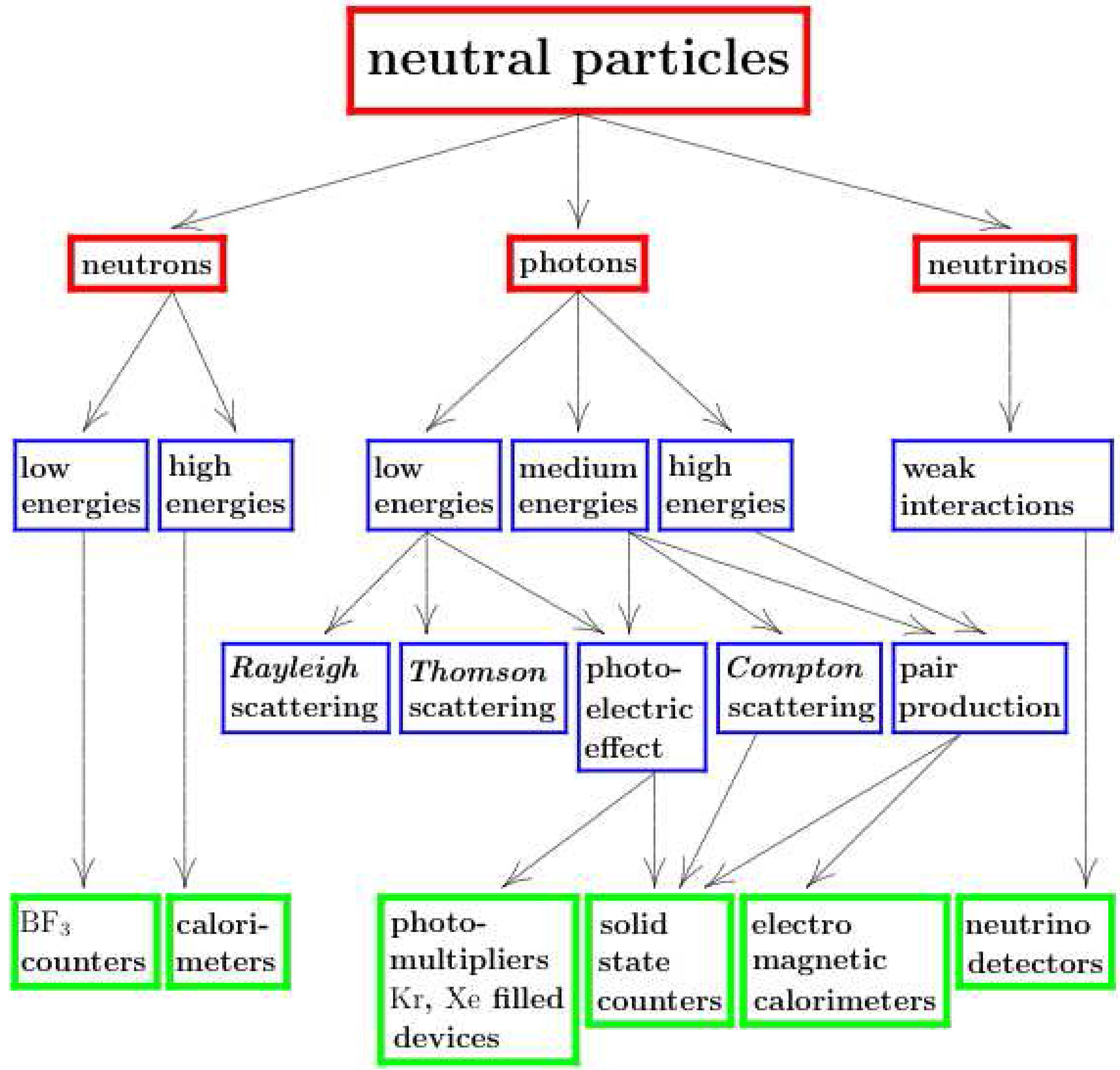
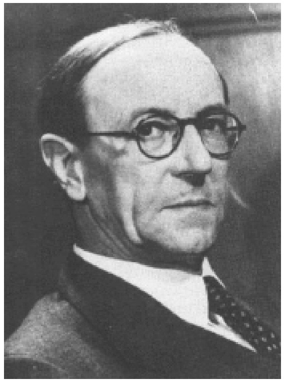
Neutral Particles



Neutron detectors

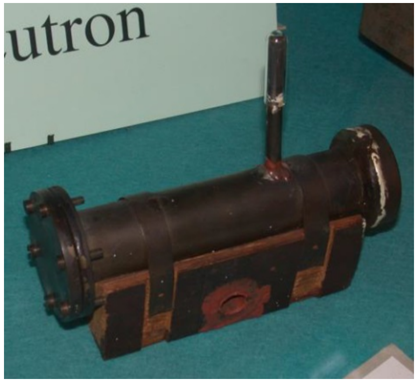
❖ Neutron detectors do **not** detect neutrons but products of neutron interaction!

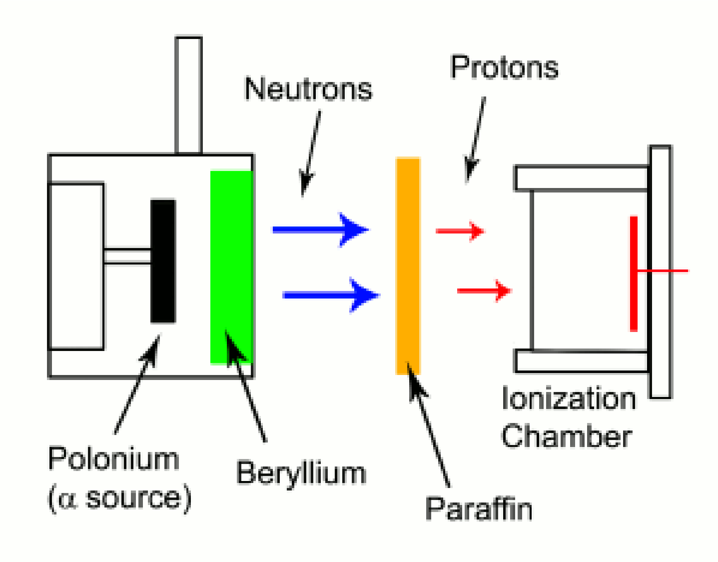


Possible Existence of a Neutron

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

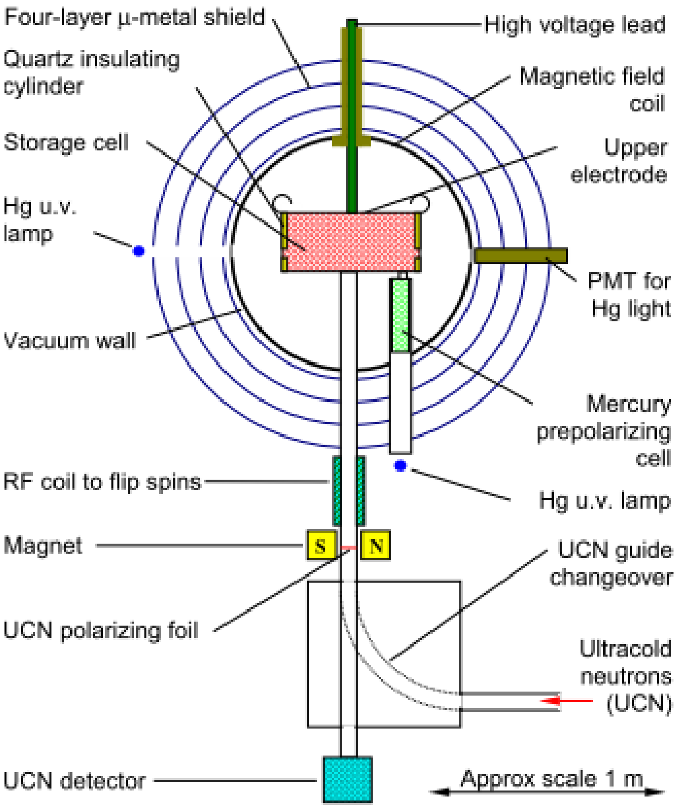




Neutrons in Science …

- Laboratory for fundamental physics: EDM

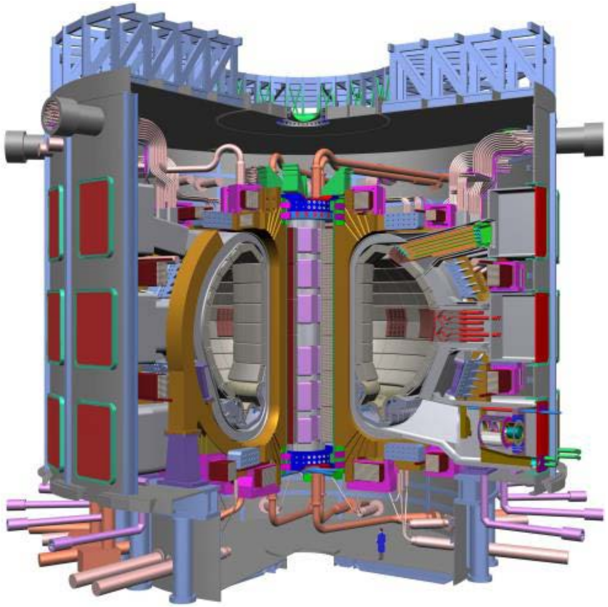
$$\hbar\omega_L \sim \mu \cdot B + d \cdot E$$

