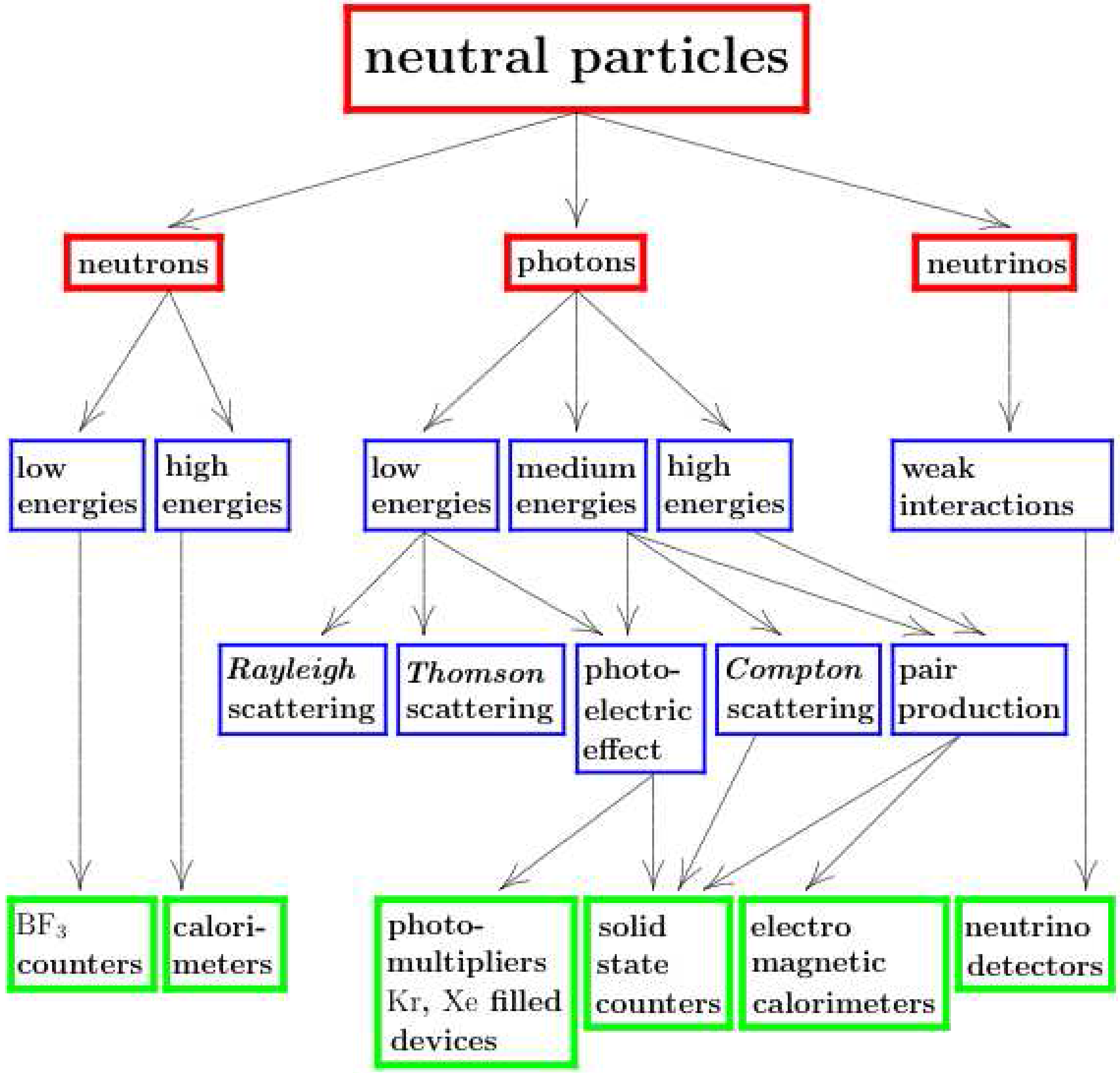
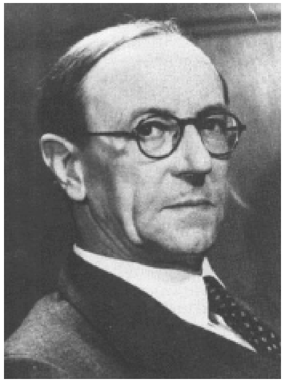
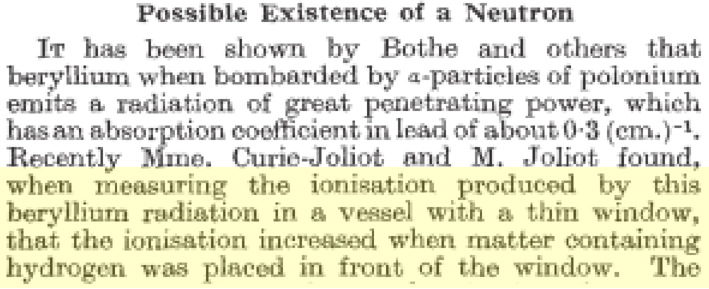
Neutral Particles



Neutron detectors

- ❖ Neutron detectors do **not** detect neutrons but products of neutron interaction!

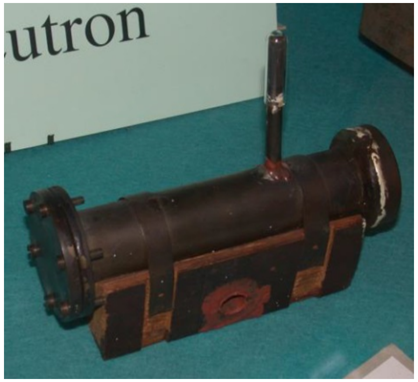


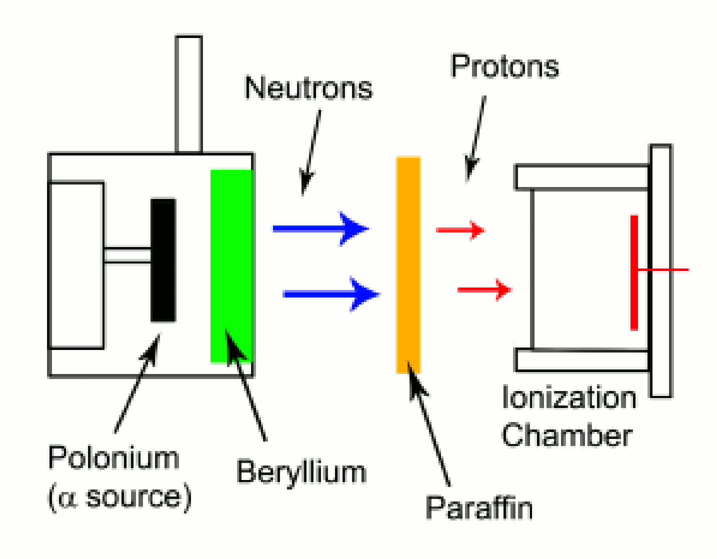


Possible Existence of a Neutron

IT has been shown by Bothe and others that beryllium when bombarded by α-particles of polonium emits a radiation of great penetrating power, which has an absorption coefficient in lead of about 0·3 (cm.)$^{-1}$. Recently Mme. Curie-Joliot and M. Joliot found, when measuring the ionisation produced by this beryllium radiation in a vessel with a thin window, that the ionisation increased when matter containing hydrogen was placed in front of the window. The

