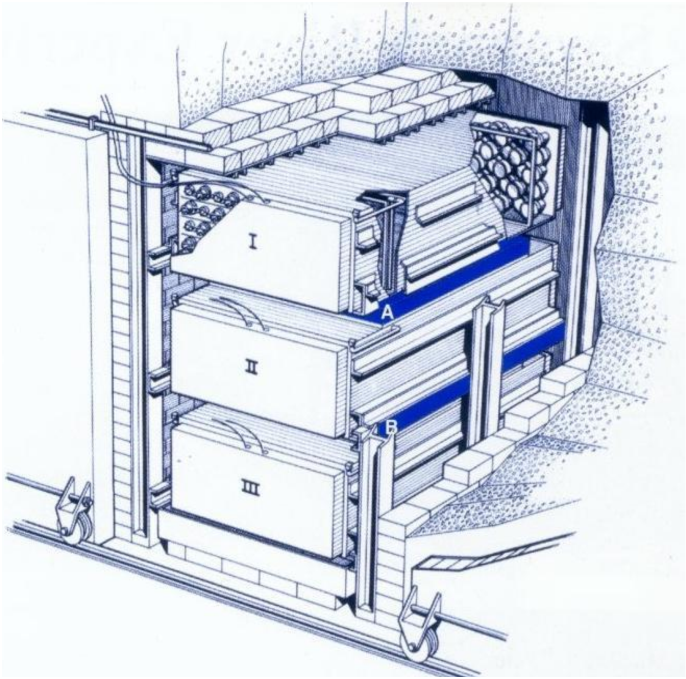
- Detector surrounded on all sides by 4 to 6 feet of paraffin alternated with 4 to 8 inches of lead, and a 6 foot thick water shield above the detector
  - **Minimise events due reactor neutrons and gamma rays, and cosmic rays**

- **Results inconclusive**: background from cosmic rays still too high; experiment needed to be moved underground

Reines and Cowan: 1956 (Savannah River)

- Savannah River experiment aimed to improve on Hanford

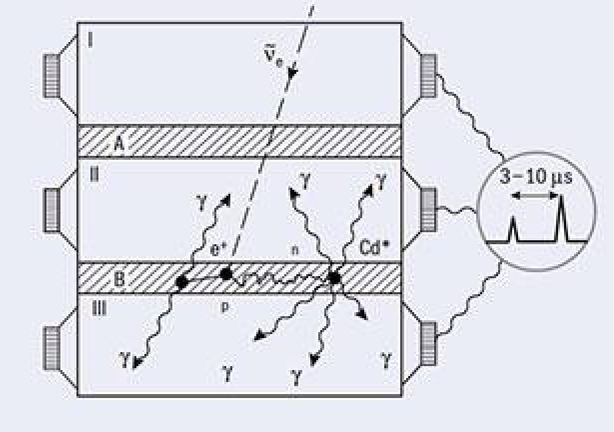
- **1956**: "Detection of the free neutrino: a confirmation"
- Detector is now based **underground**
- Improved detector design in layers
  - Three scintillation detector tanks with 110 photomultiplier tubes each (I, II, III)
  - Two target layers containing a water solution of $CdCl_2$ (A, B)



Reines and Cowan: 1956 (Savannah River)

- Essentially two detectors:
    - scintillator I, target A, scintillator II
    - scintillator II, target B, scintillator III