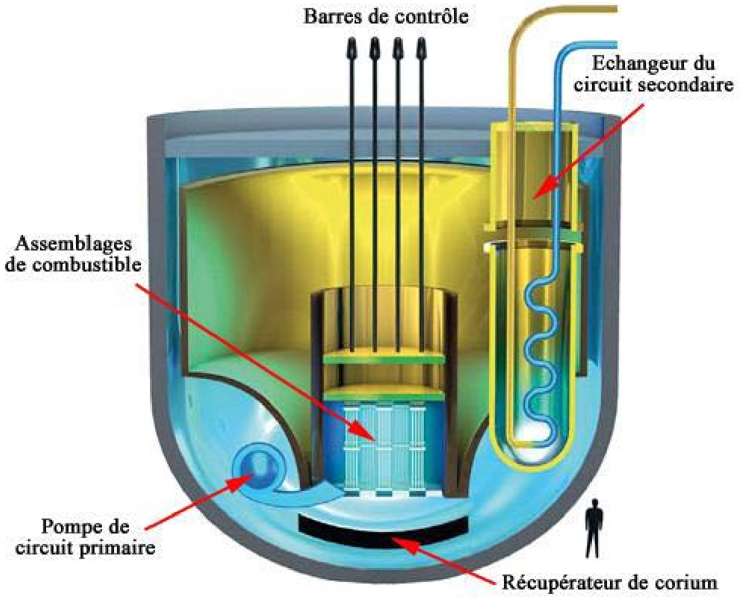


ultra cold neutron detection:
$^3He(n,p)^3H$

- Ideal tool for probing matter:
  - No Coulomb force: deep penetration
  - Strong Interaction: isotope-specific detection
  - Magnetic moment: magnetic structures
  - Low energies: crystal structures

- Neutrons can be used to produce energy
  - Fusion
  - Fission





- Biggest disadvantage: the (free) neutron is unstable:

$$\tau \approx 880\ s$$

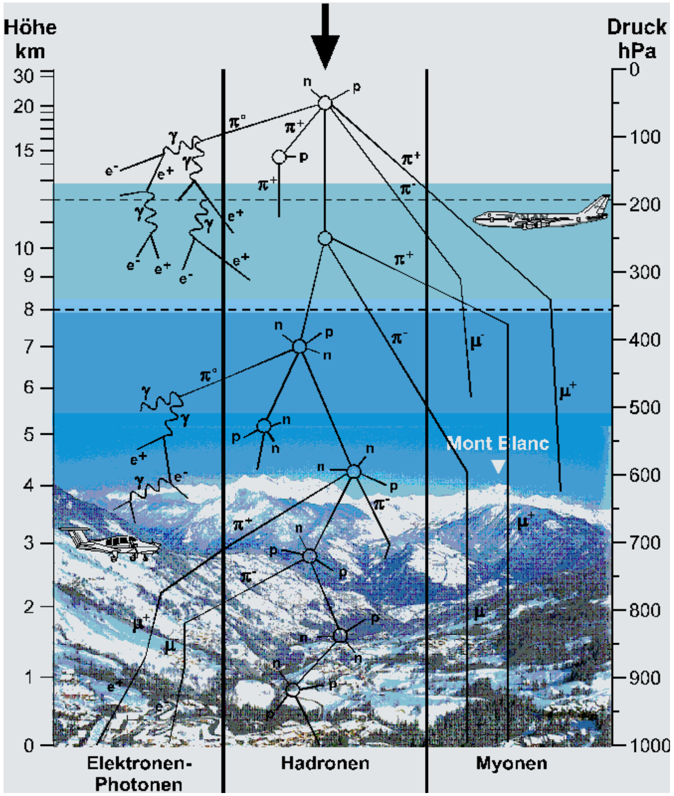
- Intense neutron sources require considerable efforts
  - Reactors
  - High-power low-energy accelerators
  - Spallation sources

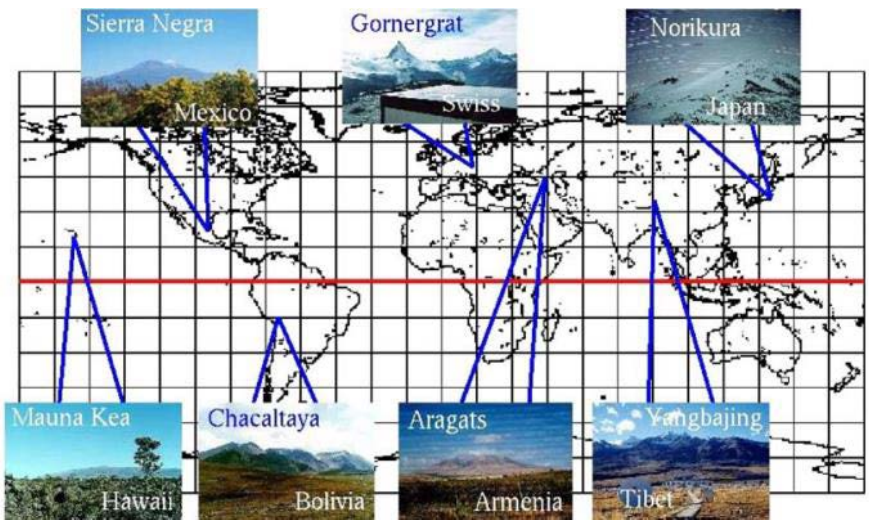
… and the world around

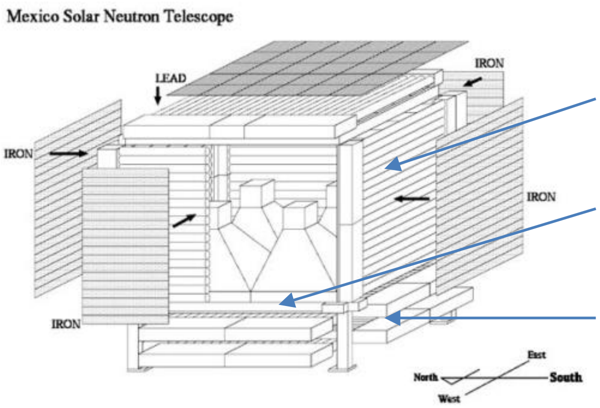
- Cosmic Neutrons:
  - Production in the atmosphere by galactic radiation
  - Production on the sun

- Neutron monitors:
  Diagnostic for solar processes

- Radiation protection at flight levels:
  $$\frac{dH_n^*}{dt} \approx 1 - 4\,\frac{\mu Sv}{h}\ at\ 12\ km$$