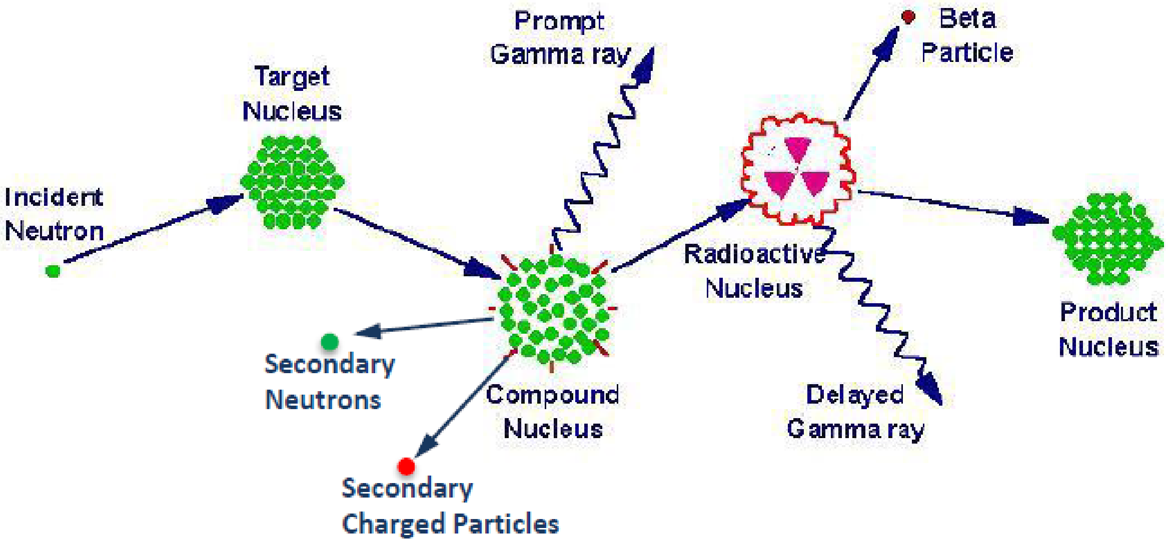
James Chadwick, Nature 132 (1932) 3252





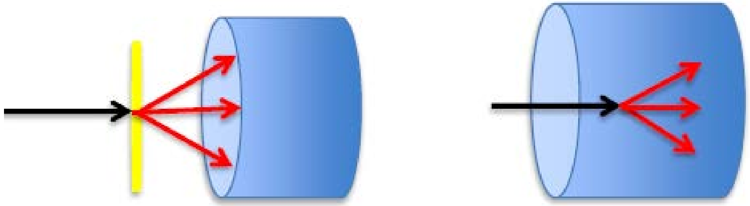
General detection principle

- Neutron detectors do **not** detect neutrons but products of neutron interaction!



Detection of a neutron is a sequential process

1. Interaction of the incident neutron: neutron transport
2. Transport of secondary particles to or within sensing elements
   hadron, ion, photon transport
3. Primary ionization by secondary particles
4. Conversion to optical photons, gas amplification:
   Transport of electrons and optical photons
5. Conversion to electrical signal



external converter (radiator) converter = detector

Interaction of Neutrons

Indirect detection technique: induce neutrons to interact and produce charged particles.

- $n + {}^{6}Li \rightarrow \alpha + {}^{3}H + 4.78\ MeV \quad \Rightarrow \quad Li(Tl)\ scintillator$
- $n + {}^{10}B \rightarrow \alpha + {}^{7}Li + 2.31\ MeV \quad \Rightarrow \quad BF_3\ gas\ counter$
- $n + {}^{3}He \rightarrow p + {}^{3}H + 0.765\ MeV \quad \Rightarrow \quad {}^{3}He - filled\ proportional\ chambers$
- $n + p \rightarrow n + p \quad \Rightarrow \quad proportional\ chambers\ with\ e.g. CH_4$
- $n + {}^{235}U \rightarrow fission\ products \quad \Rightarrow \quad coated\ proportional\ counters$
- $n + nucleus \rightarrow hadron\ cascade \quad \Rightarrow \quad calorimeters$

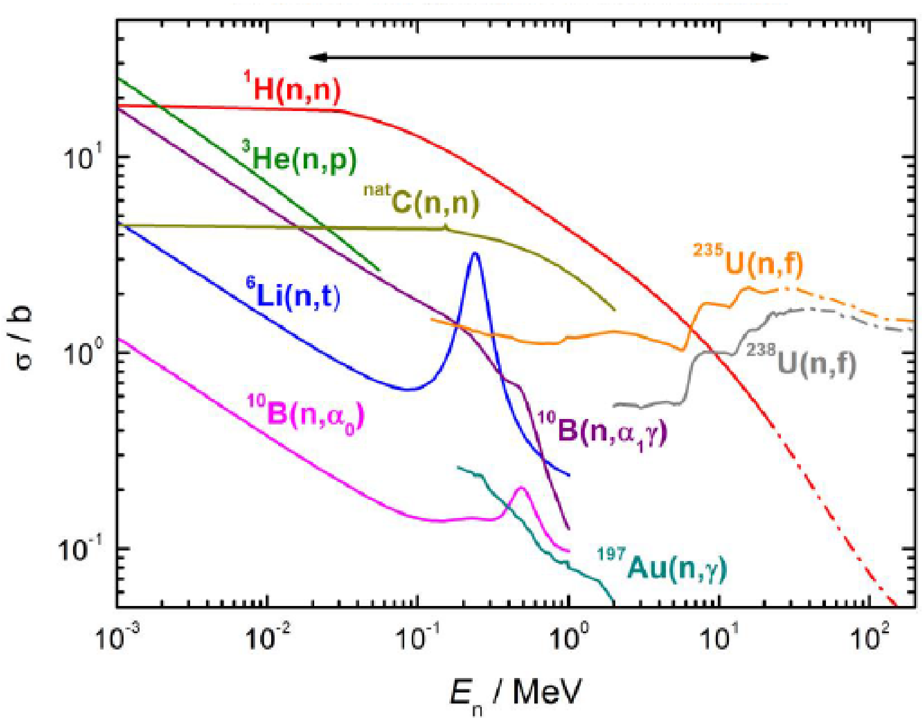
Neutron detection and identification is important in the field of radiation protection because the relative biological effectiveness (quality factor) is high and depends on the neutron energy.

$$H\ [Sievert] = q \cdot D[Gray]$$

Interaction of neutrons with matter

❖ Neutron detectors can only be detected after conversion to charged particles or photons:

Elastic scattering:	$^{A}X(n,n)^{A}X$	→ recoil nucleus $^{A}X^{Z+}$
Inelastic scattering:	$^{A}X(n,n'\gamma)^{A}X$	→ recoil nucleus $^{A}X^{Z+}$, e^-
Radiative capture:	$^{A}X(n,\gamma)^{A+1}Y$	→ e^-
Neutron emission:	$^{A}X(n,2n)^{A-1}Y$	→ radioactive daughter
Charged-particle emission:	$^{A}X(n,lcp)^{A'}Y$	→ (lcp = p, d, t, α), recoil nucleus $^{A'}Y^{Z+}$
Fission:	$n + {}^{A}X \rightarrow {}^{A1}X_1 + {}^{A2}X_2 + \nu n$	→ fission fragments



cross section relevant
for neutron detection

Neutron Detection

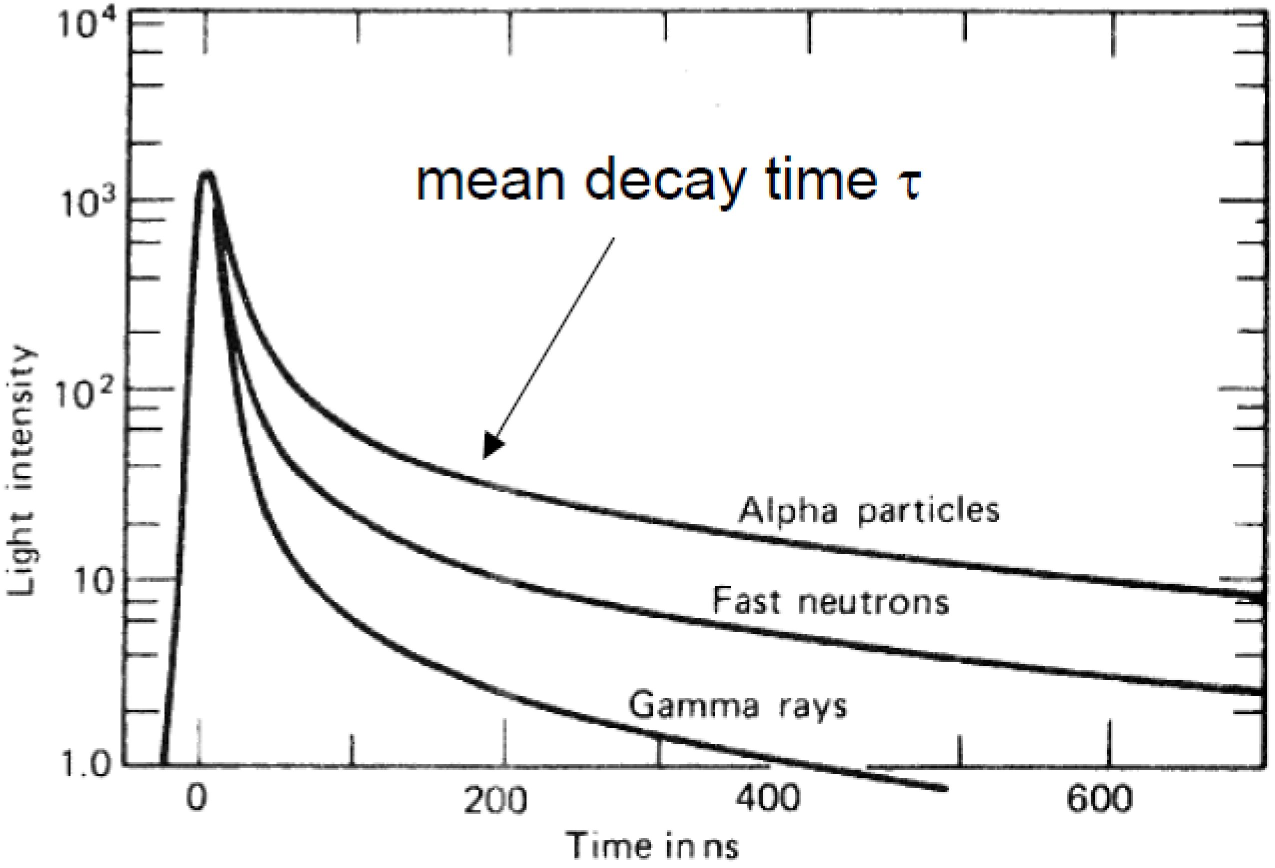
$$n + {}^{3}He \rightarrow ({}^{4}He)^{*} \rightarrow p + {}^{3}H, \quad \text{Q=0.765 MeV}$$

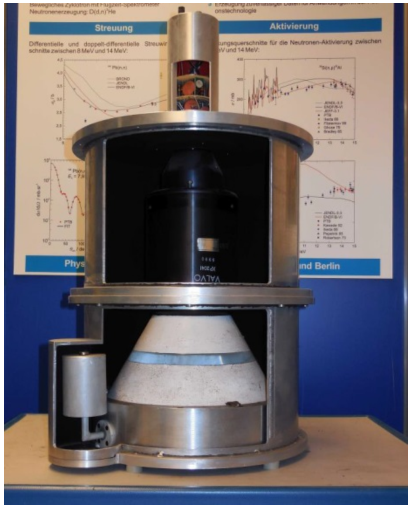
Bonner sphere

Moderate neutrons in spheres of different sizes and then detect the charged particles in a proportional counter in the center.

Pulse shape discrimination

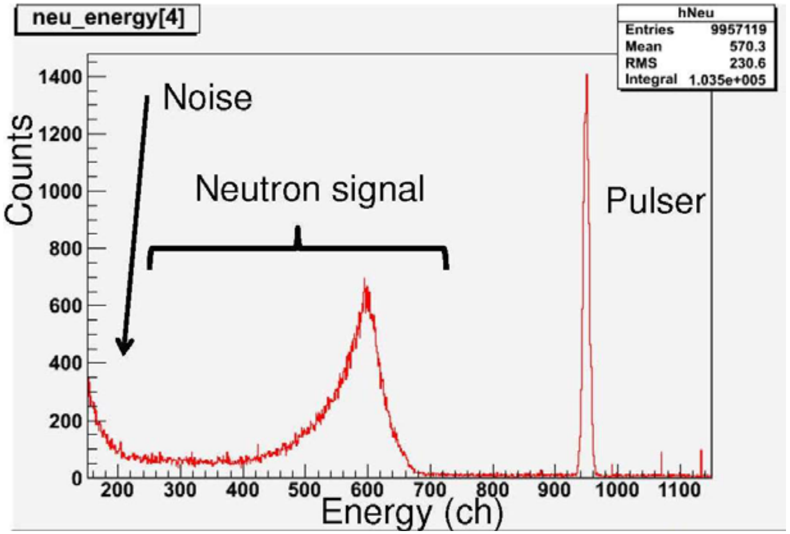
- Pulse shape discrimination (PSD) in organic scintillators are used in particularly liquid scintillators (NE213 / BC501A)
- PSD is due to long-lived decay of scintillator light caused by high dE/dx particle – neutron scatter interaction events causing proton recoil

