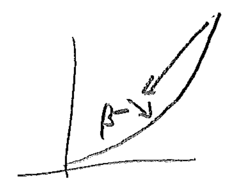
β-decay gives indirect evidence for neutrinos and an upper bound (~ few eV) on their mass

1956 Direct detection of antineutrinos from a nuclear reactor

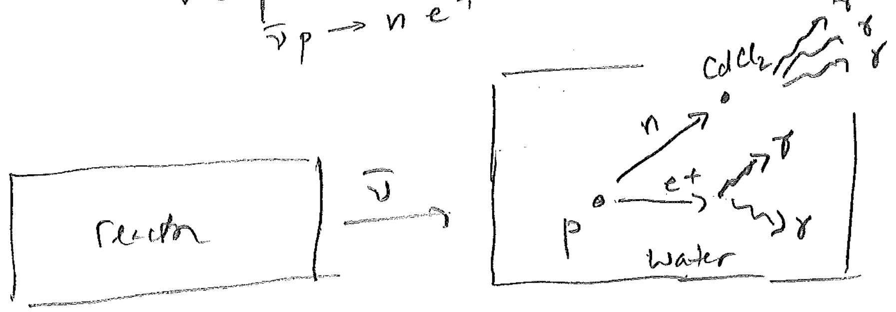
fission products copiously produce $\bar{\nu}$



$X \to Y e^- \bar{\nu}_e$

How detect them?

$$n \to p e^- \bar{\nu}$$
$$\bar{\nu} e^- p \to n$$
$$\bar{\nu} p \to n e^+$$



Signature: 2 0.511 MeV γ
followed by 3 to 4 γ w/ $E_{tot} \sim 9$ MeV
after $\sim 10^{-6}$ s

Reines - Cowan expt
at Savannah River reactor (S. Carolina)

$$Q = (m_n + m_{e+} - m_p - m_\nu)c^2 = -1.84 \text{ MeV}$$

energy required to cause reaction

Slightly more kinetic energy required to produce moving products.

(HW problems) $K_{min} = \dfrac{m_1 + m_2 + m_3}{2m_2} |Q|$

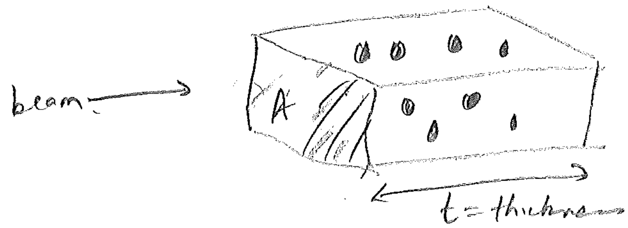
$$= \frac{m_\nu + m_p + (m_e + m_n)}{2m_p} |Q|$$

$$\approx 1.001 |Q|$$

Reactor produces $\bar{\nu}$ w/ $E_{\bar{\nu}} \sim 3$ MeV

Cross-section σ = effective area of target

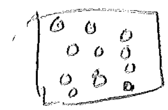
What is probability of absorption?



V = volume $= At$

n = density of targets

N = # targets $= nAt$

Total effective area of targets $= N\sigma$ $\longrightarrow$  (looking head on)

Total area $= A$

Prob. of absorption $= \dfrac{N\sigma}{A} = n\sigma t$

F = beam flux $= \dfrac{\#\text{ projectiles}}{m^2 \cdot s}$

$\dfrac{\#\text{ projectiles}}{\text{sec}} = F \cdot A$

$\dfrac{\#\text{ hits}}{\text{sec}} = F \cdot A \cdot n\sigma t = F n \sigma V$

let ϵ = efficiency of detecting events

rate $R = \dfrac{\#\text{ events detected}}{\text{sec}} = \epsilon F n \sigma V$

$$\therefore \quad \sigma = \frac{R}{\epsilon F n V}$$

1953-1956

The Reines-Cowan Experiments

Detecting the Poltergeist

Hanford Team 1953

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.