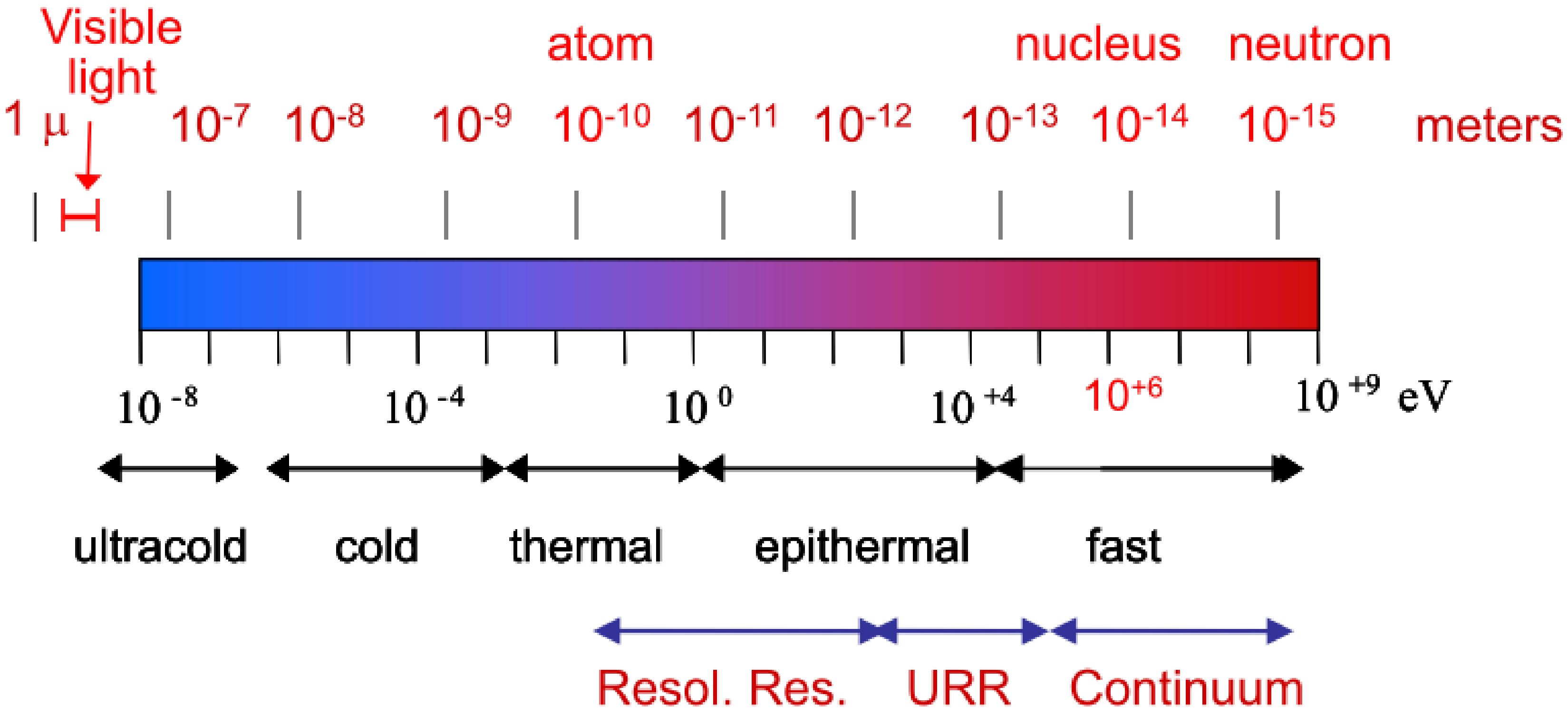
anticoin. shield

1 m^2 scintillator

prop. counters

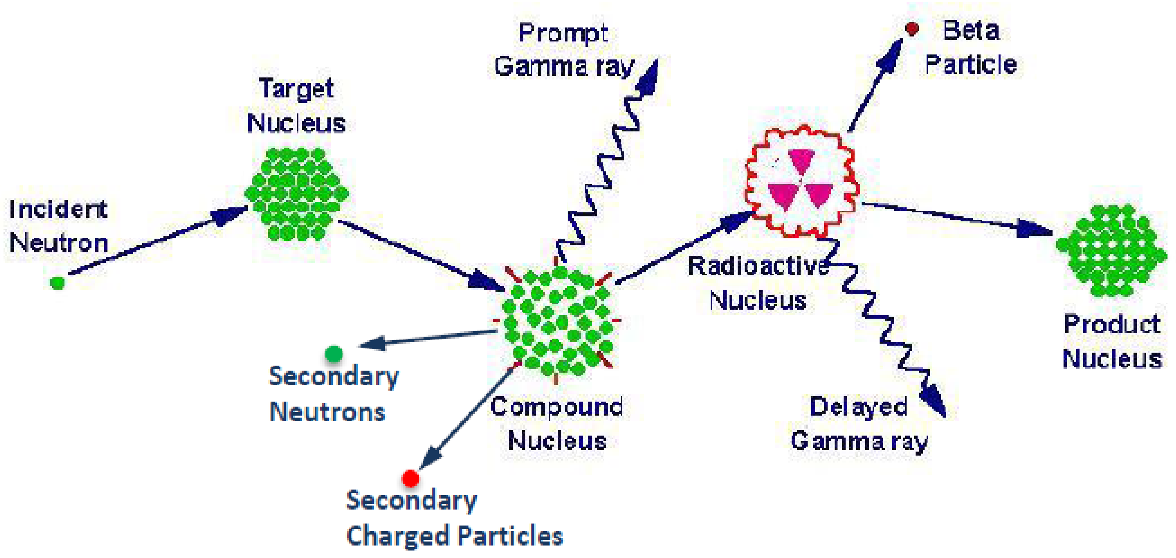
Classification of Neutrons

de Broglie wavelength: $\lambda = h/p$



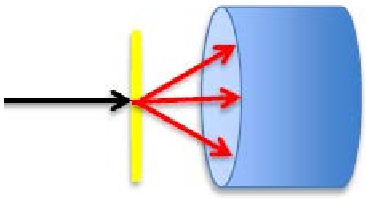
General detection principle

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

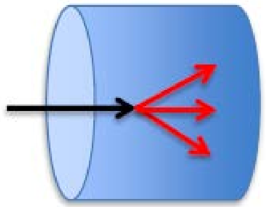


Detection of a neutron is a sequential process

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.

- $n + {}^{6}_{3}Li \rightarrow \alpha + {}^{3}_{1}H + 4.78\ MeV \quad \Rightarrow \quad Li(Tl)\ scintillator$
- $n + {}^{10}_{5}B \rightarrow \alpha + {}^{7}_{3}Li + 2.31\ MeV \quad \Rightarrow \quad BF_3\ gas\ counter$
- $n + {}^{3}_{2}He \rightarrow p + {}^{3}_{1}H + 0.765\ MeV \quad \Rightarrow \quad {}^{3}_{2}He - filled\ proportional\ chambers$
- $n + p \rightarrow n + p \quad \Rightarrow \quad proportional\ chambers\ with\ e.g. CH_4$
- $n + {}^{235}_{92}U \rightarrow fission\ products \quad \Rightarrow \quad coated\ proportional\ counters$
- $n + nucleus \rightarrow hadron\ cascade \quad \Rightarrow \quad calorimeters$

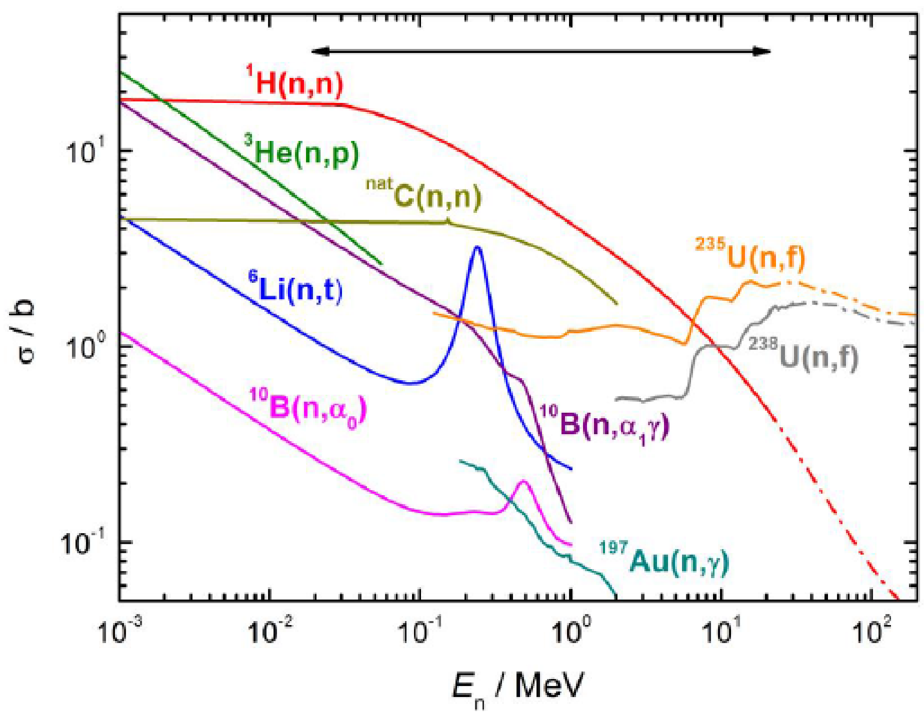
Neutron detection and identification is important in the field of radiation protection because the relative biological effectiveness (quality factor) is high and depends on the neutron energy.

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

Interaction of neutrons with matter

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

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

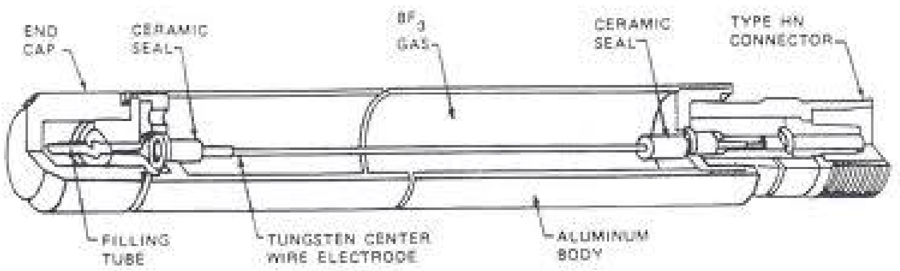


cross section relevant
for neutron detection

BF_3 and ^3He proportional counters

- Cylindrical and spherical shapes
  Large variety of sizes: I < 1 m
  and pressures: p < 1 bar (BF_3), 10 bar (^3He)

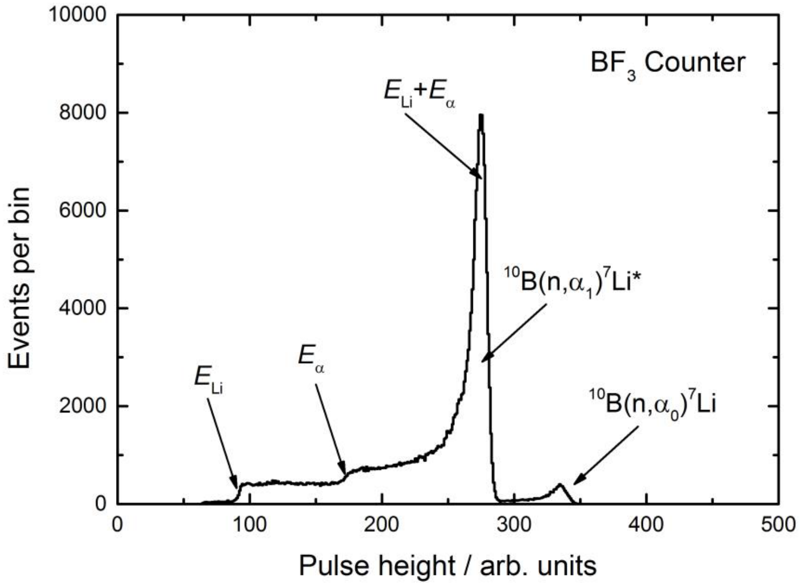
- Counters must be calibrated:
  - ^3He and BF_3 pressure ?
  - ^{10}B enrichment ?
  - Electrical field ?
  - Wall effects ?

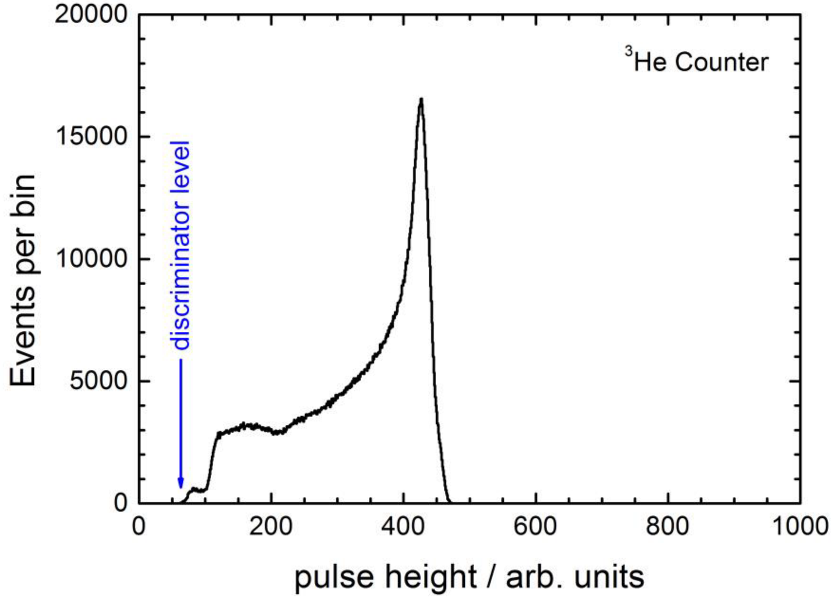


- n/γ discrimination using a pulse-height threshold

- BF_3: aging at high dose rates
  transport prohibited: HF formation!
- ^3He: more efficiency than BF3 because of larger $\sigma \cdot p$
  low Q-value makes n/γ separation difficult

BF_3 and ^3He pulse-height spectra





- Wall effect: incomplete energy deposition by one ejectile:

$$E_1 < E_{dep} < E_1 + E_2$$

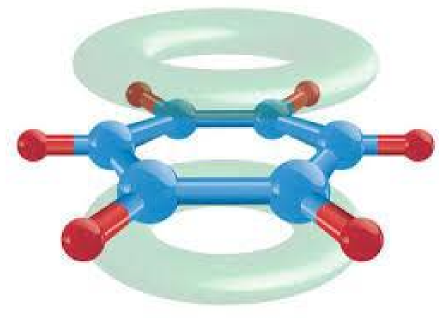
- Significant dead times: $t_{dt} = 1 - 10\ \mu s$
- Photon background suppressed by pulse-height threshold

$n + {}^{3}_{2}He \rightarrow ({}^{4}_{2}He)^{*} \rightarrow p + {}^{3}_{1}H,$ Q=0.765 MeV

Bonner sphere

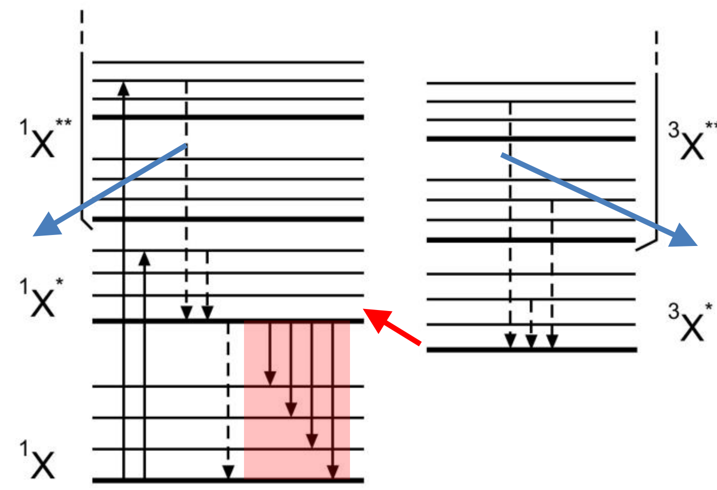
Moderate neutrons in spheres of different sizes and then detect the charged particles in a proportional counter in the center.