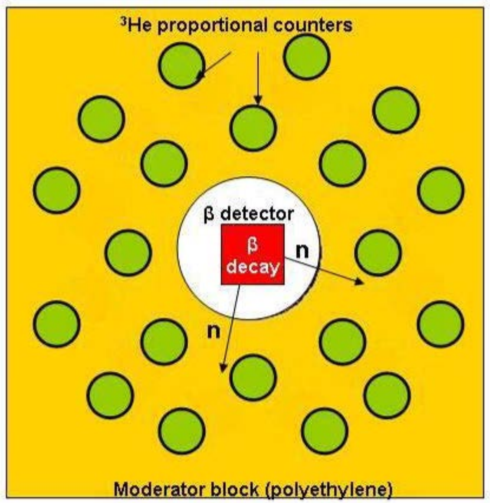




BELEN - Neutron Detection

$n + {}^{3}He \rightarrow p + {}^{3}H + 765\ keV \qquad \sigma_{th} = 5400\ b$

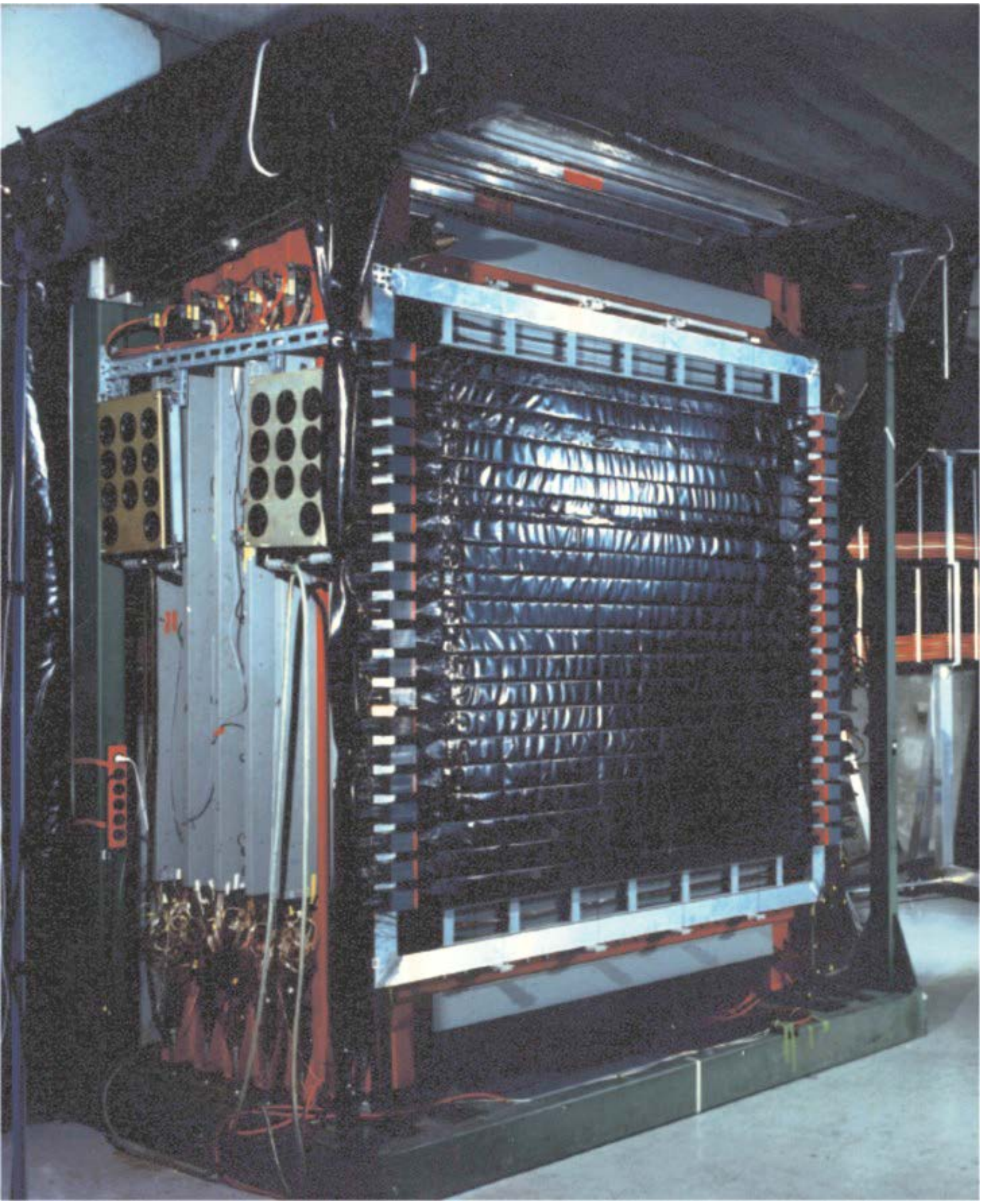


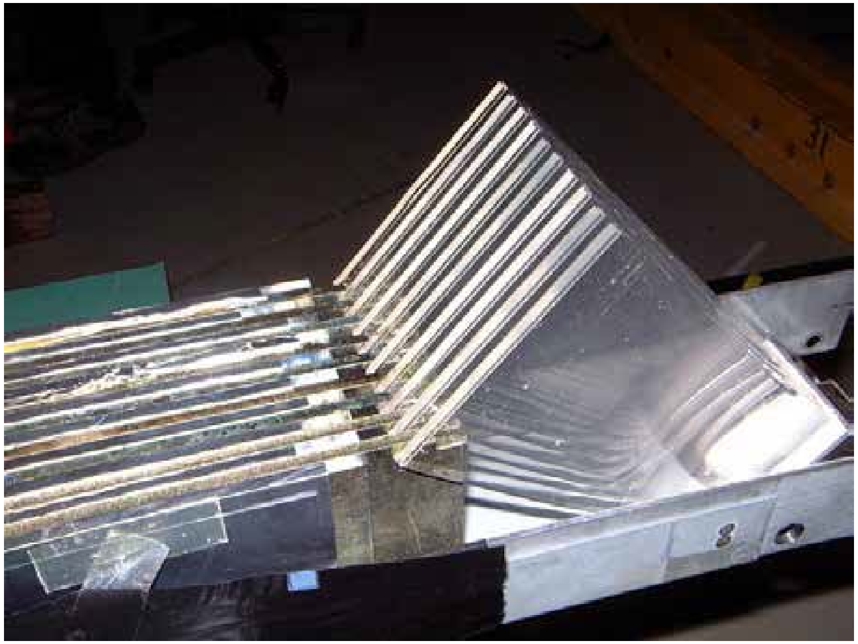


BELEN-30 (90x90x80 cm^3 PE)

- 20 ^{3}He counters (20 atm) outer ring
- 10 ^{3}He counters (10 atm) inner ring
- efficiency (1 keV – 1MeV) ~ 40%