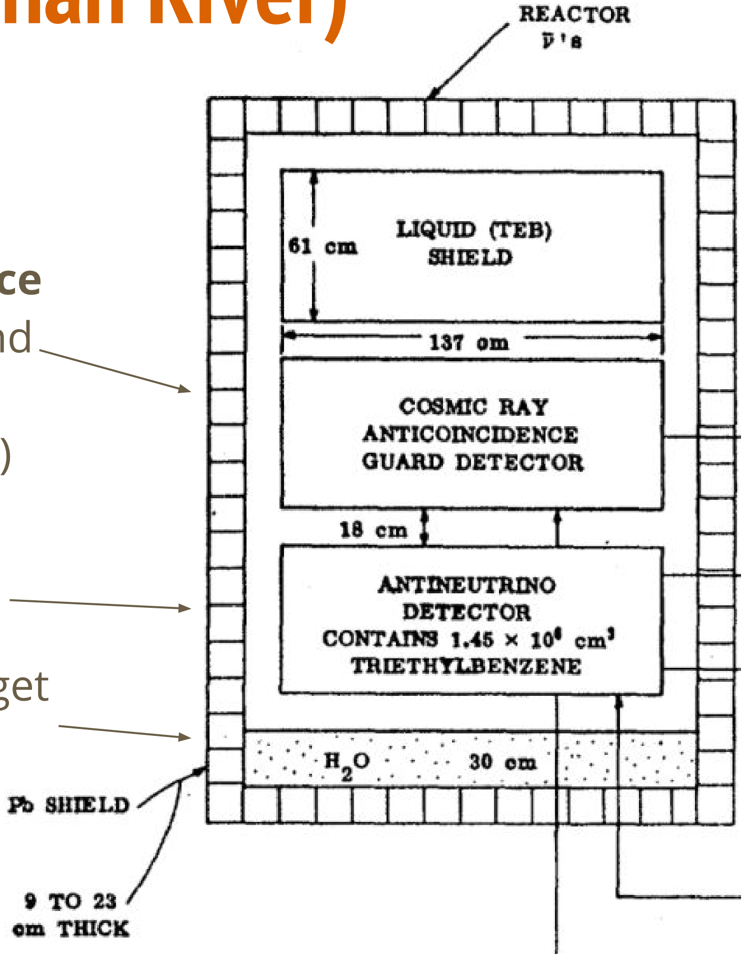
- Antineutrino reacts in water solution B, γ products detected in scintillators II and III
    - Not detected in scintillator I as the γ rays are too low in energy to reach it
    - Cosmic ray particles would likely produce events in all three