Unitary scintillators:



- Benzene ring: delocalized π orbitals
- Singlett (^1X, $^1X^*$, $^1X^{**}$) and triplet ($^3X^*$, $^3X^{**}$) states

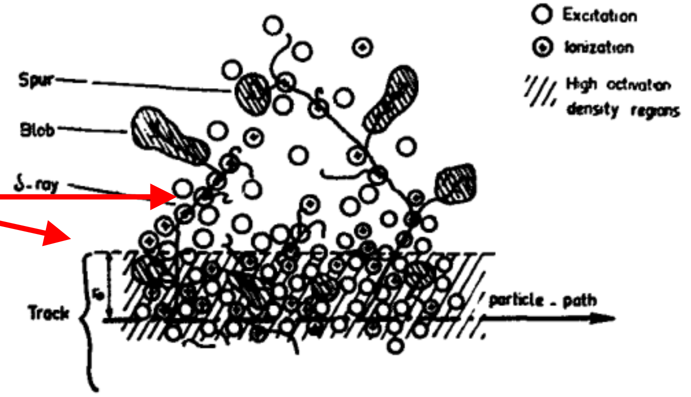
Principal physical processes:



- Excitation by electron impact, ion-ion recombination, …
- Non-rad. efficient internal degradation
  $^{1,3}X^{**} \rightarrow {}^{1,3}X^* +$ phonon
  drain via competing channels:
  quenching states
- Rad. decay $^1X^* \rightarrow {}^1X$:
  prompt fluorescence: τ = 1-80 ns, $\lambda_{fluor} > \lambda_{abs}$
- Rad. transition $^3X^{**} \rightarrow {}^1X^*$ forbidden
- Coll. deexc. $^3X^* + {}^3X^* \rightarrow {}^1X^* + {}^1X^* +$ phonon:
  delayed non-exp. fluorescence: $\tau > 300$ ns

Ionization quenching and pulse-shape discrimination

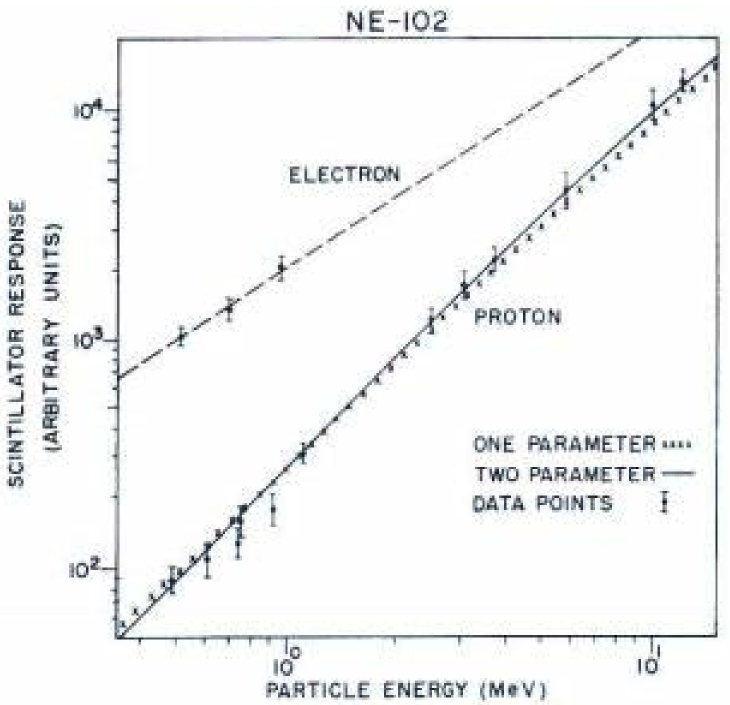
- Increased ionization density:
  - More ion-ion recombination
  - Ratio of $^{1}X^{**}$ and $^{3}X^{**}$ excitations increases
  - Temporal concentration of transient quenching states ($\tau \leq 100$ ps)



⇨ Delayed fluorescence less dependent on dE/dx than prompt fluorescence

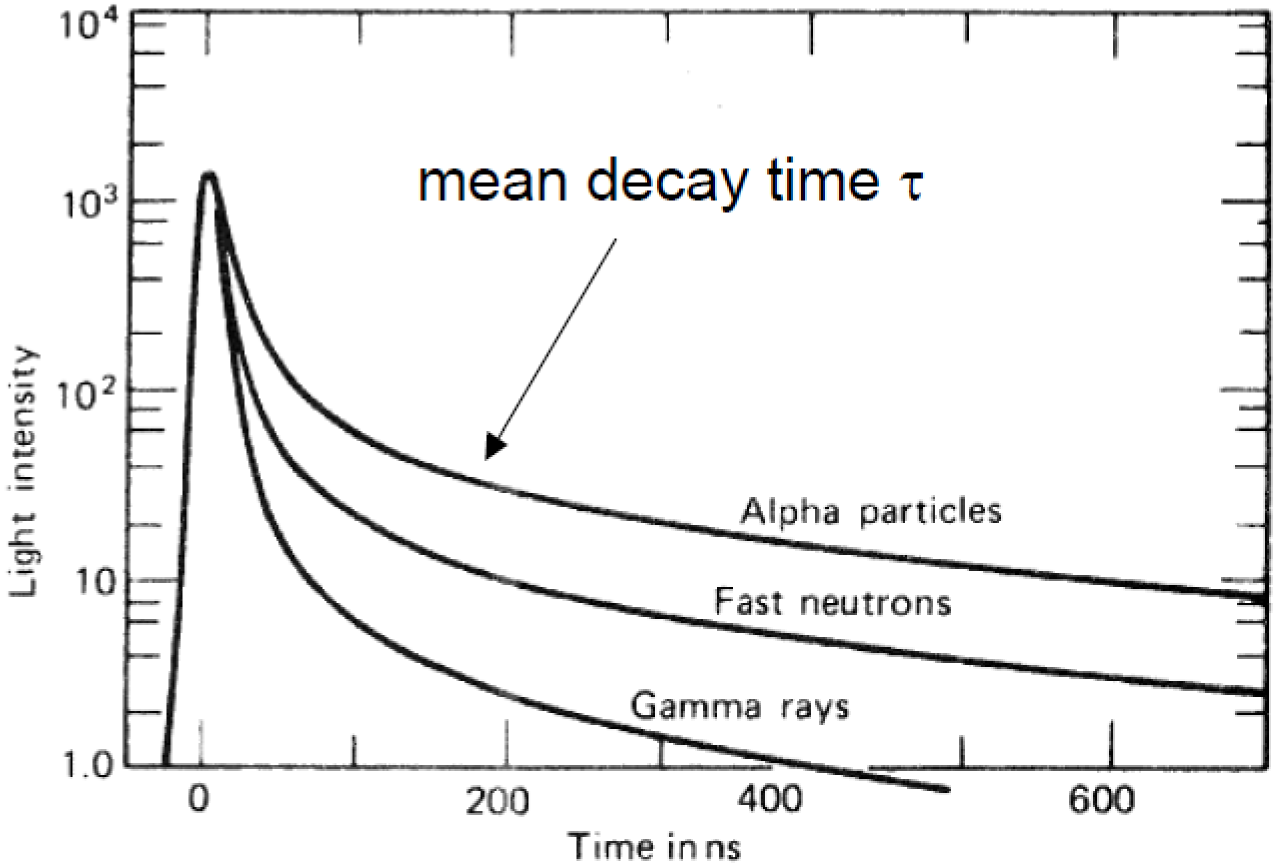
- Light yield dL(E)/dx is a non-linear function
- Scint. decay depends on dE/dx

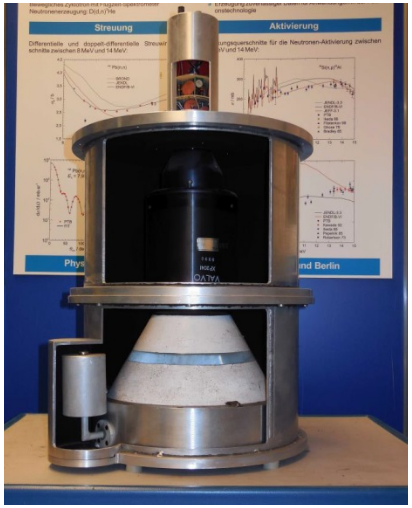
⇨ Pulse-shape discrimination of particle species (Z,A)