Large Area Neutron Detector



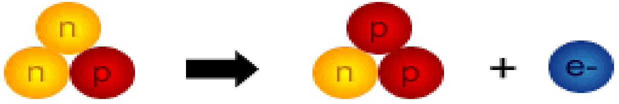


Large ***A***rea ***N***eutron ***D***etector (2m x 2m x 1m)

- neutron energy $T_n \leq 1$ GeV
- $\Delta T_n/T_n = 5.3\%$
- efficiency ~1
- passive Fe-converter

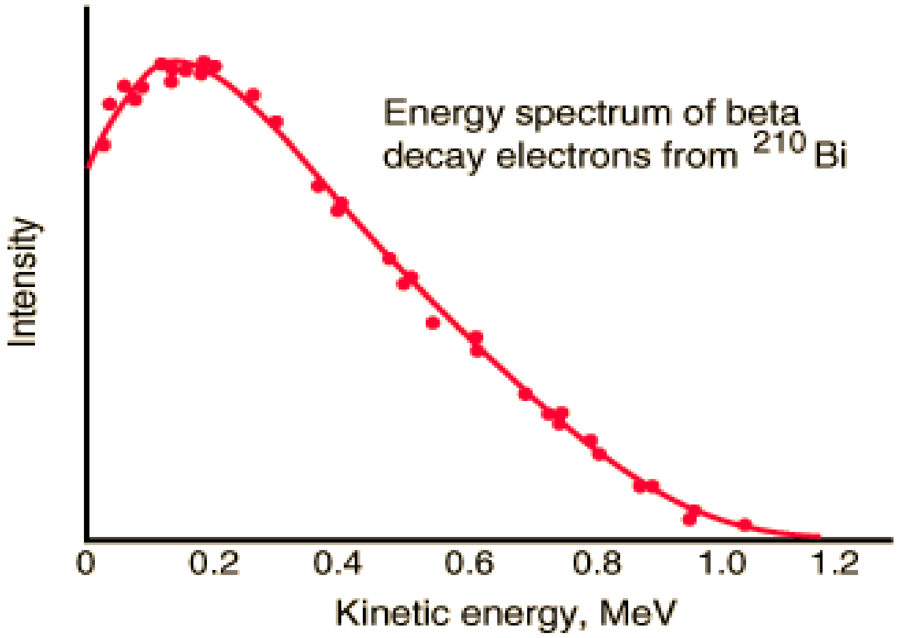
Neutrinos

Beta minus decay



Beta plus decay

- A neutron turns into a proton, emitting an electron
- A fixed energy is released
  - Q = difference in binding energy
- Charge is conserved


Energy spectrum of beta decay electrons from ^{210}Bi

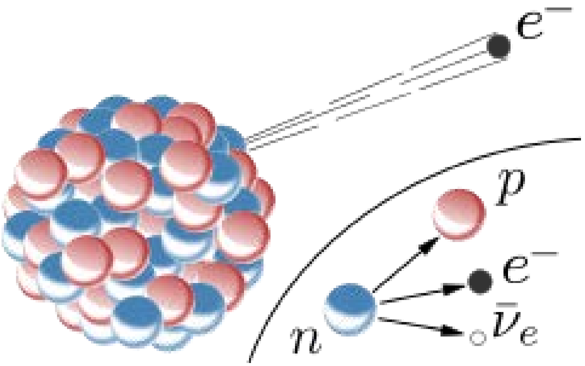
- But a spectrum of electron energies was observed!
- Are the conservation laws wrong?
- Or is something else going on?
- Many were ready to give up these fundamental laws

Neutrinos

What if beta decay were a 3 body process?

The new particle would have to be:

- → Neutral
- → Very light or massless
- → Rare interactions



Wolfgang Pauli

Pauli postulated the invisible neutrino!
In a letter addressed:
"Dear Radioactive Ladies and Gentlemen..."

Interaction of Neutrinos

- $\nu_e + n \rightarrow p + e^-$
- $\overline{\nu_e} + p \rightarrow n + e^+$ (discovery of the neutrino)
- $\nu_\mu + n \rightarrow p + \mu^-;\ \ \nu_\tau + n \rightarrow p + \tau^-$
- $\overline{\nu_\mu} + p \rightarrow n + \mu^+;\ \ \overline{\nu_\tau} + p \rightarrow n + \tau^+$

❖ Small cross section for MeV neutrinos:

$$\sigma(\nu_e N) = \frac{4}{\pi} \cdot 10^{-10} \left\{ \frac{\hbar p}{(m_p c)^2} \right\}^2 = 1.6 \cdot 10^{-44} cm^2 \quad for\ 0.5\ MeV$$

❖ Rate of solar neutrinos interacting in the Earth:

$$N \cdot \sigma \cdot d \cdot \rho \cdot flux = 6.022 \cdot 10^{23} \cdot 1.6 \cdot 10^{-44} cm^2 \cdot 1.2 \cdot 10^9 cm \cdot 5.5 \frac{g}{cm^3} \cdot 6.7 \cdot 10^{10} cm^{-2} s^{-1} = 4 cm^{-2} s^{-1}$$

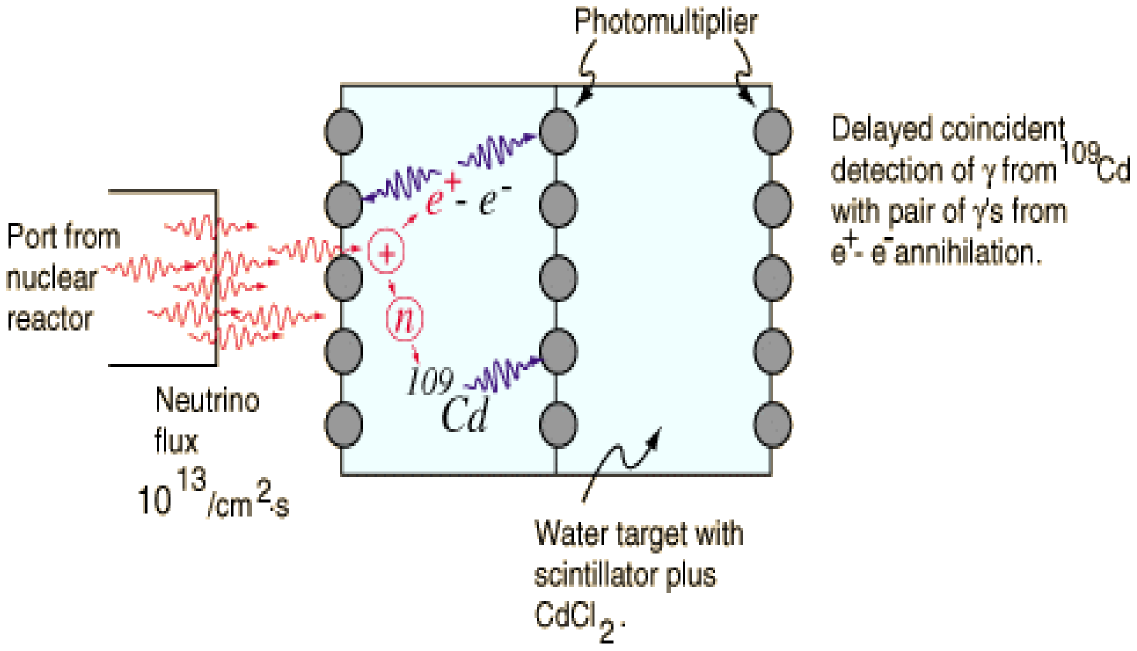
❖ For high energies (GeV-range):