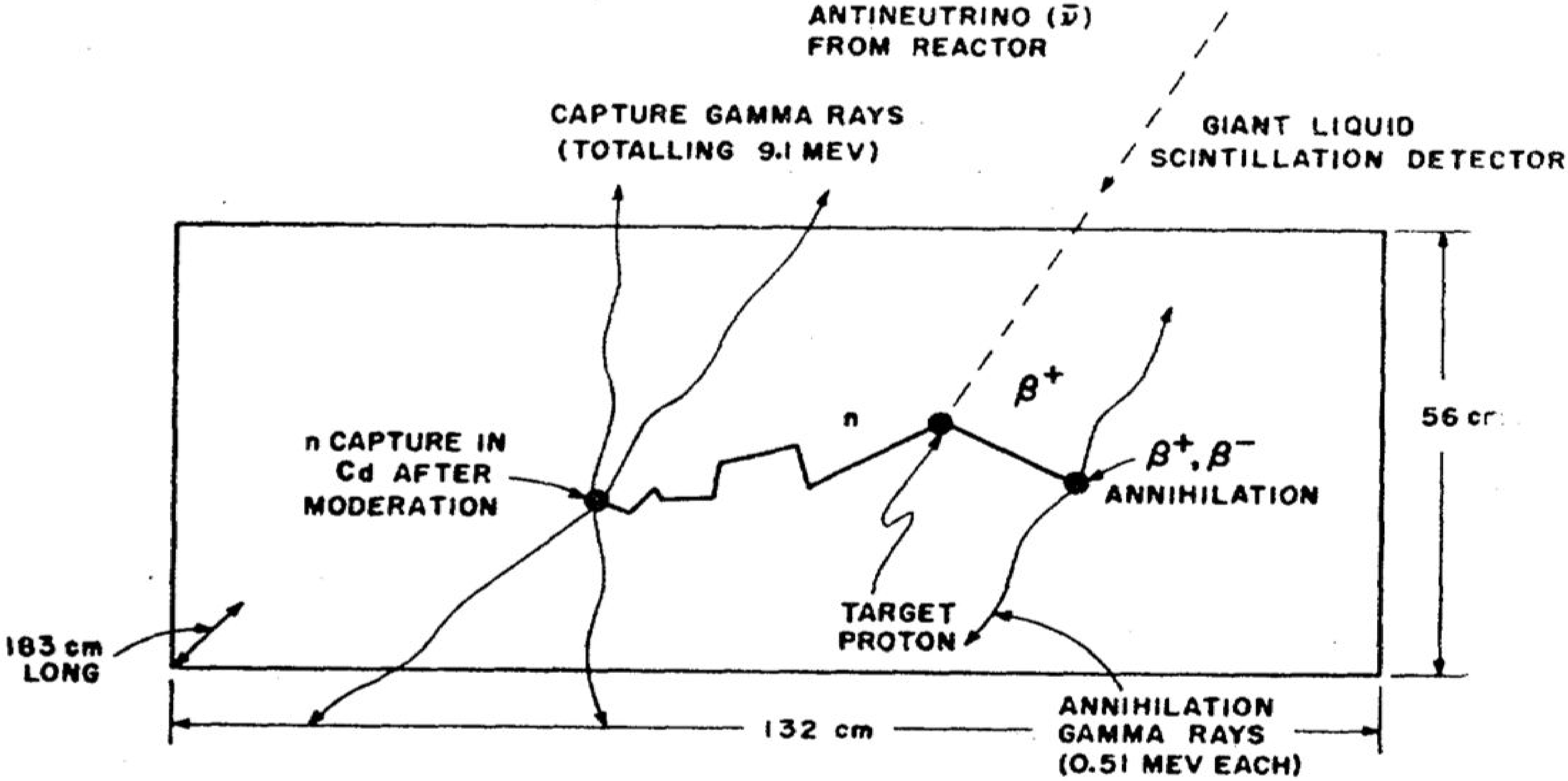
- Results from 1956 experiment were deemed conclusive, however the experiment was further improved in 1959
    - New experiment yielded a more accurate value of cross section

Reines and Cowan: 1959 (Savannah River)

- Modifications:
  - Second detector now used as **anticoincidence shield** against cosmic ray induced background counts
  - Addition of **Cd octoate** (2-ethylhexanoic acid) into the scintillator solution of the lower detector; protons of the solution are targets for the antineutrinos
  - Addition of water tank 30 cm thick below target detector



1959: Schematic of antineutrino detector



Reines and Cowan: 1959 (Savannah River)

Conditions for detection (signal/background separation):

- Not all positron signals that occur in the antineutrino detector are from an IBD
    - Acceptable beta-plus like pulse detected **BUT** a pulse greater than 0.5 MeV also detected in anti-coincidence detector

        → Event is rejected by the detector
- If a pulse of **>8 MeV** is detected from a high energy cosmic ray, the system is insensitive for 60 μs following the pulse
- Pulses triggered by electrical noise are also removed, as they have an obvious visual signature

Reines and Cowan: 1959 (Savannah River)

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- No pulse greater than 0.5 MeV in anti-coincidence detector

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Conditions for detection:

- Positron pulse between **1.5 - 8 MeV** in antineutrino detector
- No pulse greater than 0.5 MeV in anti-coincidence detector
- Between **0.75 - 25.75 μs** afterwards, detect neutron capture pulse of **3 - 10 MeV**

Reines and Cowan: 1959 (Savannah River)

- Cross-section for an antineutrino-proton interaction (for an average fission) is:

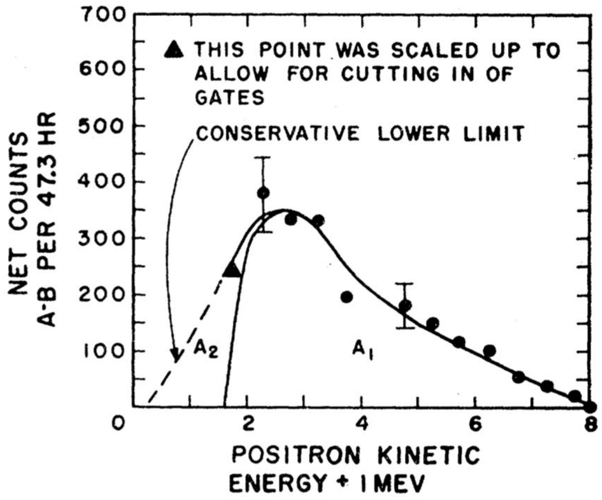
$$\bar{\sigma} = \frac{R}{3600 f n \epsilon_{\beta^+} \epsilon_n} \text{ cm}^2$$

- **R** is the observed signal rate in counts per hour (found to be 36±4), **n** is the number of target protons = 8.3×10^{28}, **f** is the antineutrino flux at the detector = $1.3 \times 10^{13}\ \bar{\nu}\ \text{cm}^{-1}\text{s}^{-1}$, $\boldsymbol{\varepsilon}_{\boldsymbol{\beta}}$ and $\boldsymbol{\varepsilon}_{\mathbf{n}}$ are the positron and neutron detection efficiency respectively.

β^+ Detection Efficiency

- The **detection efficiency of the positron will be high** as there is little chance of it leaking out of the detector

- The positron energy must also fall between **1.5 to 8 MeV** to be accepted



$$\varepsilon_\beta = 0.85 \pm 0.05$$

Neutron Detection Efficiency

- More difficult to estimate than for the positron
- Given by **3 factors**:

$$\varepsilon_n = \varepsilon_{n1} \varepsilon_{n2} \varepsilon_{n3}$$

- $\boldsymbol{\varepsilon_{n1}}$ - probability a neutron will not leak out of the detector
- $\boldsymbol{\varepsilon_{n2}}$ - probability that the neutron will be captured by cadmium in the 25 μsec (0.75 to 25.75 μsec) period after its creation
- $\boldsymbol{\varepsilon_{n3}}$ - probability that the neutron capture will result in gamma rays between the energy gates - 3 to 10 MeV

Neutron Detection Efficiency

- $\varepsilon_{n1} = 0.97$
- $\varepsilon_{n2} = 0.135$
- $\varepsilon_{n3} = 0.75 \pm 0.05$

$$\varepsilon_n = 0.97 \times 0.14 \times 0.75 = \mathbf{0.10}$$

- Due to the large uncertainty in the calculation of ε_{n2}, they assigned error limits of ±20%

Antineutrino-Proton Cross-Section

- After calculation of the efficiency of the positron and neutron detections, the cross-section of the antineutrino-proton cross-section could be calculated using the equation seen before. Therefore:

$$\bar{\sigma} = (1.1 \pm 0.26) \times 10^{-43}\ \text{cm}^2/\bar{\nu}$$

- Where they quote the root-mean-square error
- (They also calculated the cross section per fission reaction, assuming N = 6.1 $\bar{\nu}$ per fission, as

$$N\bar{\sigma} = (6.7 \pm 1.5) \times 10^{-43}\ \text{cm}^2/\text{fission})$$

Summary

- Missing energy in electron spectrum of beta decay
- Existence of neutrino proposed by Pauli in 1930
- Reines and Cowan developed experiments using inverse beta decay

    - **1953:** Inconclusive evidence
    - **1956:** Detector improvements; better shielding, needed to improve on cross section calculation
    - **1959:** Scintillator both detector and target. Calculation of cross section of $(1.1 \pm 0.26) \times 10^{-43}$ cm$^2/\bar{\nu}$, in excellent agreement with the theoretical value of $(1.0 \pm 0.16) \times 10^{-43}$ cm$^2/\bar{\nu}$

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