Pulse shape discrimination

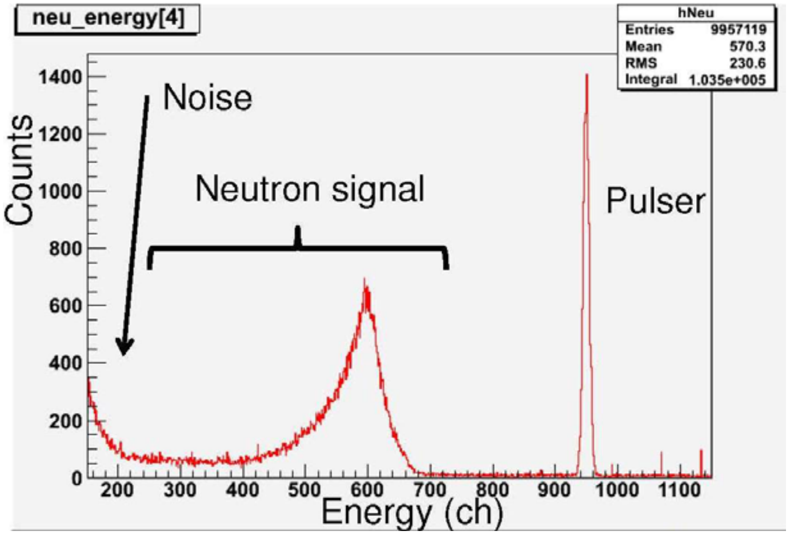
- Pulse shape discrimination (PSD) in organic scintillators are used in particularly liquid scintillators (NE213 / BC501A)
- PSD is due to long-lived decay of scintillator light caused by high dE/dx particle – neutron scatter interaction events causing proton recoil

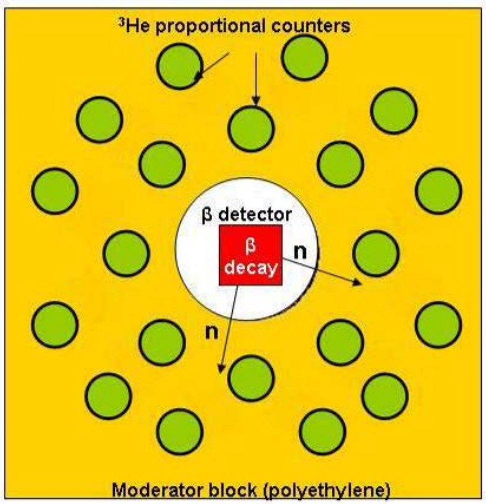




BEta deLayEd Neutron detector

$n + {}^{3}_{2}He \rightarrow p + {}^{3}_{1}H + 765\ keV \qquad \sigma_{th} = 5400\ b$





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%

Understanding the r-process

Ingredients for a (successful) r-process nucleosynthesis:

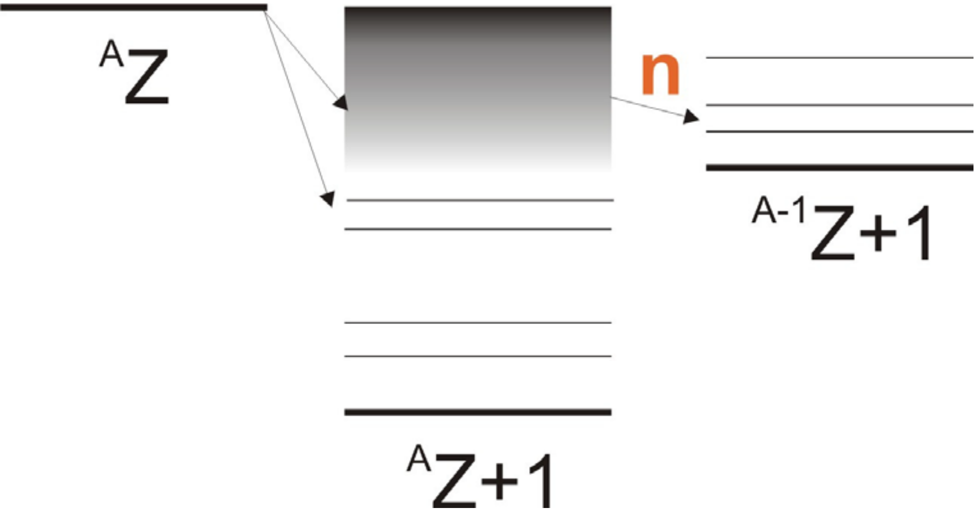
- astrophysical site (debated, neutron star mergers / CCSN ?)
  → physical conditions (explosive scenario)
  - Neutron density (>> 10^{20} cm^{-3}), exposure time τ , Y_e
  - Temperature (1-2 GK) / density vs time (trajectory)

- nuclear input (up to now theoretical calculations tuned to few experimental data available)
  - Masses (→ Q_β, S_n)
  - $t_{1/2}$ (β)
  - (n,γ) cross sections

  } → r process "path", waiting points, progenitors' abundances

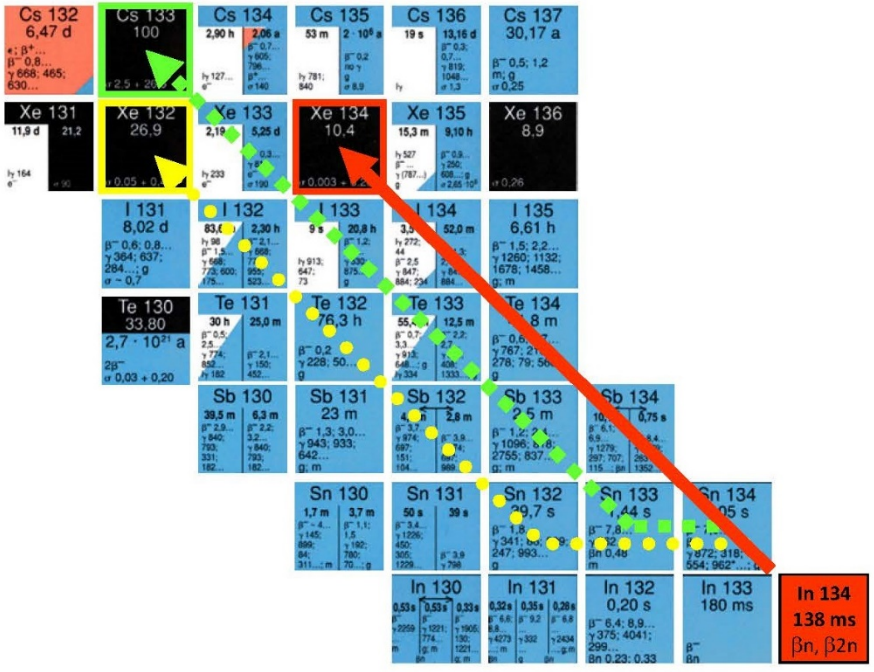
  - β-delayed neutron branching → Modified path back to stability and additional neutron source
  - others: fission parameters, $t_{1/2}$ (α)...

β-delayed neutron emission



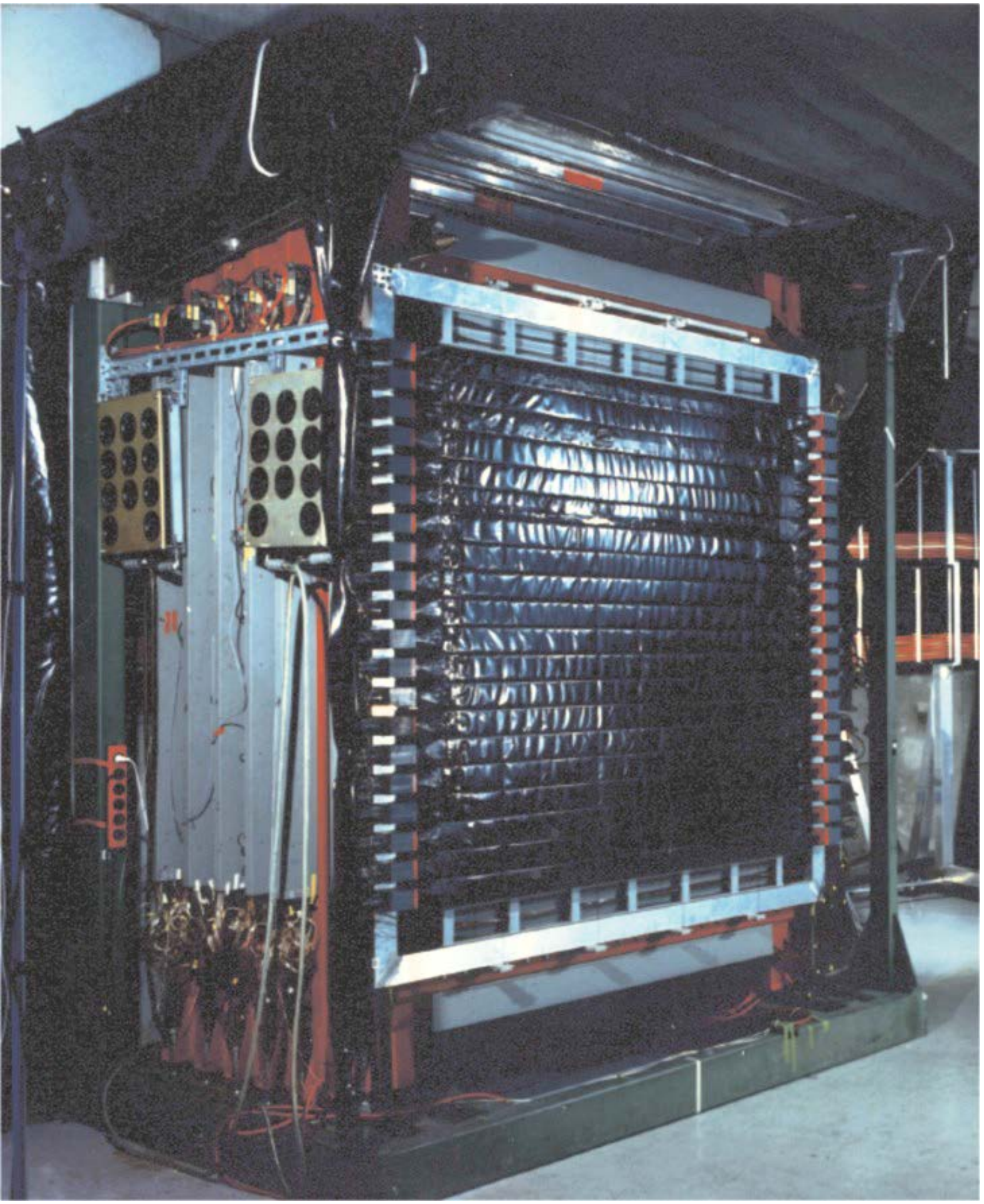
Detecting n →

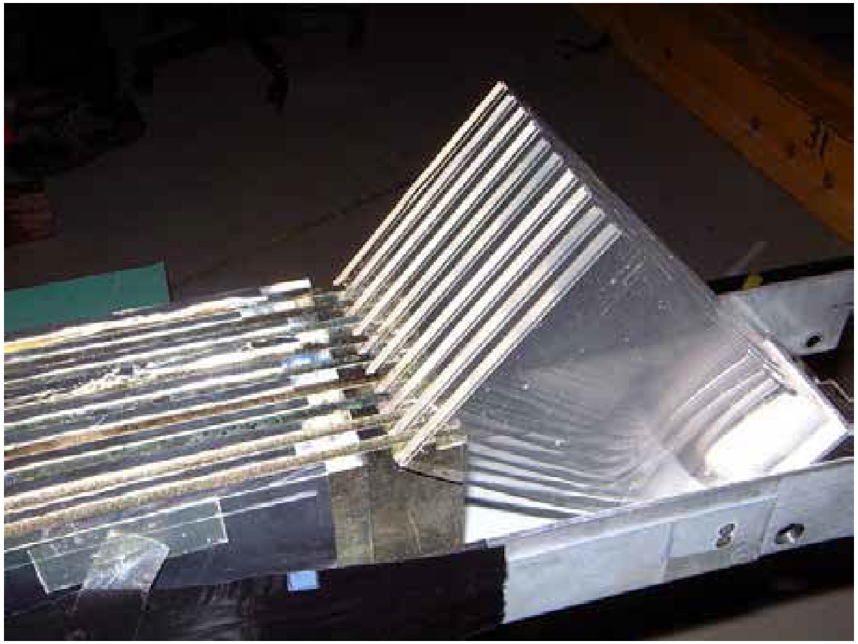
- obtain $t_{1/2}$ (^{A}Z)
- P(n) branching
- study β-strength function above S_n



- $Q_{\beta} > S_n$ (or $> S_{2n,\,3n}$)
- Discovered in 1939 by Roberts et al.
- $t_{1/2} \approx$ few ms – 55.65 s (^{87}Br)
- ^{8}He- ^{150}La: ≈ 230 datasets available
- Only one for A>150 (^{210}Tl)

Large Area Neutron Detector

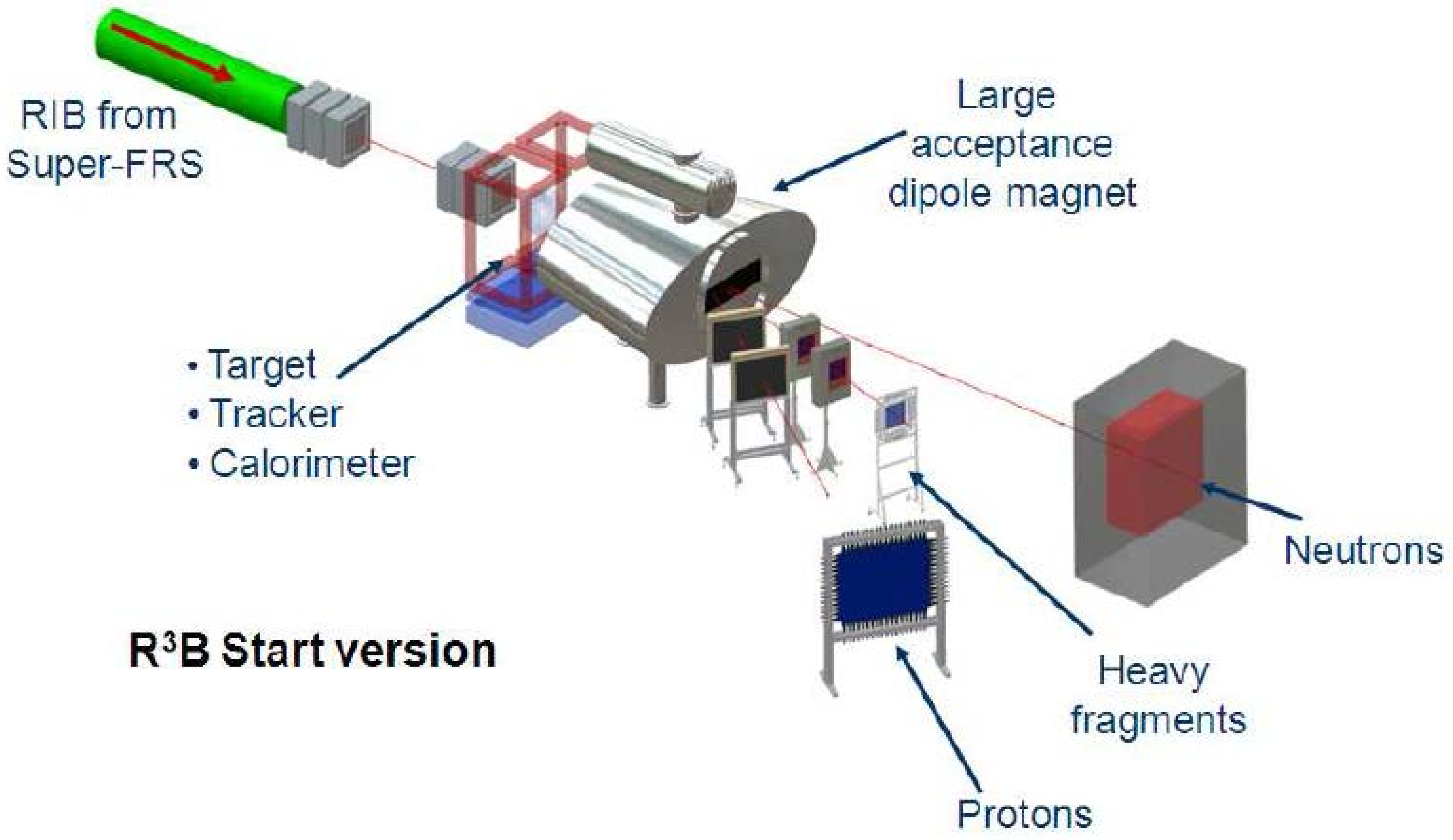




Large ***A***rea ***N***eutron ***D***etector (2m x 2m x 1m)

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

Reaction with Relativistic Radioactive Beams – R^{3}B

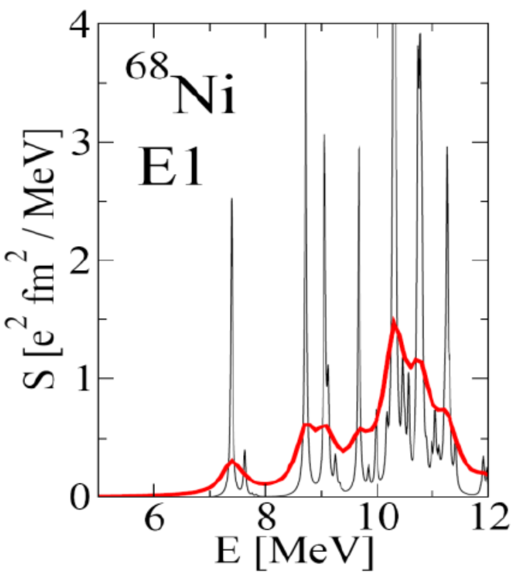


Excitation energy E* from kinematically complete measurement of all outgoing particles

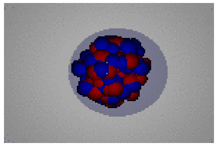
$$E^* = \left(\sqrt{\sum_i m_i{}^2 + \sum_{i \neq j} m_i m_j \gamma_i \gamma_j \left(1 - \beta_i \beta_j cos\vartheta_{ij}\right)} - m_{proj} \right) c^2 + E_{\gamma,sum}$$

Dipole strength distribution of ^{68}Ni

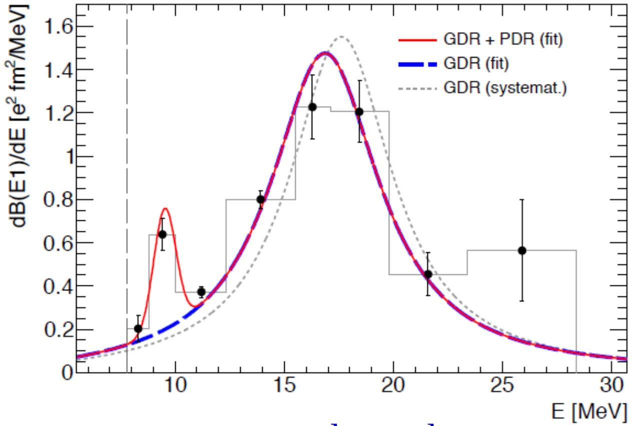
mean field calculation



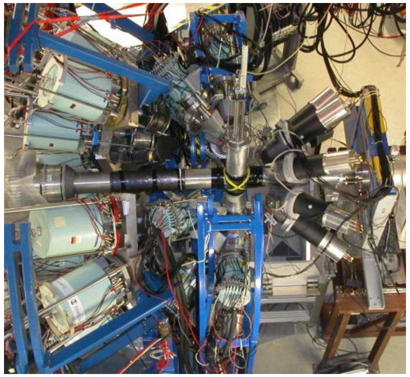
E.Litvinova et al.; PRC 79, (2009) 054312

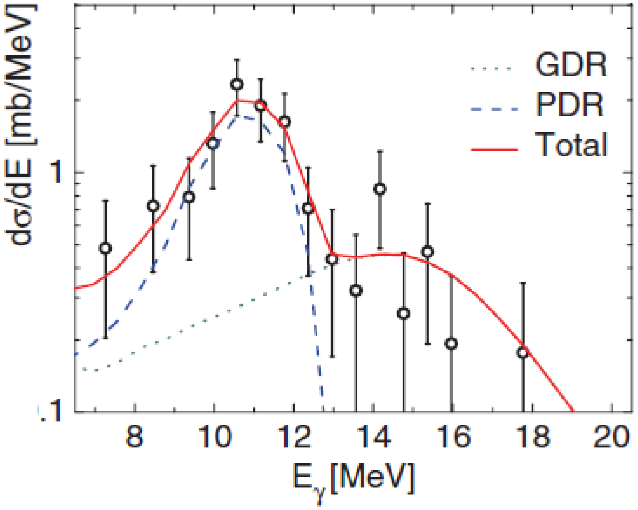


Pygmy resonance



neutron decay data





γ-ray decay data

direct γ-decay branching ratio:

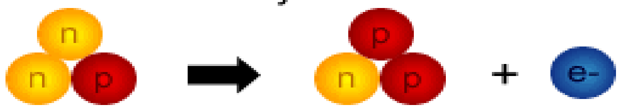
$\Gamma_0/\Gamma = 7(2)\%$

O. Wieland et al.; Phys. Rev. Lett 102, 092502 (2009)

D. Rossi et al.; Phys. Rev. Lett 111, 242503 (2013)

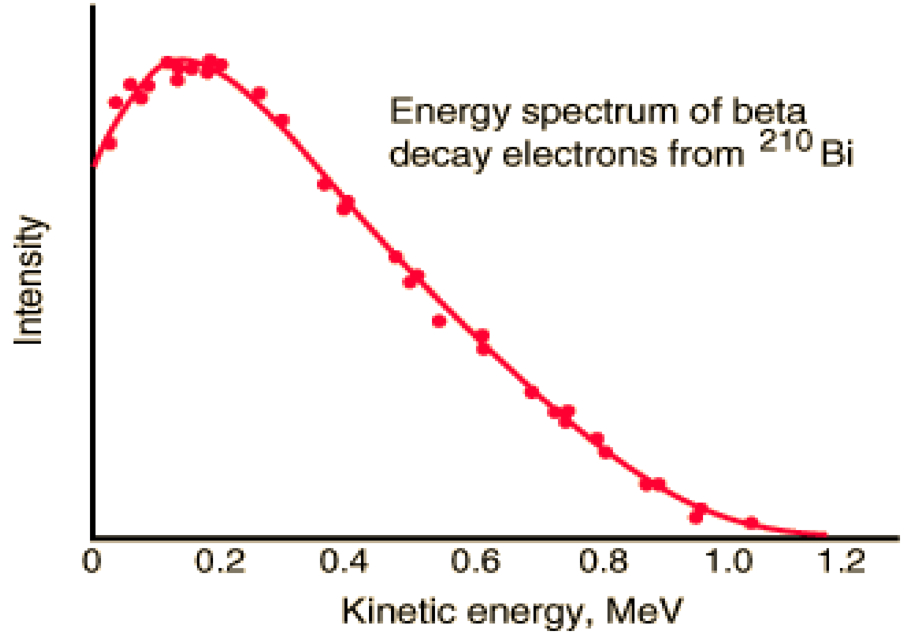
Neutrinos

Beta minus decay



Beta plus decay

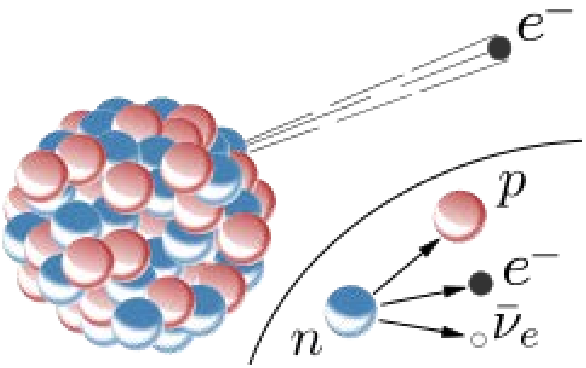
- A neutron turns into a proton, emitting an electron
- A fixed energy is released
  - Q = difference in binding energy
- Charge is conserved



- 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:

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

❖ Rate of solar neutrinos interacting in the Earth:

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

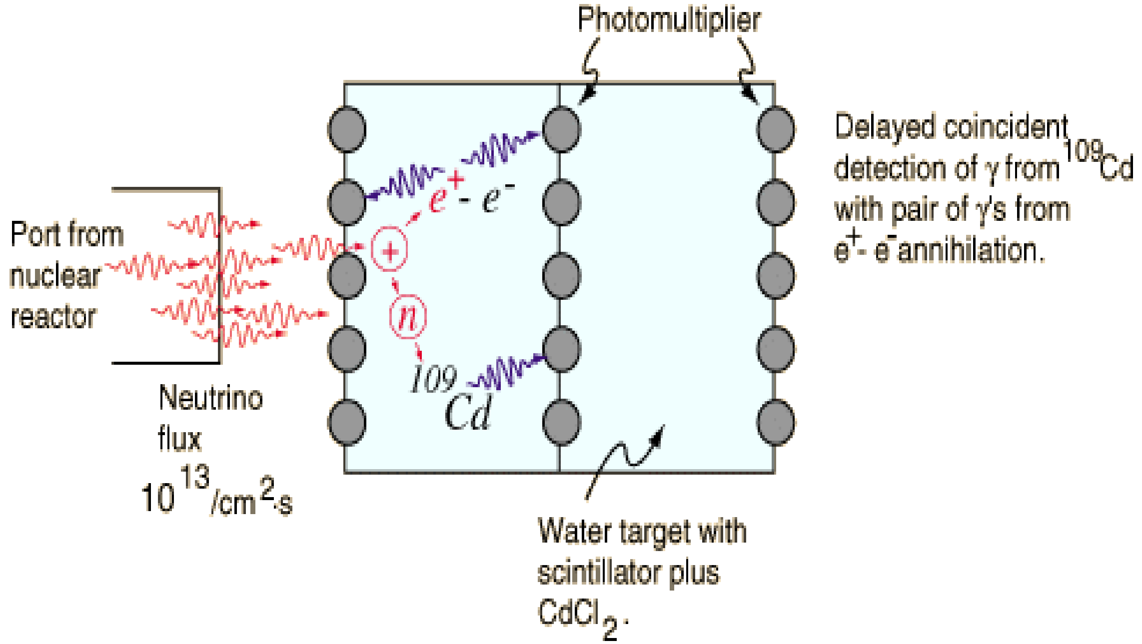
❖ For high energies (GeV-range):

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

Detecting the Neutrinos

Inverse beta decay:

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

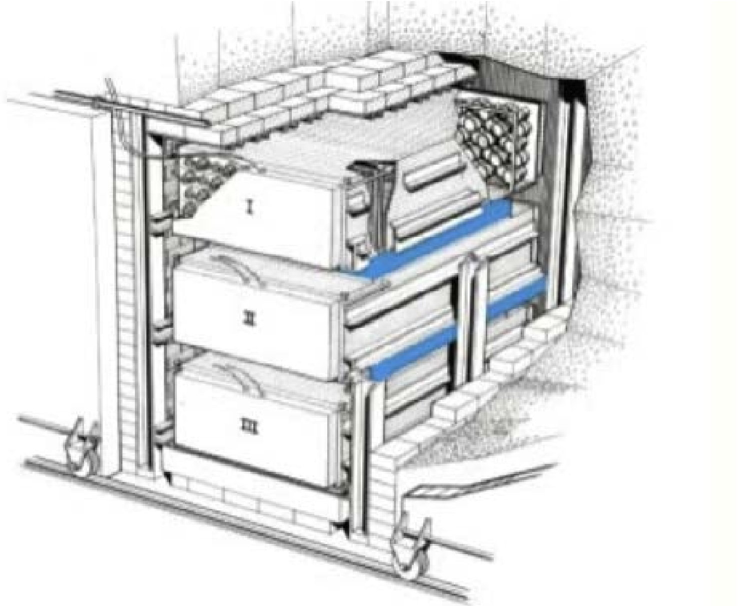


Experimental needs:

- 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

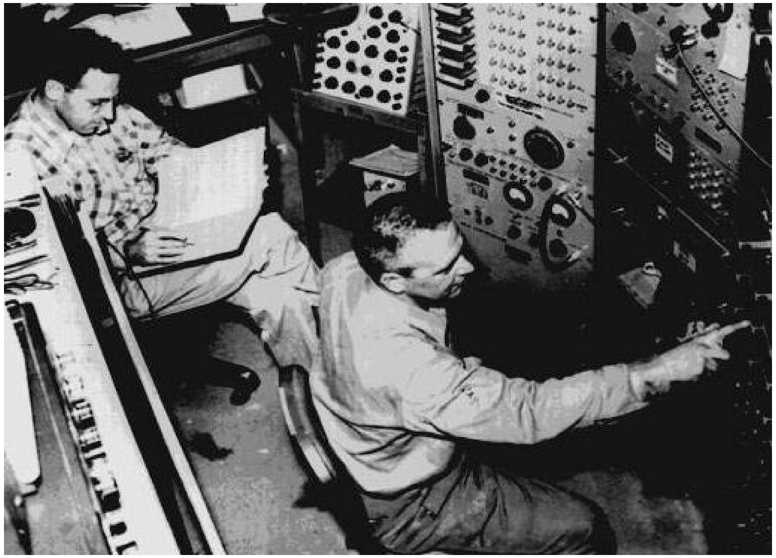
Discovery, Reines & Cowan 1956

- 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:

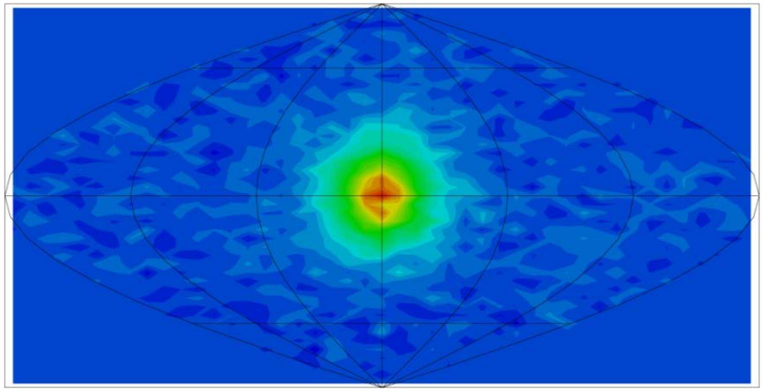
- ~3 neutrino events per hour detected
- Used on-off switch on reactor
- Neutrinos disappeared when reactor was off



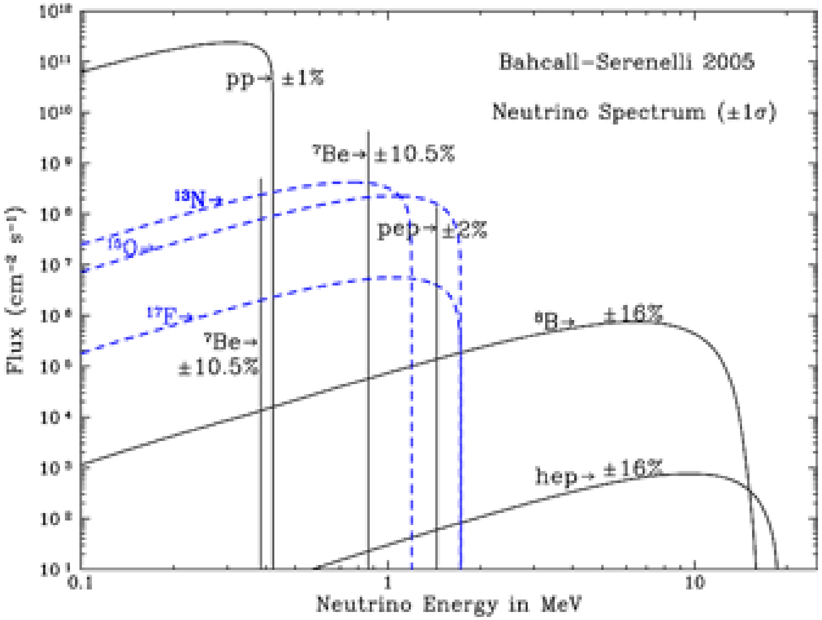
Cowan died in 1974, but Reines awarded Nobel Prize in 1995

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

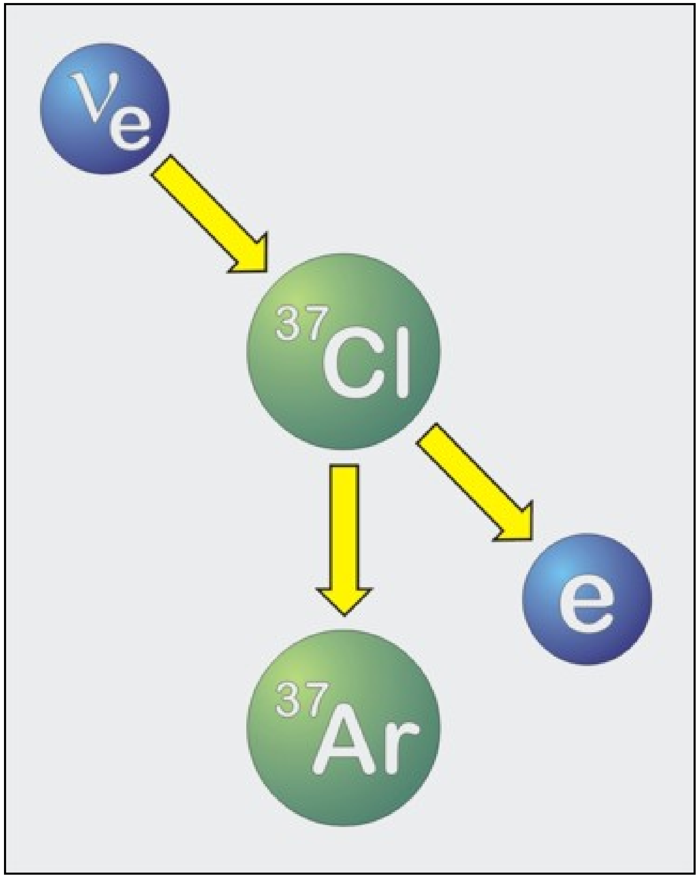


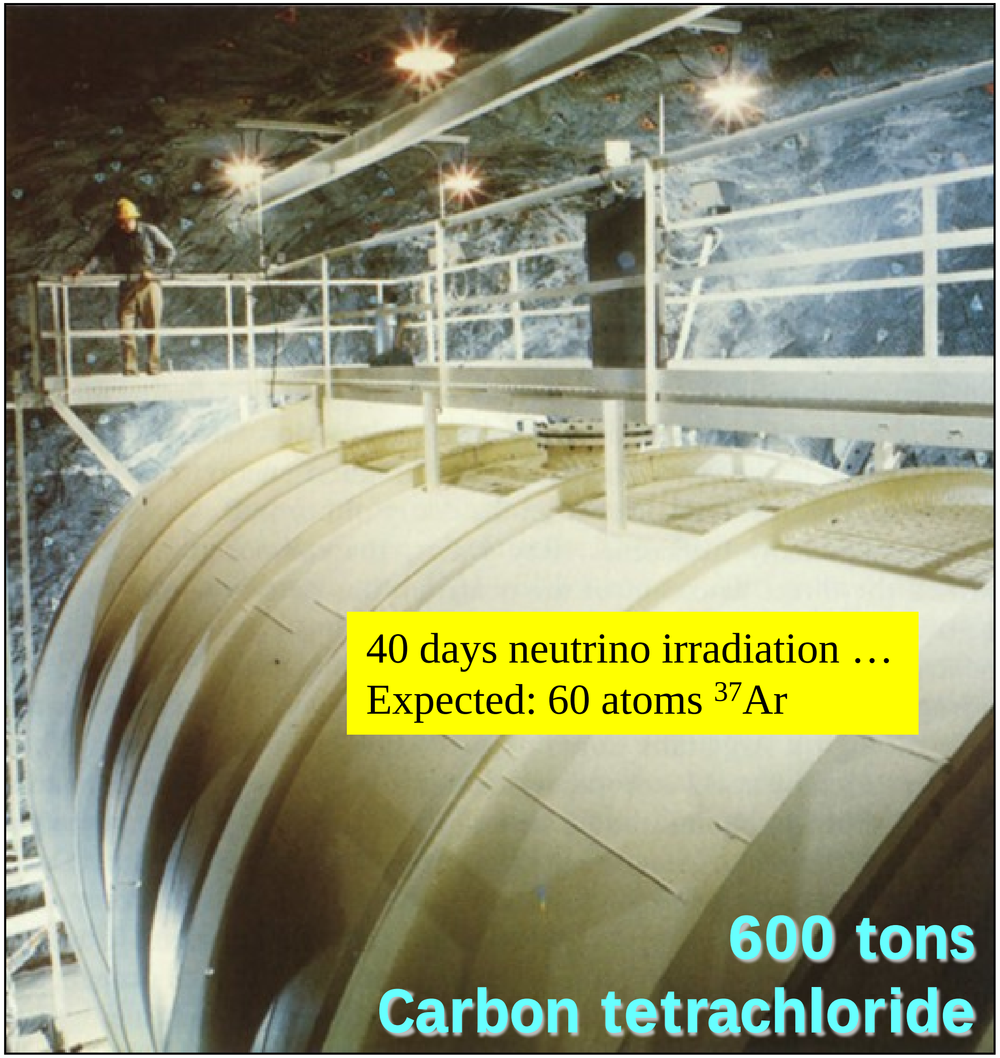
Bachall predicted the solar neutrino flux in 1964
He would refine this with an incredibly precise solar model over the next 50 years



First measurement of the solar neutrinos

Inverse beta-decay („neutrino-capture")

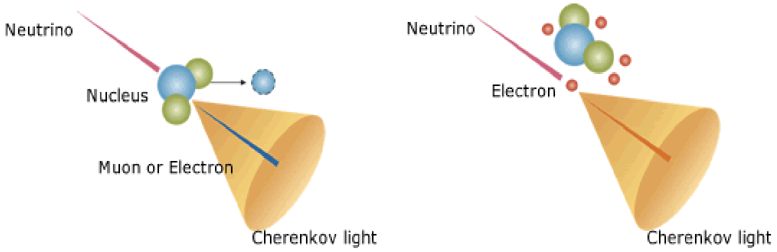




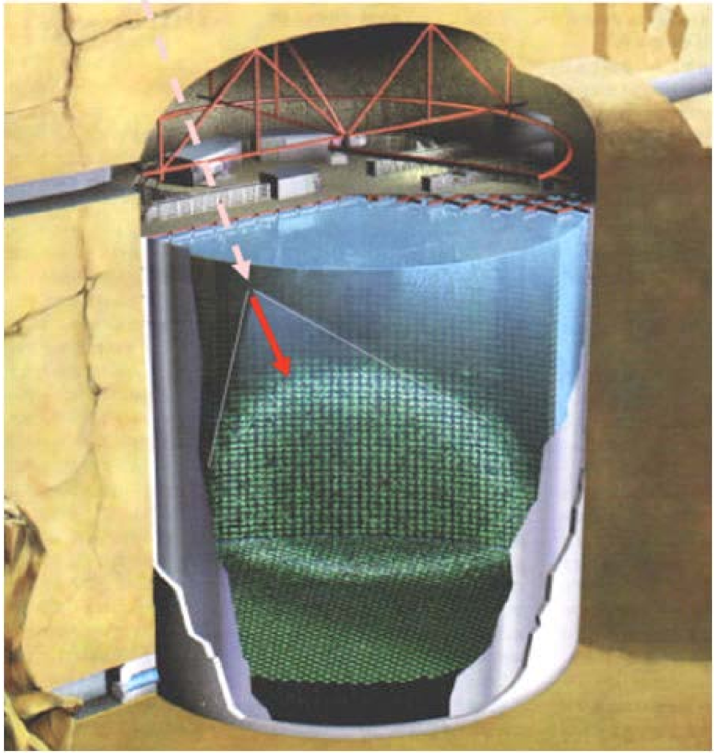
Homestake Sun neutrino-Observatory (1967–2002)

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

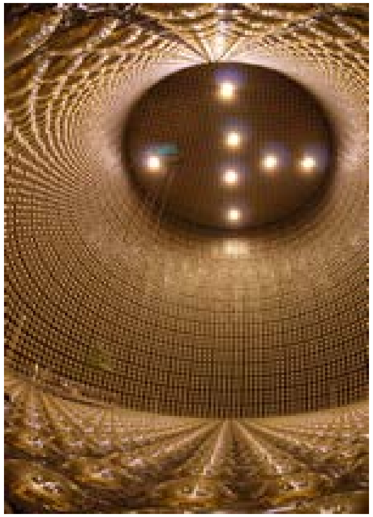


The generated charged particle emits the Cherenkov light.



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