$$\sigma(\nu_\mu N) = 0.67 \cdot 10^{-38} \cdot E_\nu[GeV] \quad cm^2/nucleon$$

Detecting the Neutrinos

Inverse beta decay:

$$\boxed{\bar{\nu}_e + p \rightarrow e^+ + n}$$

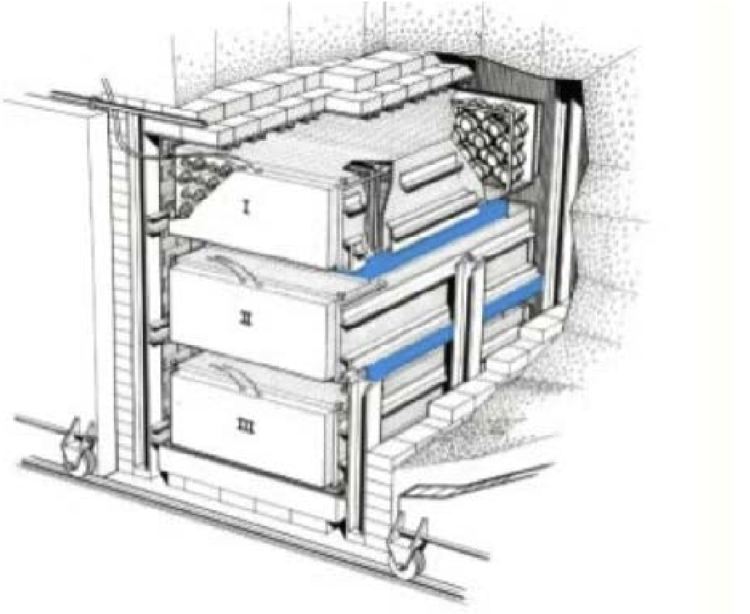


Experimental needs:

- Strong neutrino source → reactor
- Proton target → H in water
- Positron and neutron detector
  - Liquid scintillator to detect gammas
  - $CdCl_2$ target to capture neutrons
  - Delayed coincidence

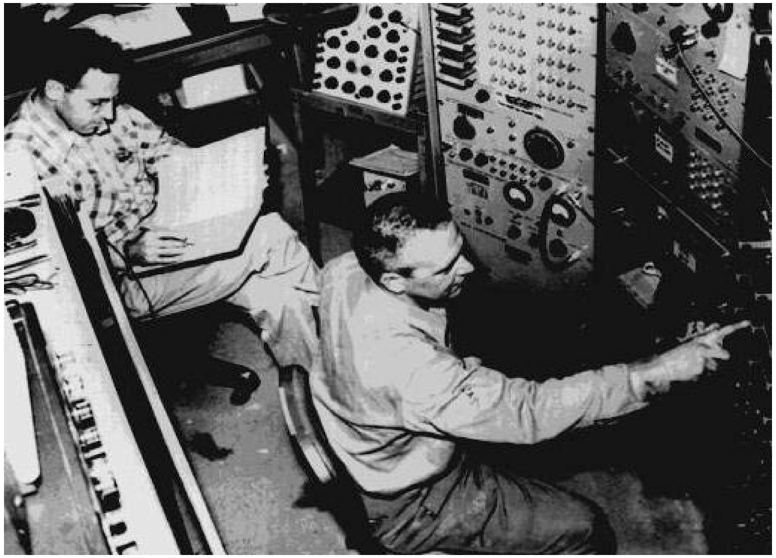
Discovery, Reines & Cowan 1956

- Conducted a series of experiments
- Stage 1: Hanford site, Washington
  - Too much background from cosmic rays
- Stage 2: Savannah River, South Carolina
  - Better shielding
  - 11 m from reactor
  - 12 m underground
- 200 liters of water with 40 kg $CdCl_2$
- Sandwiched between scintillator layers



Results:
- ~3 neutrino events per hour detected
- Used on-off switch on reactor
- Neutrinos disappeared when reactor was off

