Discovery of the electron (anti)neutrino

An experiment done in 1956

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Background

1899 — In 1899, Ernest Rutherford first described alpha particles and differentiated alpha and beta rays.

1900 — In 1900, Paul Villard discovered gamma radiation.

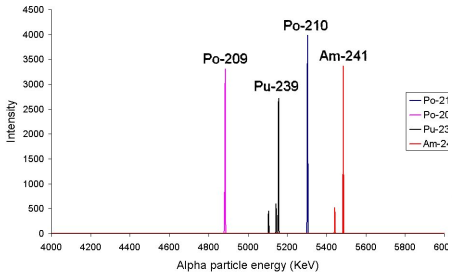
1914 — In 1914, James Chadwick confirmed that the beta particles have a **continuous spectrum.**

1930 — In 1930, Wolfgang Pauli proposed that a **“neutron”** is emitted along with the electron, which explains the continuous spectrum.

If **only one electron** is emitted in beta decay, the electron energy should be a fixed value, similar to the energies of alpha particles and gamma rays.

→ Maybe energy is not conserved in beta decay?

alpha spectrum vs beta spectrum



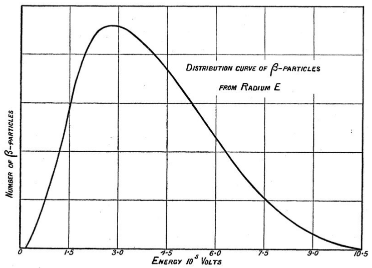


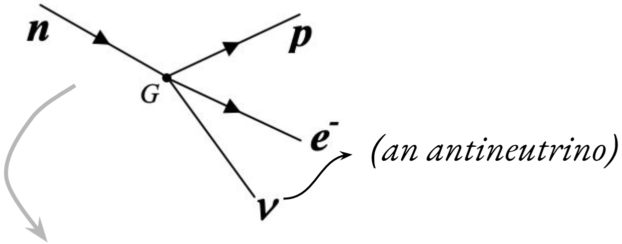
Fig. 1.

Background

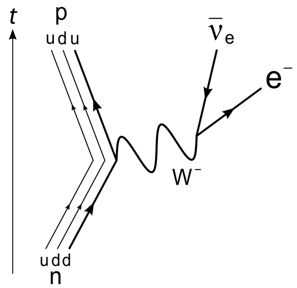
1933

In 1933, Enrico **Fermi** used the “neutron” idea and built the theory for beta decay.

In Fermi’s theory, instead of being contained in the nucleus, beta particles can be created and annihilated just like photons in atomic transitions. The Fermi constant, G_F, gives the strength of the interaction.



Fermi’s theory is a precursor to the Glashow-Weinberg-Salam (GWS) theory formulated in the 1960s, where a W boson mediates the interaction.



History of initial rejection and later publication [edit]

Fermi first submitted his "tentative" theory of beta decay to the prestigious science journal *Nature*, which rejected it "because it contained speculations too remote from reality to be of interest to the reader.[4]" *Nature* later admitted the rejection to be one of the great editorial blunders in its history.[5] Fermi then submitted revised versions of the paper to Italian and German publications, which accepted and published them in those languages in 1933 and 1934.[6][7][8][9] The paper did not appear at the time in a primary publication in English.[5] An English translation of the seminal paper was published in the American Journal of Physics in 1968.[9]

Fermi found the initial rejection of the paper so troubling that he decided to take some time off from theoretical physics, and do only experimental physics. This would lead shortly to his famous work with activation of nuclei with slow neutrons.

Fun facts:)

Background

1933

According to the Pauli-Fermi theory, neutrinos are **spin ½ Dirac particles** that carry energy, momentum but no charge. Therefore, antineutrinos presumably also exist.

According to the theory, the **neutron β⁻ decay** is as follows:

$$n^0 \to p^+ + \beta^- + \nu_- \qquad (1)$$

1956

In 1956, Clyde L. **Cowan** and Frederick **Reines** conducted an experiment at the Savannah River Plant that successfully detected the neutrino from the inverse neutron decay.

$$\nu_- + p^+ \to \beta^+ + {}^0n$$

The **inverse neutron decay**, where an electron antineutrino scatters off a proton, can be used to prove the existence of the neutrino.

Experimental setup and data taking

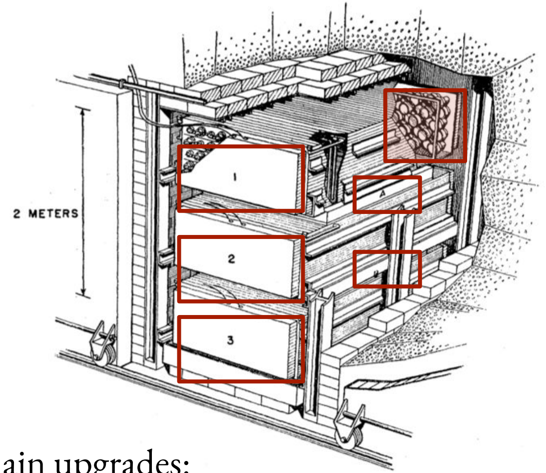
I From 1953 to 1956

$$\nu_- + p^+ \rightarrow \beta^+ + {}^0n \qquad (6)$$

In order to capture the inverse beta decay, an intense antineutrino beam, proton targets, and a detector that can record a positron and a neutron simultaneously are required.

In **1953**, a preliminary experiment, utilizing a large liquid scintillation detector, was carried out near a Hanford reactor. *"Although a high background was experienced due to both the reactor and to cosmic radiation, it was felt that an identification of the free neutrino had probably been made."*

A second experiment, delivering a more definitive conclusion, was done in **1956**.

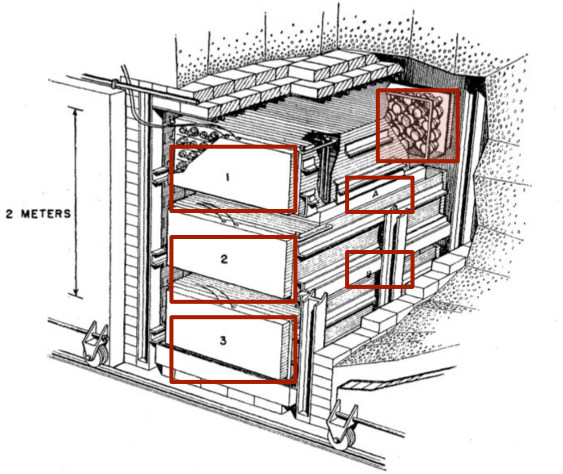


The **1956 experiment** has three main upgrades:

- The detector was moved to the **Savannah River Plant**, which offered a more intense neutrino beam.
- The detector itself was improved. It employed a "**club sandwich**" arrangement, with two target tanks in between three liquid scintillation detectors, which also had more photomultiplier tubes at the ends.
- Lastly, the **shielding** of the detector was improved and can better attenuate reactor neutrons and cosmic rays. The detector was encased in a lead-paraffin shield and placed deep underground.

Experimental setup and data taking

II The club sandwich detector



The **“club sandwich”** detector contained two independent “triads”, which both used the center detector.

The **target tank** (A and B) is 7.6 cm deep, 132 cm wide, and 183 cm long. It contained about 200L water and cadmium chloride solution. The cadmium-hydrogen atomic ratio, α, is about 0.010.

- The size of the tank was chosen to increase the number of protons available, while avoiding the positron radiation being absorbed in the water.

The liquid scintillator **detector** (1, 2, and 3) is about 58cm deep.

- With this depth, the detector can absorb the neutron capture radiation efficiently.

Experimental setup and data taking

III An inverse neutron decay in the top triad

When an anti-ν event happened, the reactor **anti-ν** entered a target tank A, it interacted with a proton in water.

Then, a positron and a neutron were emitted. The **positron** was captured by an electron in water, emitting two gamma rays to counter 1 and 2.

The **neutron** would diffuse and get captured by cadmium in the water, giving a few gamma rays.

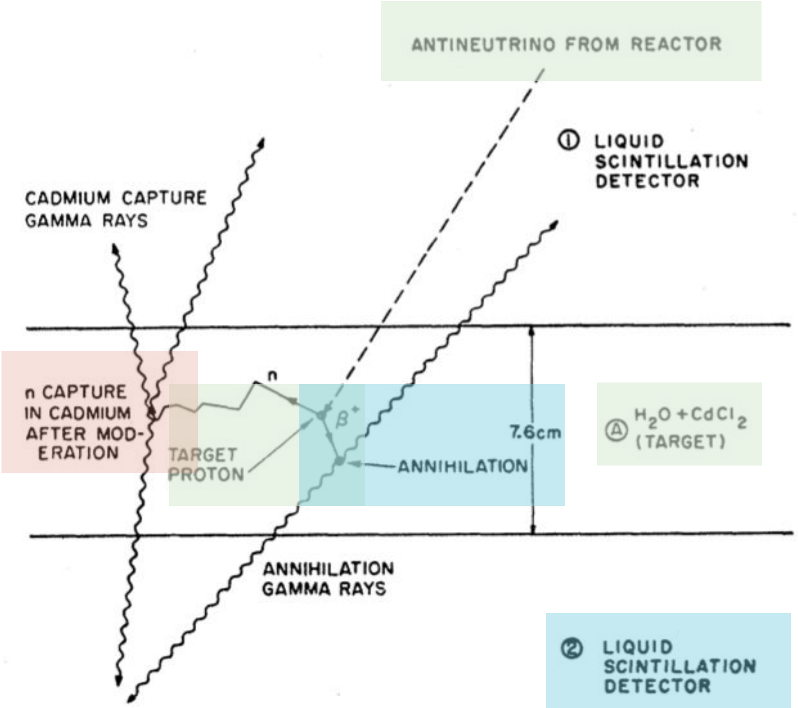


FIG. 1. Schematic diagram of antineutrino experiment.

Experimental setup and data taking

IV Where the signal goes?

After an event happened, the scintillation light was translated by the photomultipliers at both ends of the detectors to electronics stored in a trailer van outside.

A Signals from the two triads were amplified independently.

B **Accepted beta and neutron pulses**, in the top or bottom triad, triggered triple-beam beta (high gain) and neutron (low gain) oscilloscopes to record signals stored on delay lines in parallel.

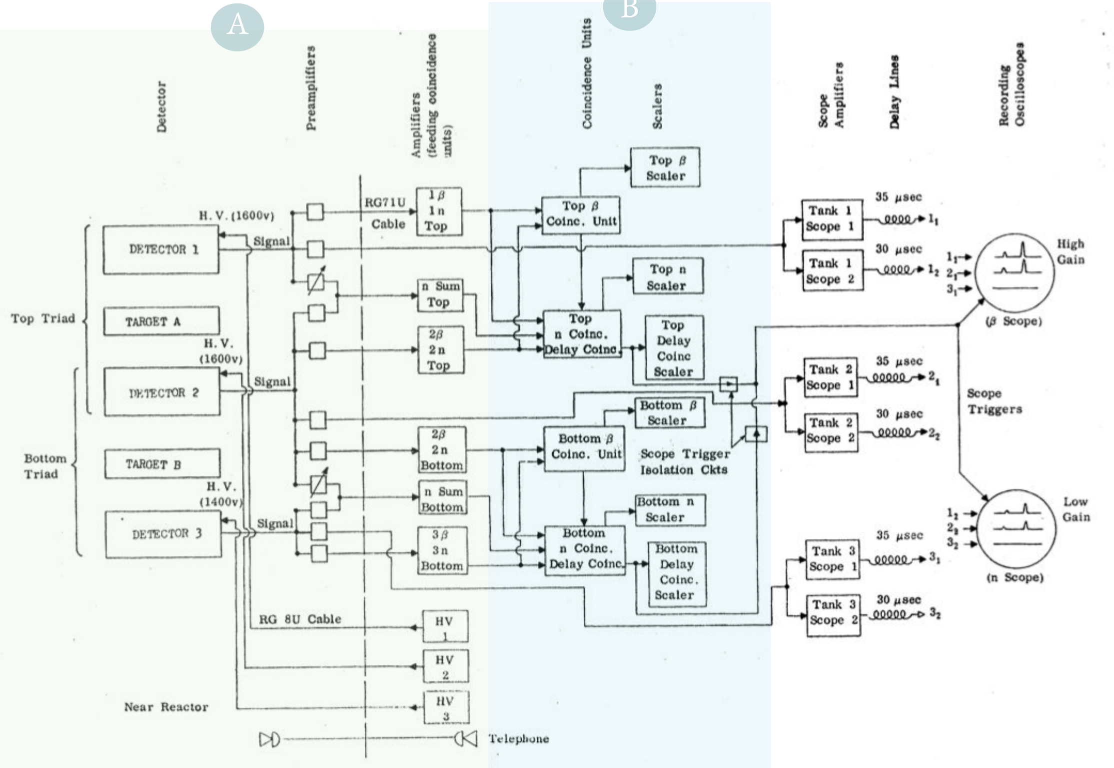


FIG. 4. Schematic diagram of detector and associated electronics.

Experimental setup and data taking

V What are accepted events?

Take the top triad antineutrino event as an example.

The beta and neutron pulses are accepted if:

- The two pulses in counter 1 and 2 from the **positron annihilation** had an energy between 0.2 and 0.6 MeV each and are less than 0.2 us apart (the time resolution of the system).
- Once the beta pulses are accepted, the second pair of **neutron-capture gamma rays** is accepted if the second pair occurred between 0.75 and 30 us after the first pair and if they each had an energy >0.2MeV, with a total energy of 3~11 MeV.
- These criteria were determined based on the positron annihilation and neutron capture radiation spectrum and optimized to achieve high detection efficiencies while minimizing backgrounds.

Experimental setup and data taking

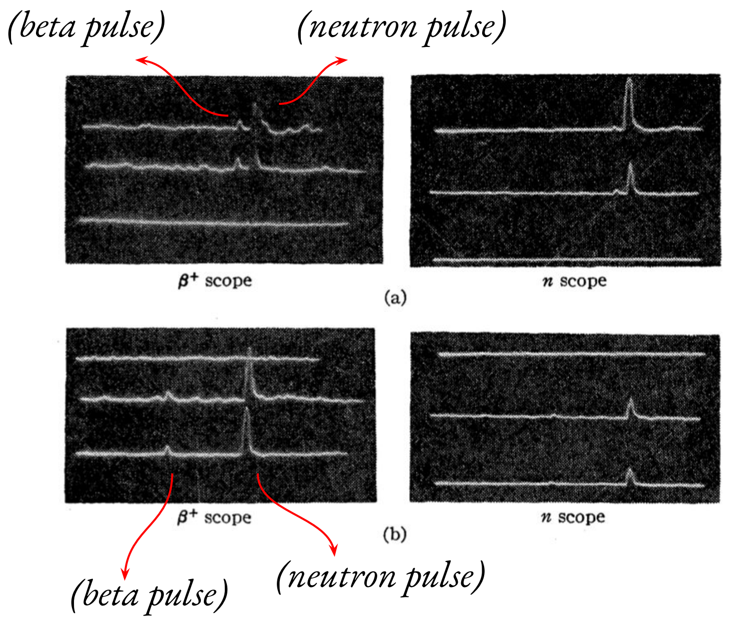
VI The anti-ν event data

The event data: pulse energy, delay time and count rates

Fig (a) and (b) show two accepted events at the top and bottom triad respectively with both low and high gains.

The **energies** deposited by all the pulses and the **delay time** between pairs of pulses are determined from the calibrated traces.

	top1	top2	bottom2	bottom3
β (MeV)	0.30	0.35	0.25	0.30
n (MeV)	5.8	3.3	2.0	1.7
Delay (us)	2.5		13.5	

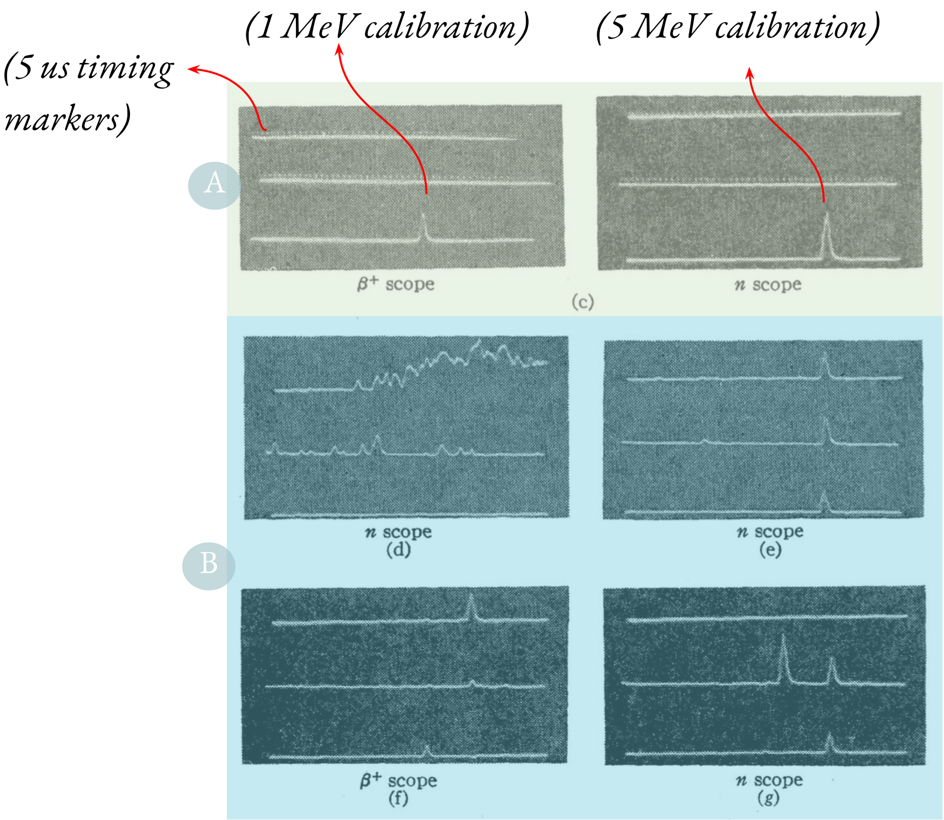


Experimental setup and data taking

VII Calibration and background rejection

A The oscilloscope **energy calibration**, converting the pulse height to energy deposited in the scintillator, is done using the cosmic ray muon mesons and a precision pulser. The **time calibration** is done using standard time markers on the trace from a crystal oscillator, as shown in Fig (c). Here, the event selection criteria were removed.

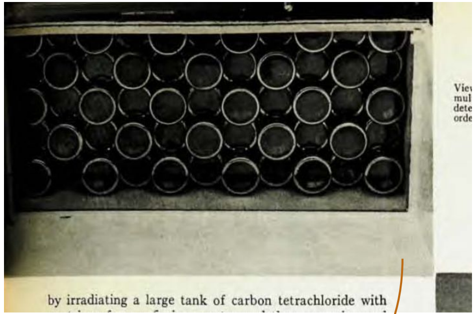
B The oscilloscope recordings can also further reject backgrounds, such as events from electrical noise (Fig (d)) and **penetrating cosmic rays** (Fig (e) and (f)). Fig (g), potentially due to cosmic rays, was rejected because of the extra pulse.



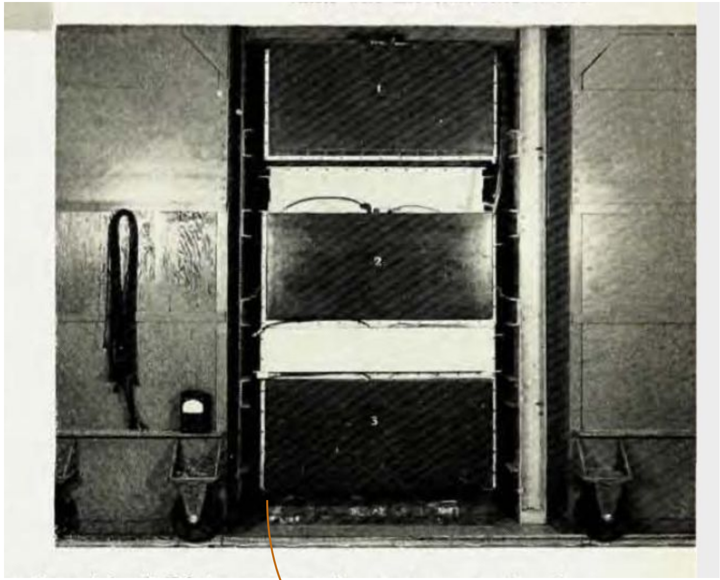
Experimental setup and data taking

Cool black-and-white pictures:)

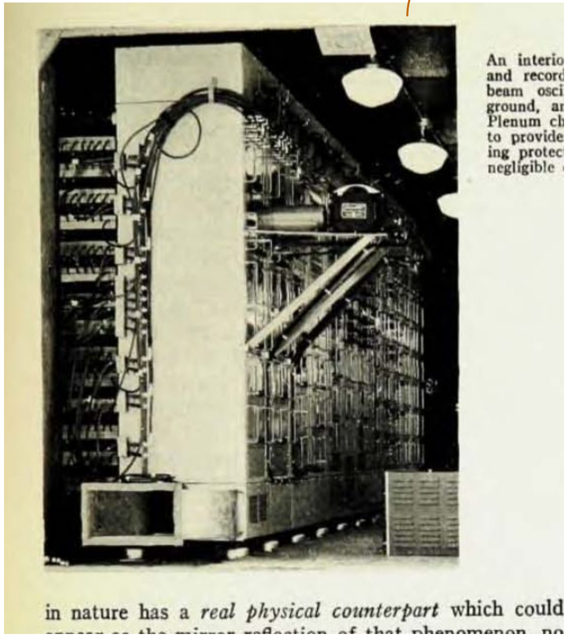
Trailer electronics



Photomultipliers



Two triads



Results and analysis

Given the ability to record pulse energies, delay time for anti-ν like events, there are 5 main arguments made to validate the discovery of the (electron) (anti)neutrino.

A. Firstly, the signals observed were associated with the reactor. And, the signal rate, or the scattering cross section, agrees with the prediction based on the neutrino theory and the antineutrino flux.

B. Secondly, the first pair of pulses was due to positron annihilation radiation.

C. Thirdly, the second pair of pulses was due to cadmium capture of a neutron.

D. Fourthly, the signal was a function of the number of target protons.

E. Lastly, the reactor-associated signal was not caused by reactor gamma rays or neutrons.

Results and analysis

A Calculate the antineutrino-like event rate and prove it is dependent on the reactor power. Lastly, verify this observed rate is consistent with the expected inverse beta decay cross section.

- The **antineutrino-like event rates** are recorded separately for the top and bottom triad, as shown in the table.
  - The anti-ν flux factor is a number proportional to the flux. At α=0.01, most neutrons are captured by 11 us. Thus, only counts from 0.75-7 us are accepted as signals.
  - The difference of counts when the reactor is on and off is huge, proving that the rate is dependent on the reactor power.
  - The accidental background rate is calculated with counts from 11-25 us corrected by a factor of 6.25/14. The net rate is (signal rate - accidental background rate).
  - Subtracted by the reactor-independent background rate, the final signal rate is 1.69±0.17 hr^{-1} and 1.24±0.12 hr^{-1} for the top and bottom triad respectively.

TABLE II. Summary of second series.

Triad	$\bar{\nu}$ flux factor	Run length (hr)	Counts from 0.75–7 μsec	Counts from 11–25 μsec	Accidental background (hr^{-1})	Net rate (hr^{-1})
Top	1.13	379.1	919	427	0.50±0.02	1.92±0.09
	0	38.8	27	40	0.46±0.07	0.23±0.15
Bottom	1.12	383.5	815	398	0.46±0.02	1.66±0.08
	0	128.0	119	145	0.50±0.04	0.42±0.09

Results and analysis

A Verify the observed rate is consistent with the expected anti-ν scattering cross section.

- To calculate the inverse beta decay cross section, the equation is as follows:

$$\sigma = \frac{R}{3600 F N \epsilon_n \epsilon_\beta} \text{ cm}^2, \qquad (3)$$

  - R = 1.5±0.1 hr^{-1}, the average signal rate per triad
  - F = 1.2×10^{13} $cm^{-2}s^{-1}$, the average anti-ν flux at the detector
  - N = 1.1×10^{28}, the number of hydrogen nuclei in each target tank
  - ε_n = 0.17±0.06, the neutron detection efficiency
  - ε_β = 0.15±0.02, the positron detection efficiency

detector.[11] Therefore

$$\sigma = \frac{1.5 \pm 0.1}{3600 \times 1.2 \times 10^{13} \times 1.1 \times 10^{28} (0.17 \pm 0.06)(0.15 \pm 0.02)},$$

$$\sigma = (1.2_{-0.4}^{+0.7}) \times 10^{-43} \text{ cm}^2.$$

This value is in agreement with the theoretically expected value[12] of $(1.0 \pm 0.17) \times 10^{-43}$ cm².

- The theoretical values are determined based on the number of antineutrinos expected at different anti-ν energies and the neutrino scattering cross section as a function of ν energies.
- The neutron and positron detection efficiencies are determined using external neutron and positron sources, Pu-Be and Cu^{64} respectively, in the target tank.

Results and analysis

B Prove that a reactor-associated positron causes the first smaller pulse.

- One way to prove the first smaller pulse are from a positron is to compare the **pulse-height spectrum** (the number of pulses recorded at different energies).
    - The reactor-associated first pulse spectrum is the top plot, the number of antineutrino events at different first pulse energies.
    - To compare, a positron source (Cu^{64}) was dissolved in water and the positron pulses were recorded. The external positron pulse spectrum is shown in the bottom plot.
    - The background pulses (including pulses taken when the reactor was off and pulses with long delay time) are plotted as well.
    - The top plot resembles the pulse spectrum of the positron source more than the background, which indicates the first pulse is due to positron annihilation.

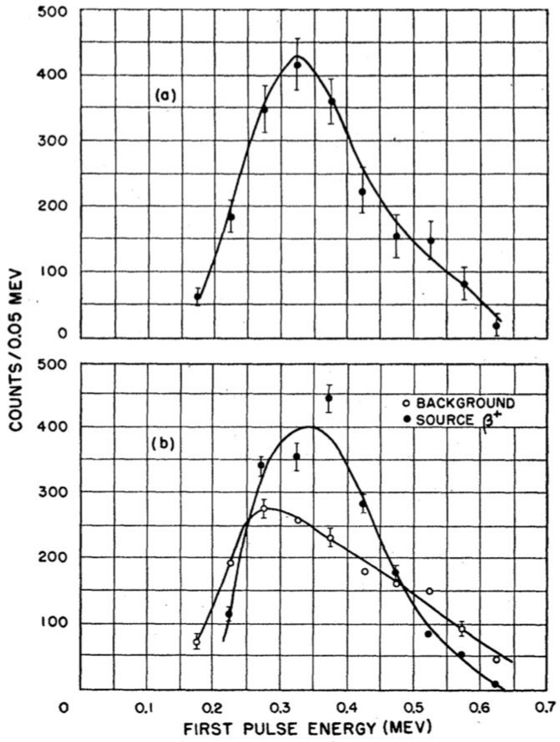


FIG. 13. (a) Pulse-height spectrum, first pulses of $\bar{\nu}$-like events. (b) Background and β^+ source spectra for comparison purposes.

Results and analysis

B Prove that a positron causes the first smaller pulse.

- Adding **lead shields** of various thicknesses between counter 2 and target tank B could also indicate that the first pulse is due to a positron.
  - With lead shields, the signal rates dropped due to the attenuation of radiation from tank B.
  - Importantly, the decreased detection efficiency is mostly due to the attenuation of the positron annihilation.
  - This is proved by putting the positron source (Cu^{64}) and the neutron source in the target tank. The positron signal rate and the neutron signal rate were determined for the various lead thicknesses. Indeed, the positron signal rate decreased much more and therefore can account for most of the anti-ν signal rate decrease.

Results and analysis

C Prove that a neutron causes the second larger pulse.

- One way to prove that the second pulse of antineutrino-like events are due to neutrons is to vary the cadmium concentration in the water target and compare the **time-delay spectrums** (number of events at different delay time)with predictions.
  - The plot here shows the time delay spectrums for α=0.010 and α=0.005. The two smooth curves are theoretical neutron capture rates vs capture time.
  - Indeed, the time delay distributions agree well with predictions. Increased cadmium concentration increases the rates and shifts the distribution towards shorter delay time.
  - The event rate at α=0 is consistent with that of accidental background, as expected.

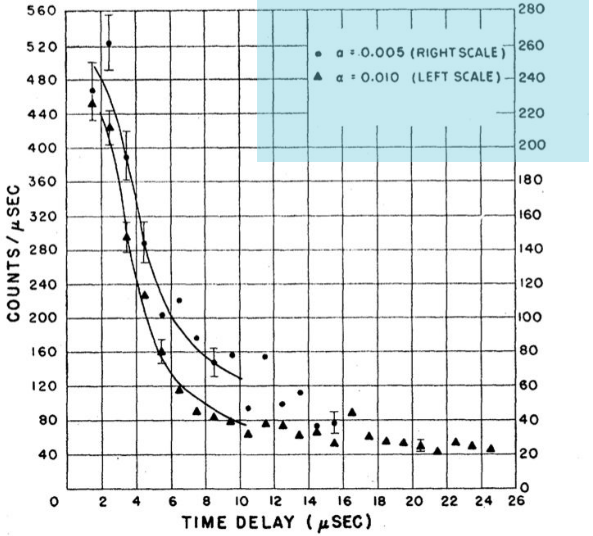


Fig. 14. Time-delay distributions of signal plus background for two different cadmium concentrations. The curves are theoretical[4] (neutron) distributions plus the calculated random background of 50 counts per channel for α=0.005 and 0.010.

Results and analysis

C Prove that a neutron causes the second larger pulse.

- The **pulse-height spectrum** of the second pulses can also be checked.
  - Different from the spectrum of the first pair of pulses, the number of reactor-associated events are plotted against the total energy of the second pair of pulses.
  - As seen from the plot, the second pulse spectrum is different from the background spectrum. It peaks at ~5 MeV and has an end-point near 9 MeV, as expected for neutron capture.

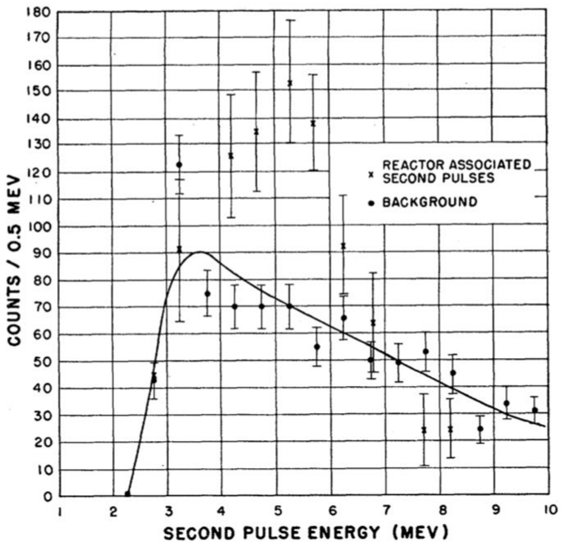


FIG. 15. Pulse-height spectrum for second pulses of $\bar{\nu}$-like events.

Results and analysis

D The dependence of the antineutrino events on the target proton numbers was established by diluting the target tank water with **heavy water**.

- Since the antineutrino deuteron scattering cross section is about 1/15 of the antineutrino proton cross section and the neutron detection efficiency in the mixture is roughly the same. The event rate is expected to drop by about a half. The observed rate did drop greatly as expected, establishing the dependence.

E Several ways can prove that the observed antineutrino events are not due to reactor neutrons and gamma rays. The previous heavy water test proves that the signals were not due to reactor neutrons as the rate dropped greatly. A direct test is done using additional **sawdust shield**.

- 76 cm thick sawdust shields were placed in front of and at the back of the detector, the less shielded area. The shields can attenuate the fast neutrons by a factor of 10 and the gamma rays by a factor of 5 or more. However, for identical runs with and without the shields, the signal rate didn't change much, indicating it's not due to reactor neutrons and gamma rays.

Conclusion

- Pauli and Fermi proposed the neutrino to solve the beta decay mystery.
- Reines and Cowan designed an experiment using large liquid scintillators to prove its existence.
- Various results from the experiment concluded that the reactor (anti)neutrino agreeing with the theoretical prediction was detected.

Reference

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Significance

"Each new discovery of natural science broadens our knowledge and deepens our understanding of the physical universe ; but at times these advances raise new and even more fundamental questions than those with which they answer. "

Frederick Reines and Clyde L. Cowan

Thanks!

Questions?