In 1951, when Fred Reines first contemplated an experiment to detect the neutrino, this particle was still a poltergeist, a fleeting yet haunting ghost in the world of physical reality. All its properties had been deduced but only theoretically. Its role was to carry away the missing energy and angular momentum in nuclear beta decay, the most familiar and widespread manifestation of what is now called the weak force. The neutrino surely had to exist. But someone had to demonstrate its reality. The relentless quest that led to the detection of the neutrino started with an energy crisis in the very young field of nuclear physics.

183 cm × 132 cm

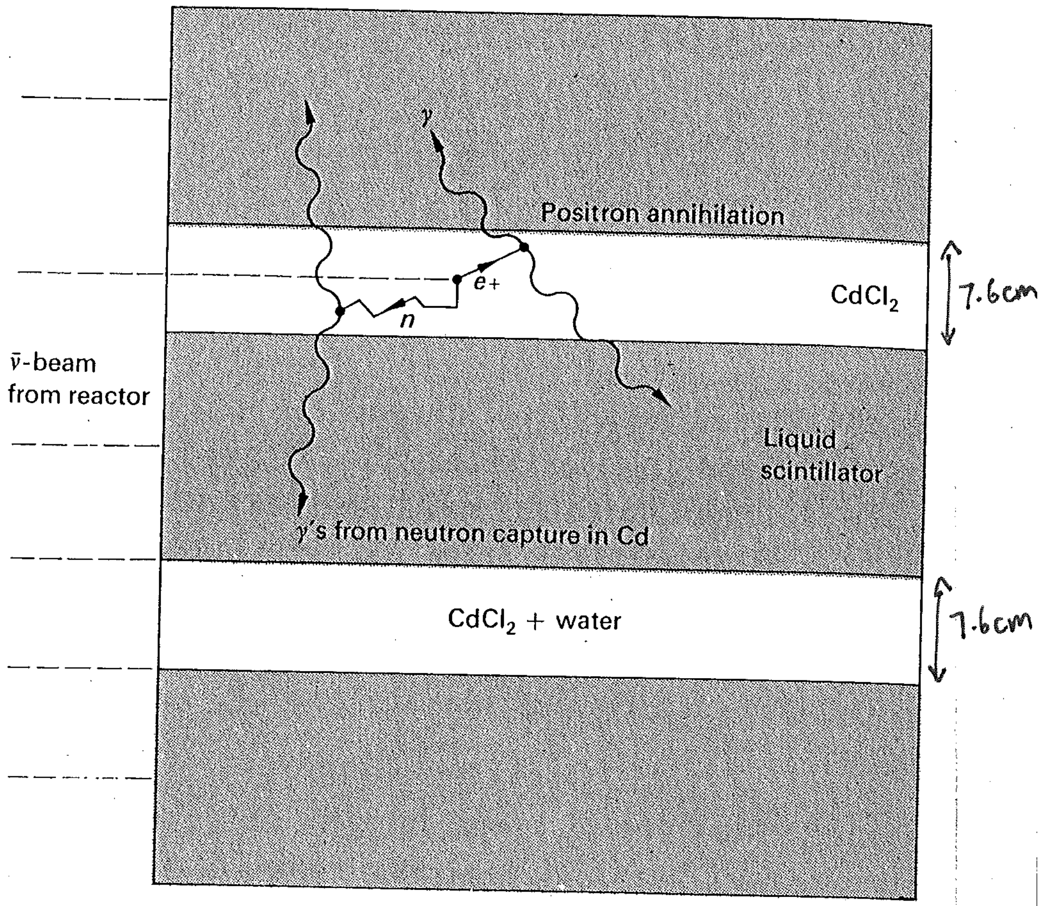


Fig. 6.4 Schematic diagram of the experiment by Reines and Cowan (1959), interactions of free antineutrinos from a reactor.

Perkins

water volume ≈ 400,000 cm^3

6' 4 $\frac{1}{3}$'

183cm × 132cm × 2(7.6cm) = 367,000 cm^3

Asimov: 6 $\frac{1}{4}$' × 4 $\frac{1}{2}$' × 6''

[$\bar{\nu}\ {}^{16}O \to e^+\ {}^{16}N$
has threshold of 11.44 MeV] DV-4

Experiment

$V = 3.7 \times 10^5\ cm^3$

$n = \frac{\#\ protons}{cm^3} = \left(\frac{2\ protons}{H_2O}\right)\left(\frac{6\times10^{23}\ H_2O}{mole}\right)\left(\frac{mole}{18\ g}\right)\left(\frac{1\ g}{cm^3}\right) = 6.7 \times 10^{22}\ \frac{protons}{cm^3}$

[$nV = 2.5E28$ protons
paper says 2.2E28?]

reactor flux $F = 1.2 \times 10^{13}\ \frac{\bar{\nu}}{cm^2 \cdot s}$

$\epsilon = 0.025$

measured rate
(difference between reactor on & reactor off) $= \frac{70\ events}{day} = 8.1 \times 10^{-4}\ \frac{events}{sec}$

$\Rightarrow \sigma_{\bar{\nu}p \to e^+n} = 1.1 \times 10^{-43}\ cm^2$

[~ expected σ for $E_\nu = 1$ MeV]
[1956: $\sigma_{exp} = 6E{-}44\ cm^2 \pm 25\%$]

This is very small!

Compare to typical σ for n absorption by a uranium nucleus.

$\sigma_n \sim \pi R^2, \quad R = A^{1/3} r_0$

$\sim 170\ fm^2$

$\sim 1.7 \times 10^{-24}\ cm^2$

$\left(\begin{matrix} A^{1/3} = 38 \\ \pi \sim 3 \\ r_0^2 \sim 1.5 \end{matrix}\right)$

Define 1 barn $= (10\ fm)^2 = 10^{-24}\ cm^2$

$\sigma_{\bar{\nu}p \to e^+n} = 1.1 \times 10^{-19}$ barns [very small barn]

[$\frac{1}{n\sigma} = \frac{cm}{10^{23} \cdot 10^{-43}} = 10^{20}\ cm = 100\ ly$
$1\ ly = (3E7s)(3E10\ cm/s) = 10^{18}\ cm$] ← HW

What about ν detection? (not $\bar{\nu}$)

Recall β^+ decay: ${}^{A}_{Z}X \to {}^{A}_{Z-1}Y\, e^+ \nu$

$$\nu\, e^+\, {}^{A}_{Z-1}Y \to {}^{A}_{Z}X$$

$$\nu\, {}^{A}_{Z-1}Y \to {}^{A}_{Z}X\, e^-$$

eg $$\nu\, {}^{37}_{17}Cl \to {}^{37}_{18}Ar\, e^-$$

$$Q = \Delta({}^{37}Ar) - \Delta({}^{37}Cl) = -0.814 \text{ MeV}$$

$\longrightarrow \nu$

dry cleaning fluid
CCl_4 carbon tetrachloride
C_2Cl_4 perchloroethylene

$\to {}^{37}Ar$ (flush out + concentrate)

(Ray Davis, 1955 [F+H, p. 187])
(Davis + Harmon, 1959)

(${}^{36}Ar$, ${}^{38}Ar$, ${}^{40}Ar$ stable)

${}^{37}Ar$ unstable w/ $T_{\frac{1}{2}} = 35$ days

EC: $e^-\, {}^{37}_{18}Ar \to {}^{37}Cl\, \nu$ ($Q = 0.814$ MeV)

$\downarrow$
[Auger electrons]

ν is neutral. Is $\nu = \bar{\nu}$?

Reactor neutrinos should cause $^{37}Cl \to {}^{37}Ar$.

Not found!

Difference between ν + $\bar{\nu}$? Lepton number (Konopinski, Mahmoud 1953)

$L(e^-) = L(\nu) = 1$

$L(e^+) = L(\bar{\nu}) = -1$

$\bar{\nu} p \to n e^+$ $L = -1$ both sides

$\nu n \to p e^-$ $L = 1$ " "

$\bar{\nu} n \not\to p e^-$ L violated