Cowan died in 1974, but Reines awarded Nobel Prize in 1995



Solar Neutrinos

Electron neutrinos produced in fusion chain

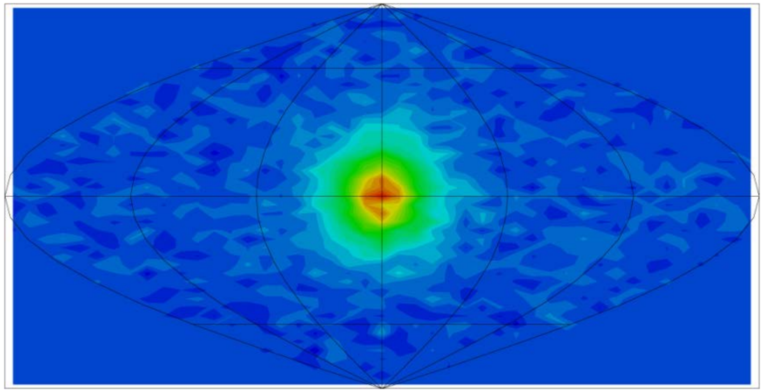
99% of solar neutrinos from pp fusion

First observed in 2014 by Borexino

Small fraction from 7Be and 8B

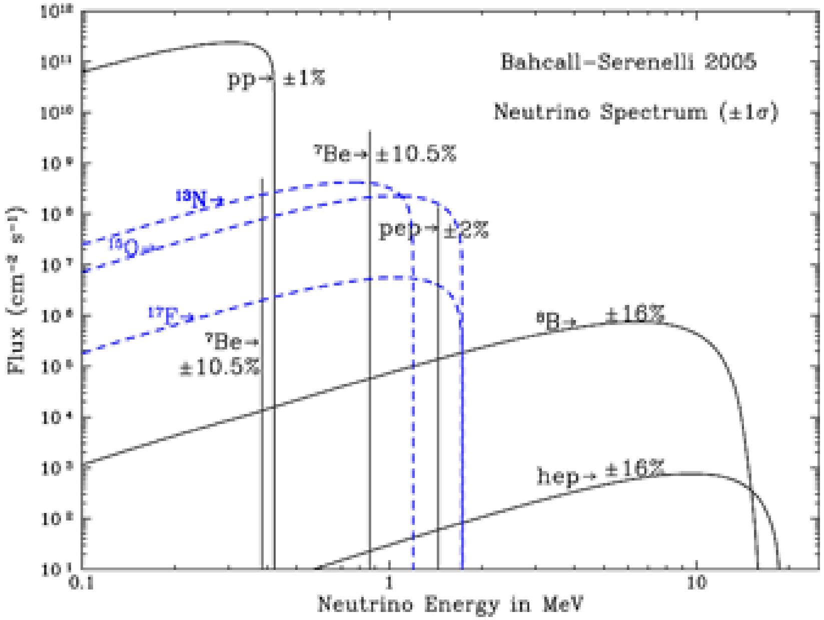
Extend to high E

Easier to detect



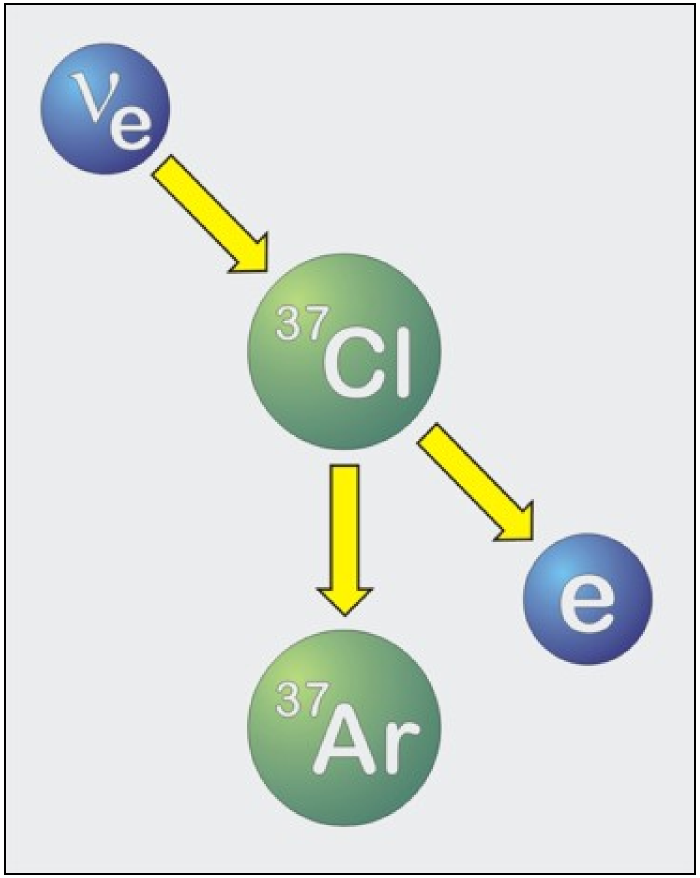
Bachall predicted the solar neutrino flux in 1964

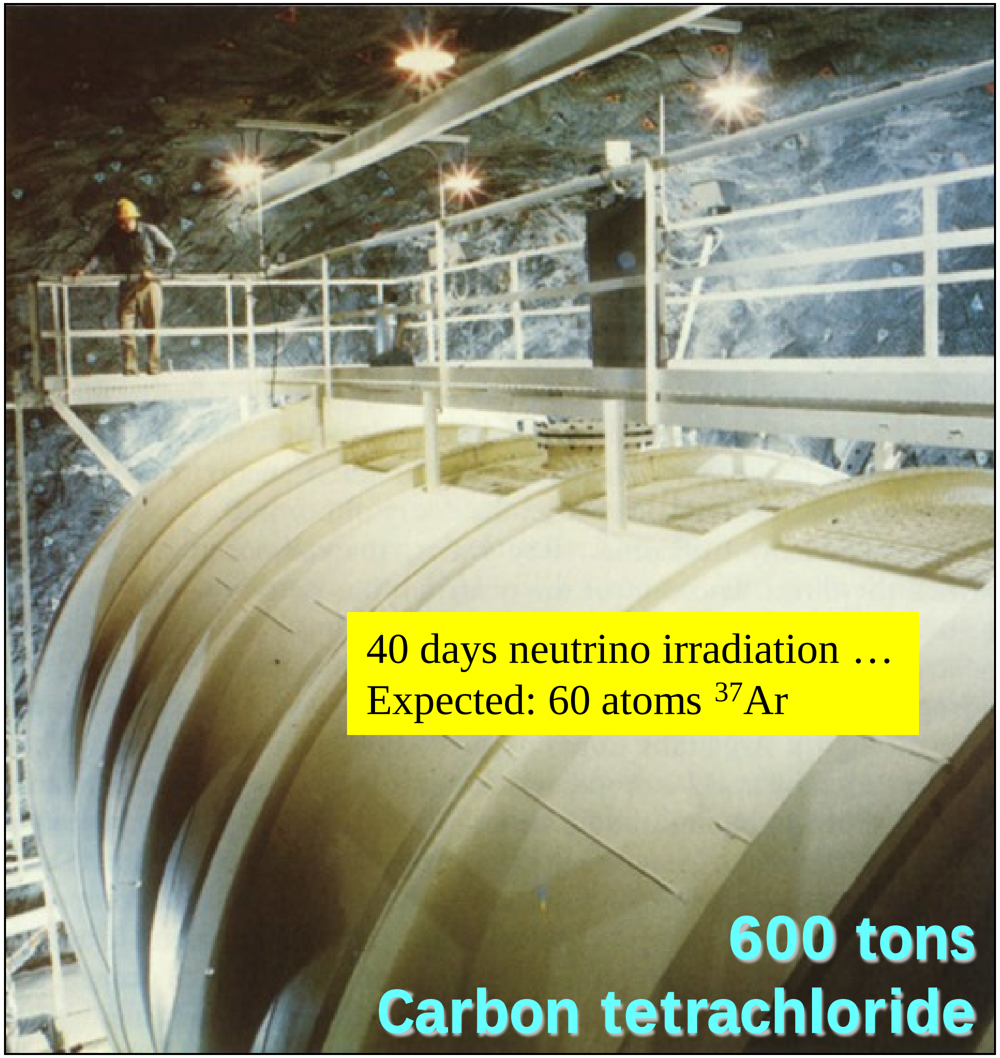
He would refine this with an incredibly precise solar model over the next 50 years



First measurement of the solar neutrinos

Inverse beta-decay („neutrino-capture”)





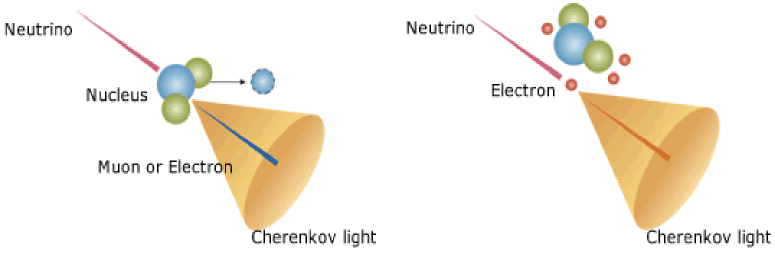
40 days neutrino irradiation …
Expected: 60 atoms ^{37}Ar

600 tons
Carbon tetrachloride

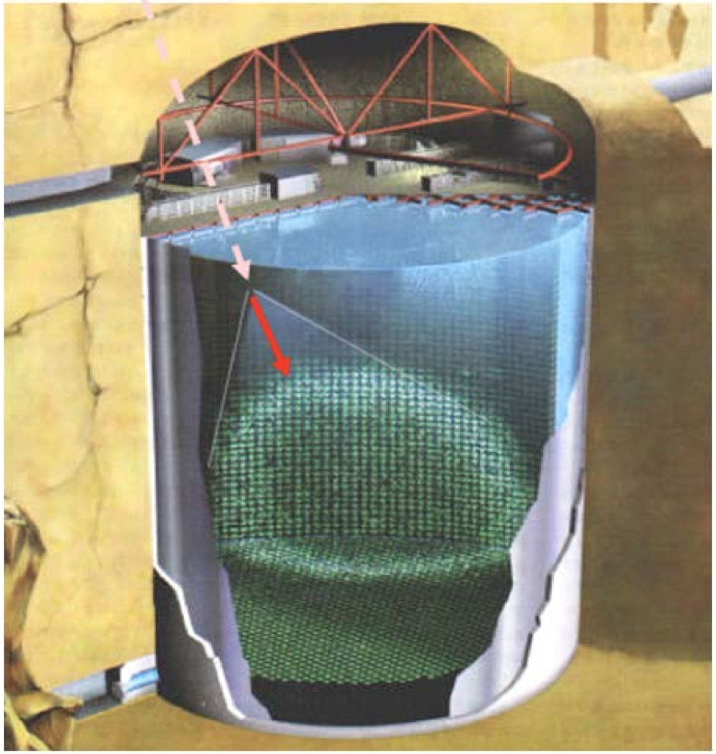
Homestake Sun neutrino-Observatory (1967–2002)

Super Kamiokande – Detection Concept

- Muon neutrinos interact with nucleons via charged current to produce ultra relativistic muons
- The muons travel faster than the speed of light in the detector (still slower than c)
- This produces a cone of Cherenkov light
  - Same principle as a sonic boom
- Light is detected by photo sensors

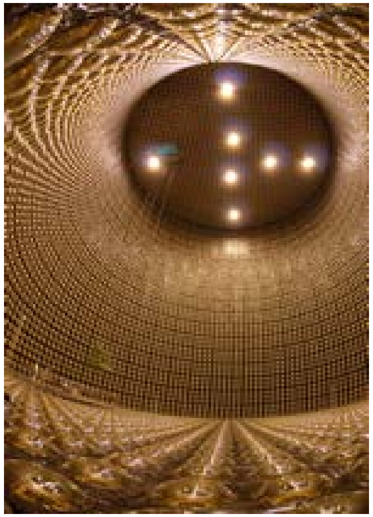


The generated charged particle emits the Cherenkov light.

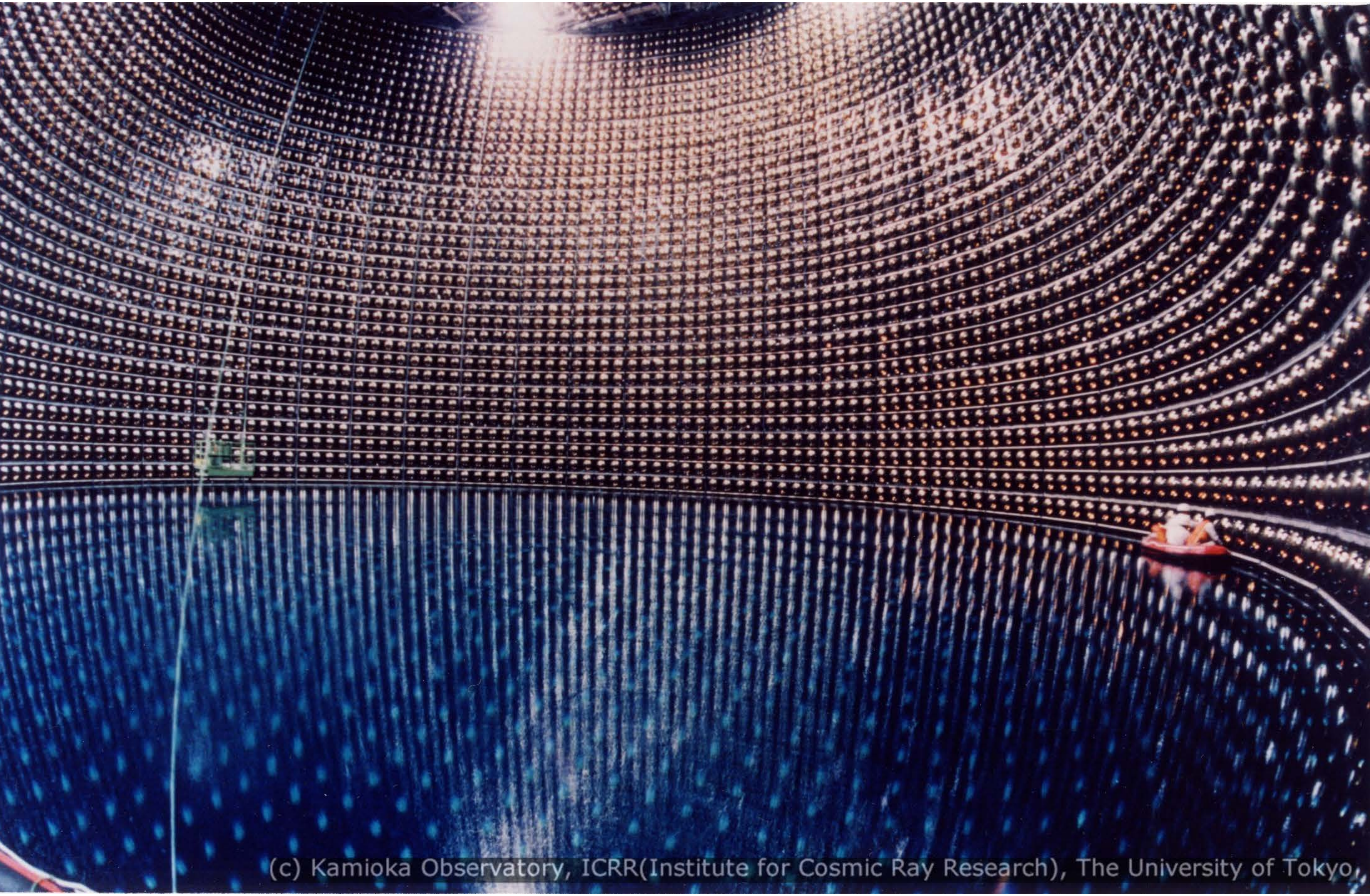


Super Kamiokande – the Detector

- 40 m water tank
- Filled with 50 ktons pure water
- Largest water Cherenkov detector in the world!
- >11,000 photomultipliers (PMTs) to detect light
- PMTs + electrical connections waterproof


Super Kamiokande – the Detector



(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo