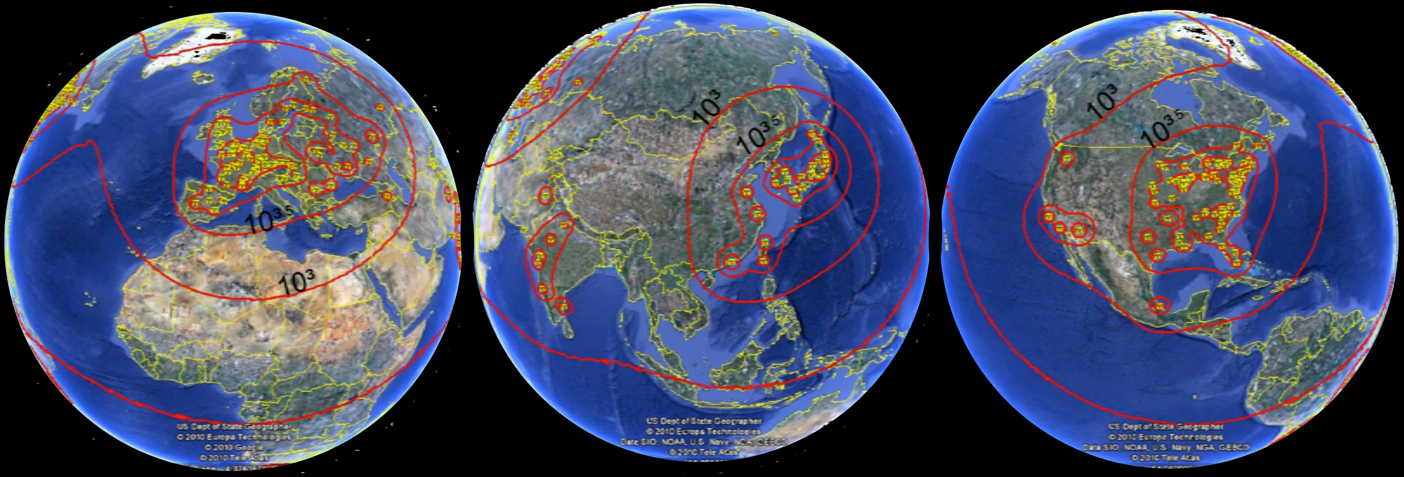
Reactor antineutrino



Thierry Lasserre
Saclay

Nuclear Reactor Antineutrinos

- 1946 :

Pontecorvo suggested to use nuclear reactors in order to perform neutrino experiments.

- 1953-1959 :

Reines and Cowan showed that neutrinos are real particles using nuclear reactors as a source.

- Since then :

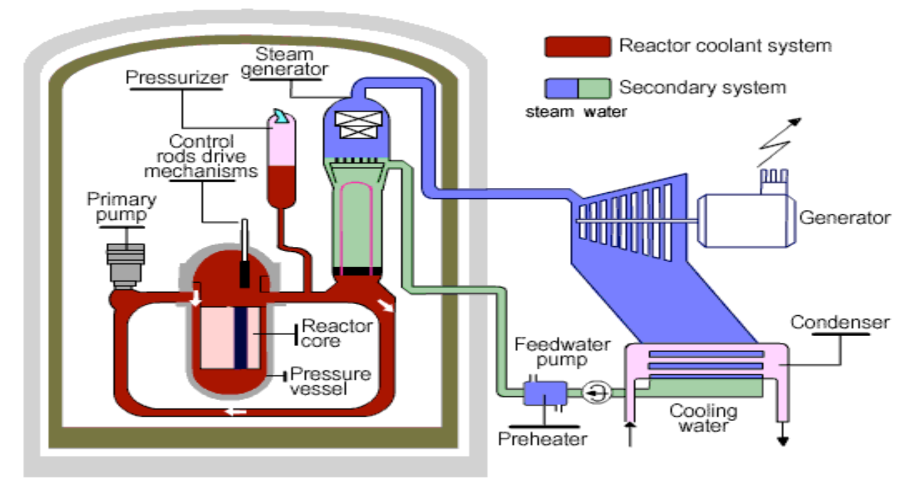
Reactors, powerful sources with $6\text{x}10^{20}$ /sec electron antineutrinos emitted by a modern 4 $\text{GW}_{\text{thermal}}$ reactor, have been used often in neutrino studies.

(Petr Vogel, 2005)

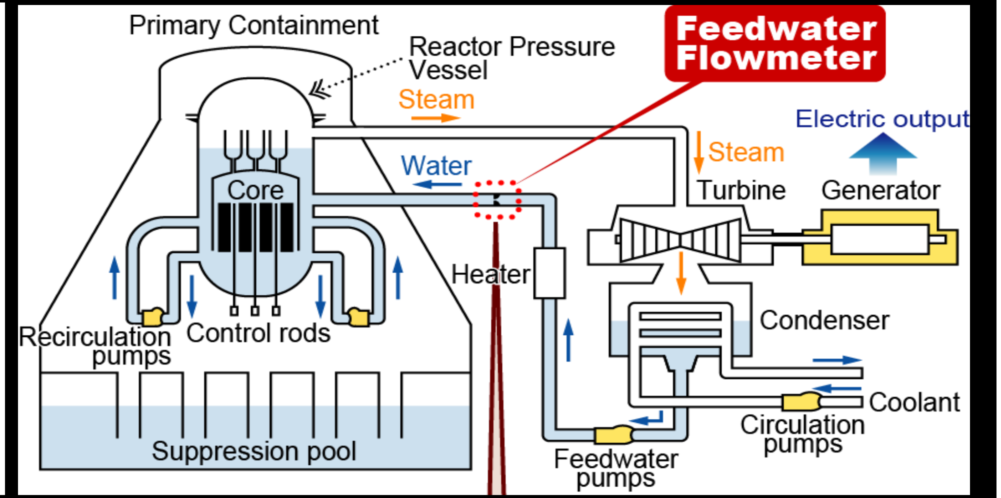
Reactor Neutrino Flux

Pressurized Light Water Reactor

- **Reactor Vessel:**
  - ^{235}U Fuel in assemblies
  - LW is used as neutron moderator
  - Control rods
- **Primary Circuit Loop:**
  - Fission heats LW (300°C, 155 bars)
  - Water is use as heat carrier
- **Secondary Circuit Loop:**
  - Heat exchange with primary Water Circuit
  - Water is converted in Vapor
- **Generator**
  - Production of electricity
- **Third Cooling Loop**
  - Condensation of the Vapor into water
  - Cooling source: river, sea, or ‘evaporation’ tower if needed



PWR



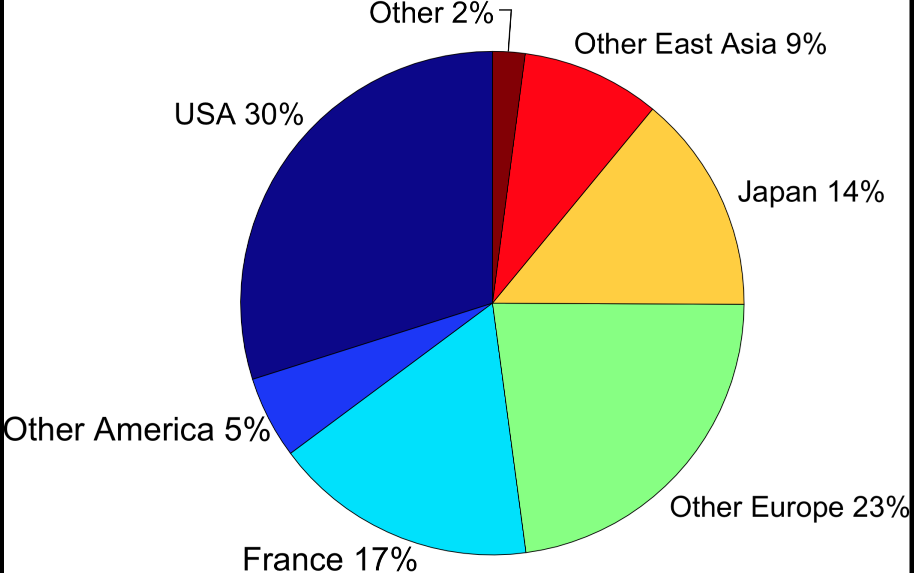
BWR

Nuclear Reactors

- **Power Nuclear Stations:**
  - 201 in the world (most of them having multiple units)
  - Total thermal power = 1134 GWth total thermal power
  - Mixed fuel (^{235,238}U & ^{239,241}Pu)
  - Thermal neutron flux (0.025 eV)
  - Extended neutrino source:
    - 3-4m diameter, 4m high

- **Non-Power Nuclear Reactors:**
  - Research reactors used as neutron source
  - Reactors used for propulsion
  - Highly enriched in ^{235}U
  - Thermal neutron flux
  - Extended/Compact neutrino source (0.6mx0.6m possible)

- **Pressurized Light Water Reactor (PWR)**
- **Boiling Water Reactor (BWR)**
- **CANDU (heavy water)**
- **Naval**
- **Research**
- **Weapons Production**
- **New Technology**



Nuclear Fuel

- **Uranium based fuel**
  - Mainly ^{238}U (99.2745%, $T_{1/2}$=4.47 10^9 y)
  - 0.7% of ^{235}U (fissile, $T_{1/2}$=703.8 10^6 y)

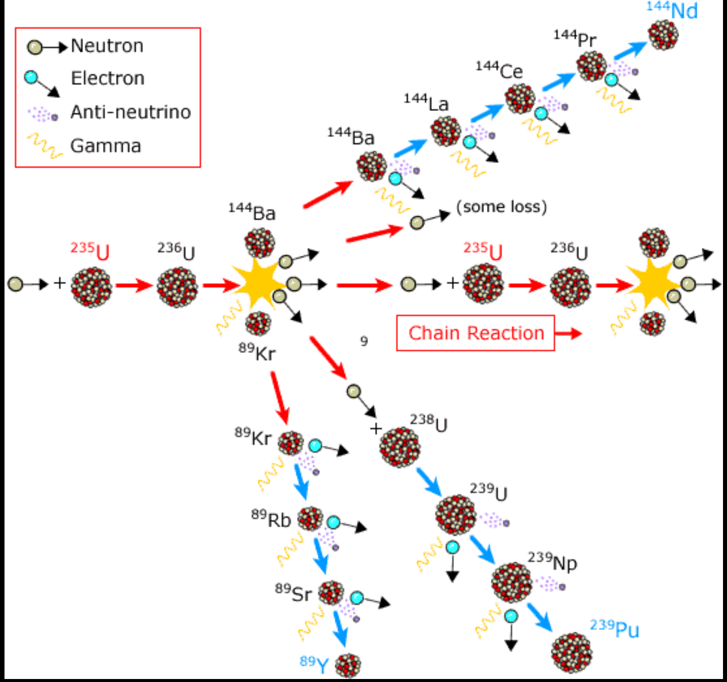
  → in form of UO_2

- **^{238}U**
  - High neutron capture threshold (0.8 MeV)
  - No fission with thermal neutrons
  - Some fissions induced by fast neutrons

- **Enrichment in ^{235}U (3.5% in PWR)**
  - Fission chain reactions induced by thermal neutrons on ^{235}U

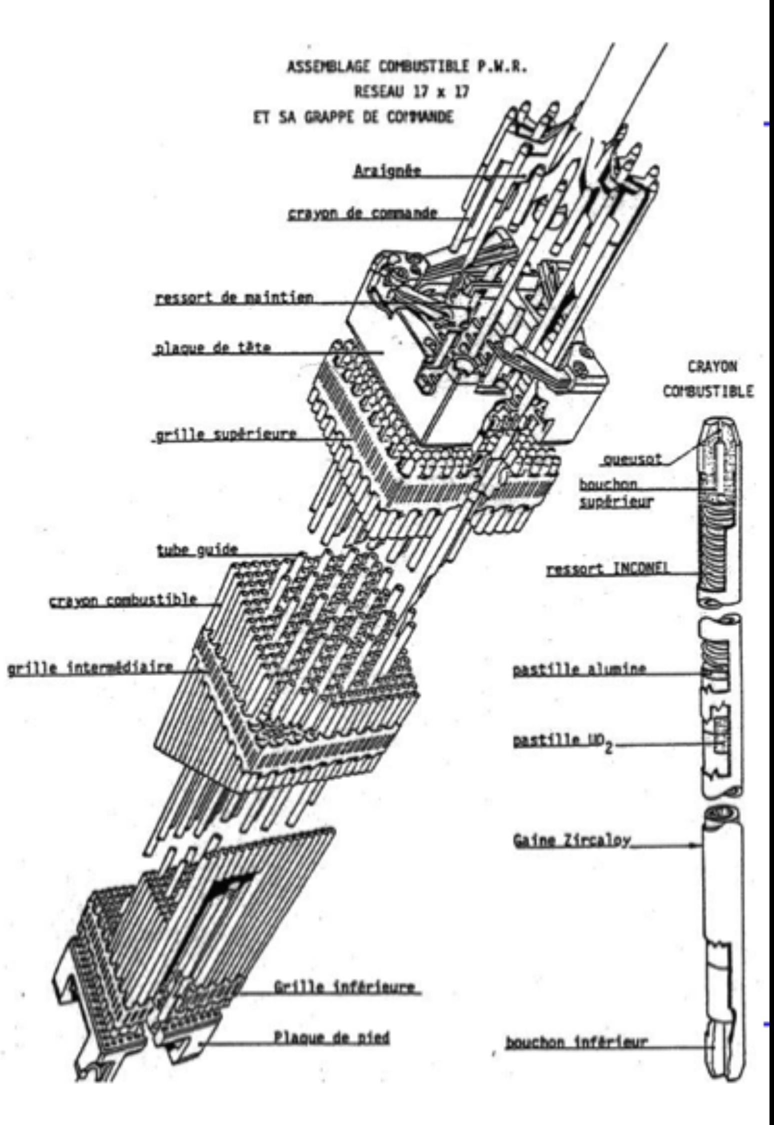
- **But other reactions:**
  - ^{238}U capture neutrons

  → in-situ production of ^{239}Pu, ^{241}Pu



Nuclear Fuel

- Fuel in N4-reactors (Chooz)
    - 120 tons of UO_2
    - $^{235}U \approx 3.45\%$: 3.60 tons
- 205 fuel assembly
    - 264 rods per assembly
    - 272 "pellets" per rods
    - 8 g per "*pellets* "
- Loading/unloading
    - by third
    - every 1.5 years
- Energy extracted
    - 45 GW.d/ton = 3.9 10^{15} J/t



Fission Products (FP) & Yield (FY)

- Fission of ^{235}U: **U(235,92) + n_{th} → X(A1,Z1) + Y(A2,Z2) + 2 n_{fast}**

  The many X and Y are called ‘Fission Fragments’ or ‘Fission Products’

  Highest fission yields for the couple: Zr(94,40) and Ce(140,58)

- Example : U + n → 94Kr + 140Ba + 2n + 200 MeV

  - ^{140}Ba → ^{140}La (β^-, 13 days, 1 MeV)
    - ^{140}La → ^{140}Ce (β^-, 40 h, 2.2 MeV)

  - ^{94}Kr → ^{94}Rb (β^-, 0.2 s, 7.5 MeV)
    - ^{94}Rb → ^{94}Sr (β^-, 2.7 s, 10 MeV)
      - ^{94}Sr → ^{94}Y (β^-, 75 s, 3.4 MeV)
        - ^{94}Y → ^{94}Zr (β^-, 19 min, 4.9 MeV)

- On average 6 neutrons have to β-decay to 6 protons to reach stability → 6 ν
- On average 1.5 ν (25%) are emitted with energy > 1.8 MeV

Plutonium Production

- ^{238}U has a 0.8 MeV threshold for neutron induced fission

- $^{238}U + n \rightarrow {}^{239}U + \gamma$

  $\hookrightarrow {}^{239}Np + e + \nu$ (23.45 m)

  $\hookrightarrow {}^{239}Pu + e + \nu$ (2.36 d)

- $^{239}Pu + n \rightarrow {}^{240}Pu + \gamma$

- $^{240}Pu + n \rightarrow {}^{241}Pu + \gamma$

- ^{238}U and ^{240}Pu have small cross sections for *fast* fission

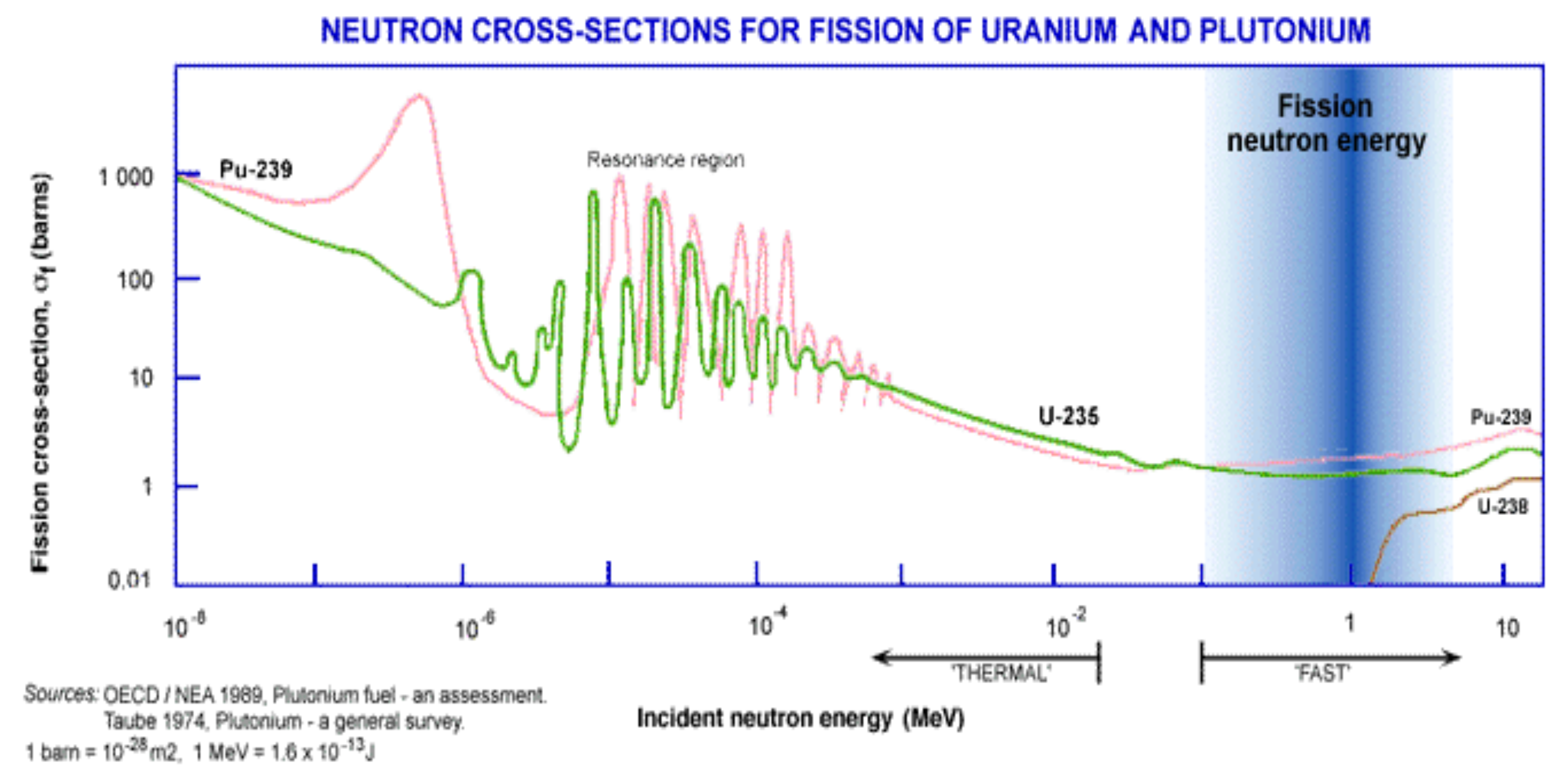
- ^{239}Pu, ^{241}Pu are fissile isotopes (with thermal neutrons)

→ Content of nuclear fuel changes with time as the reactor core “evolves”.

Fission Cross Section

$^{235}U + n_{th} \rightarrow X + Y + 2\ n_{fast}$

$^{239}Pu + n_{th} \rightarrow X + Y + 2\ n_{fast}$



Sources: OECD / NEA 1989, Plutonium fuel - an assessment.
Taube 1974, Plutonium - a general survey.
1 barn = 10^{-28} m2, 1 MeV = 1.6 x 10^{-13} J

Nuclear Chain Reaction

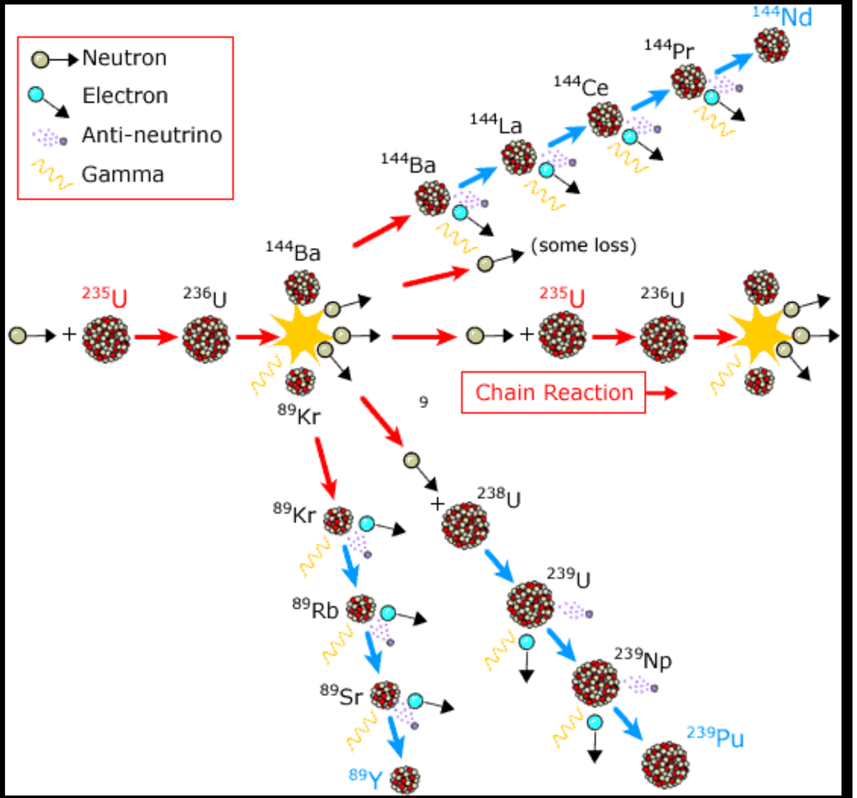
- Nuclear reactors are copious, isotropic sources of electron antineutrinos

- Neutrinos come from β-fission fragments, not directly from the fission

- Fission of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

- β-decay of neutron rich fission fragments
  - $X(A,Z) \rightarrow Y(A,Z+1)+e^{-}+$anti-$v_e$
  - 200 MeV / fission is released
  - Fission rate is 4 GW / 200 MeV ~ 2.10^{20} fissions / sec
  - 6 anti-v_e emitted per fission
  - 7.5 10^{20} anti-v_e/s for a typical 4 GW core

- Antineutrino spectrum is time dependent as the beta daughters come into equilibrium



Reactor Antineutrino Flux Estimate

Fissions in nuclear cores (average)

200 MeV et 6 neutrinos per fission of $U^{235,238}$, $Pu^{239,241}$

- 200 MeV released per fission:

  → 200 MeV = 200 * 10^6 * 1,6 10^{-19} J = **3,2 10^{-11} Joules**

- Thermal Power:

  → 1 GW = 1 **10^9 W (J / s)**

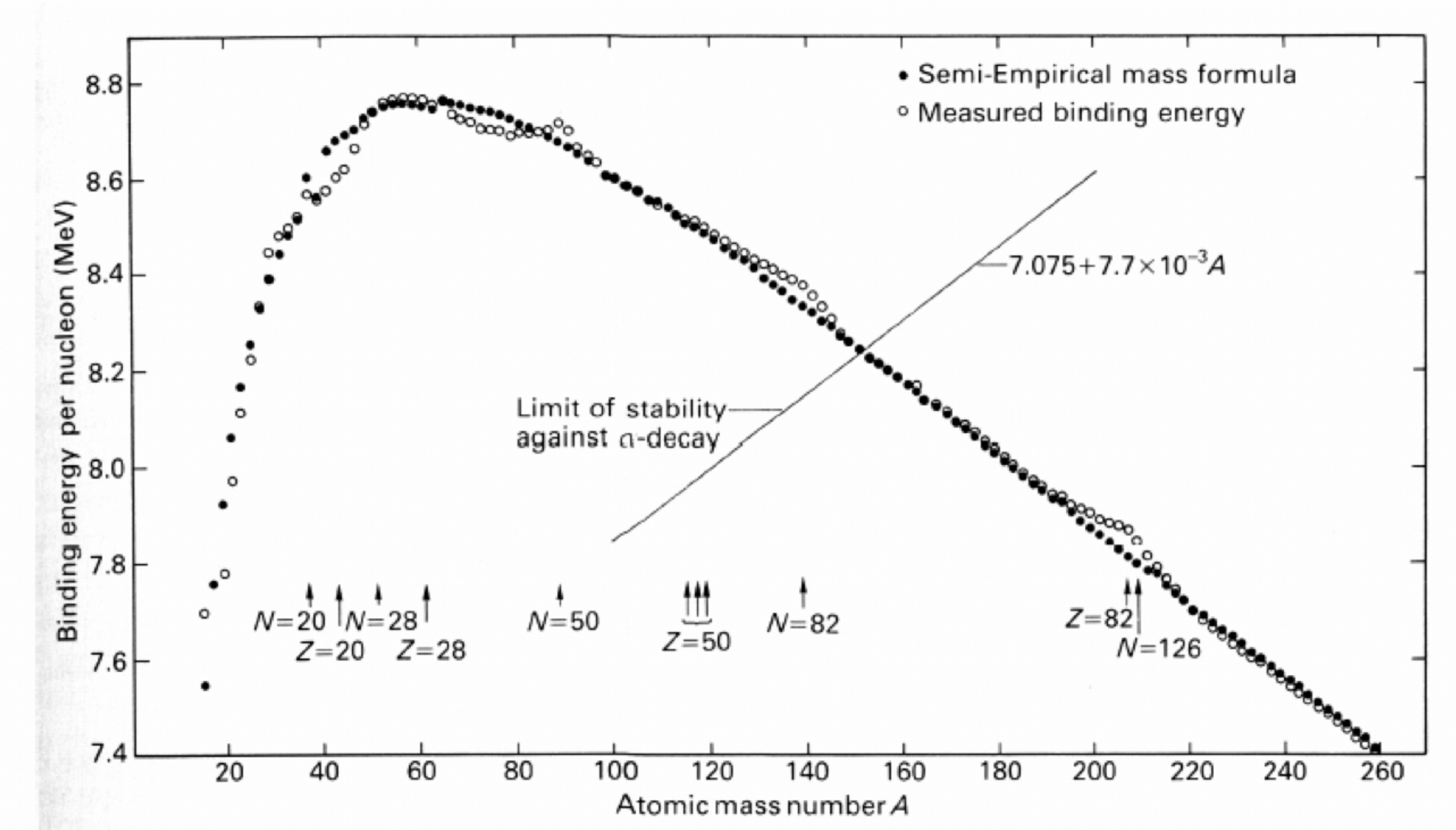
- Electron anti-neutrinos

  → 10^9 W / **3,2 10^{-11} Joules * 6**

  → **2 10^{20} neutrinos / s**

Energy Released per fission

- Considering: $${}^{238}_{92}\mathrm{U} \rightarrow {}^{119}_{46}\mathrm{Cs} + {}^{119}_{46}\mathrm{Cs}$$
  - U(92,238) : B(Z,A)/A=7.6 MeV/nucleon
  - Cs(46,119): B(Z,A)/A=8.5 MeV/nucleon
  - Energy released = 238x8.5 MeV – 2x119x7.6 = 215 MeV



Time Evolution of the antineutrino spectrum

- **Inverse beta decay threshold: Q=1.8 MeV**
  - Ensures that only large Q-value decays are observed
  - Ensures that only short half-life decays are observed
  - Typical time to equilibrium is a few hours

- **Spent-fuel**
  - Fuel stored > a few years on power plant site for cooling
  - Potential emitted of antineutrinos
  - Main isotopes with Q>1.8 MeV: ^{140}Ba, ^{144}Ce, ^{106}Ru, ^{90}Sr
  - Typically add <0.1% due to long half life and low Q → negligible

- But there are other time-dependent effects…

Long Lived Fission Products & Yield

Isotope	$T_{1/2}$	Fission Yield ^{235}U	Fission Yield ^{239}Pu	Mass (kg)	ß EndPoint	$\frac{M \times \langle\sigma\rangle}{T_{1/2}}$
^{131}I	8.02 d	$2.88\ 10^{-2}$	$3.84\ 10^{-2}$		0.971	-------
$^{140}Ba/^{140}La$	12.752 d	$6.12\ 10^{-2}$	$5.59\ 10^{-2}$	6.15	3.762	
^{141}Ce	32.501 d				0.581	-------
^{89}Sr	50.53 d				1.495	-------
$^{95}Zr/^{95}Nb$	64.02 d				1.16	-------
$^{144}Ce/^{144}Pr$	284.893 d	$5.26\ 10^{-2}$	$3.73\ 10^{-2}$	5.44	2.997	
$^{106}Ru/^{106}Rh$	373.59 d	$4.02\ 10^{-3}$	$4.28\ 10^{-2}$	3.06	3.678	
$^{147}Pm/^{147}Sm$	2.6234 y	$2.09\ 10^{-2}$	$2.04\ 10^{-2}$		0.224	-------
$^{90}Sr/^{90}Y$	28.79 y	$5.90\ 10^{-2}$	$2.10\ 10^{-2}$	3.81	2.280	
^{137}Cs	30.07 y	$6.27\ 10^{-2}$	$6.55\ 10^{-3}$		1.176	-------
^{99}Tc	$0.21\ 10^{6}$ y					
^{93}Zr	$1.5\ 10^{6}$ y					
135Cs	2.0 106 y					
^{129}I	$16.\ 10^{6}$ y					

Masses are given for the full load of Uranium
after a combustion at 45 GW days per ton of fuel (GW . d / t)

Fuel Evolution: Burnup

- Fuel evolve with time

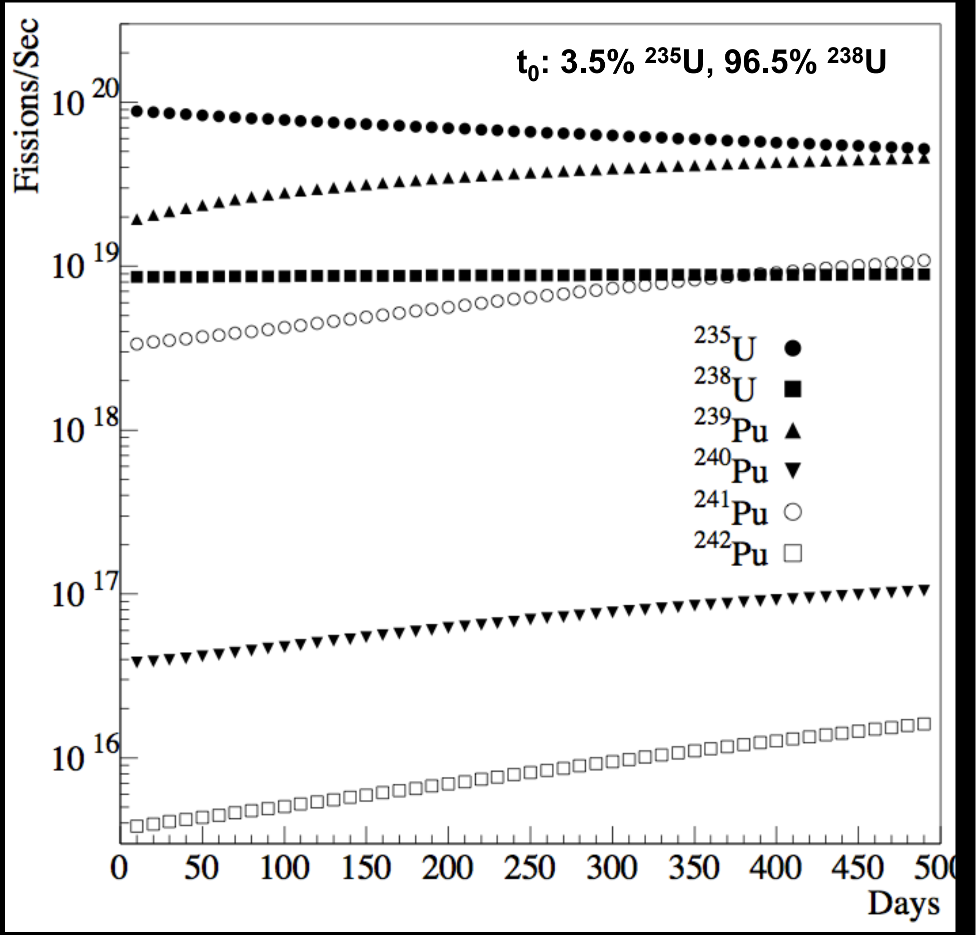
- A typical cycle last 500 days

- Then 1/3 of the fuel is being replaced

- Four main fissioning isotopes
    - ^{238}U: 53.8%
    - ^{239}Pu : 32.8%
    - ^{238}U : 7.8%
    - ^{241}Pu : 5.6%
    - Others <0.1%

- Plutonium breeding during fuel cycle (250 kg) changes the antineutrino flux
    - N (s^{-1})= a . (1+k) P (GW)
    - k : burnup factor (Pu/U fraction)
    - A <10% correction

Need information from the power company



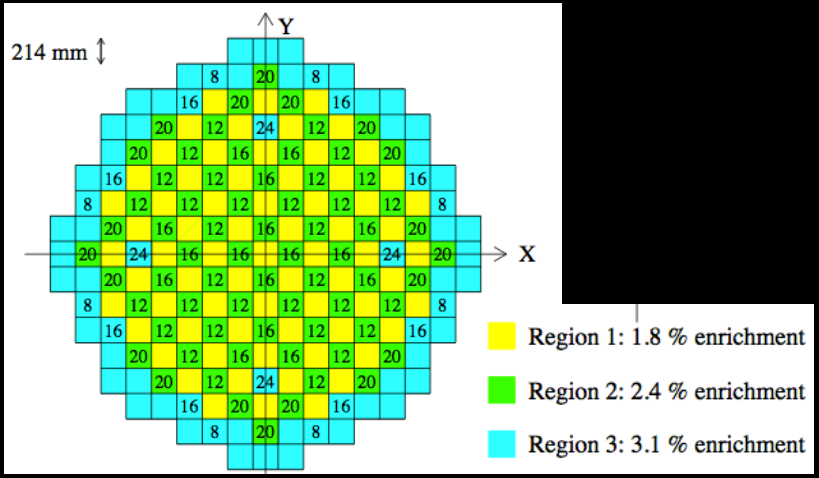
Reactor Power Time Variation

- Example: CHOOZ experiment Eur.Phys.J.C27:331-374,2003

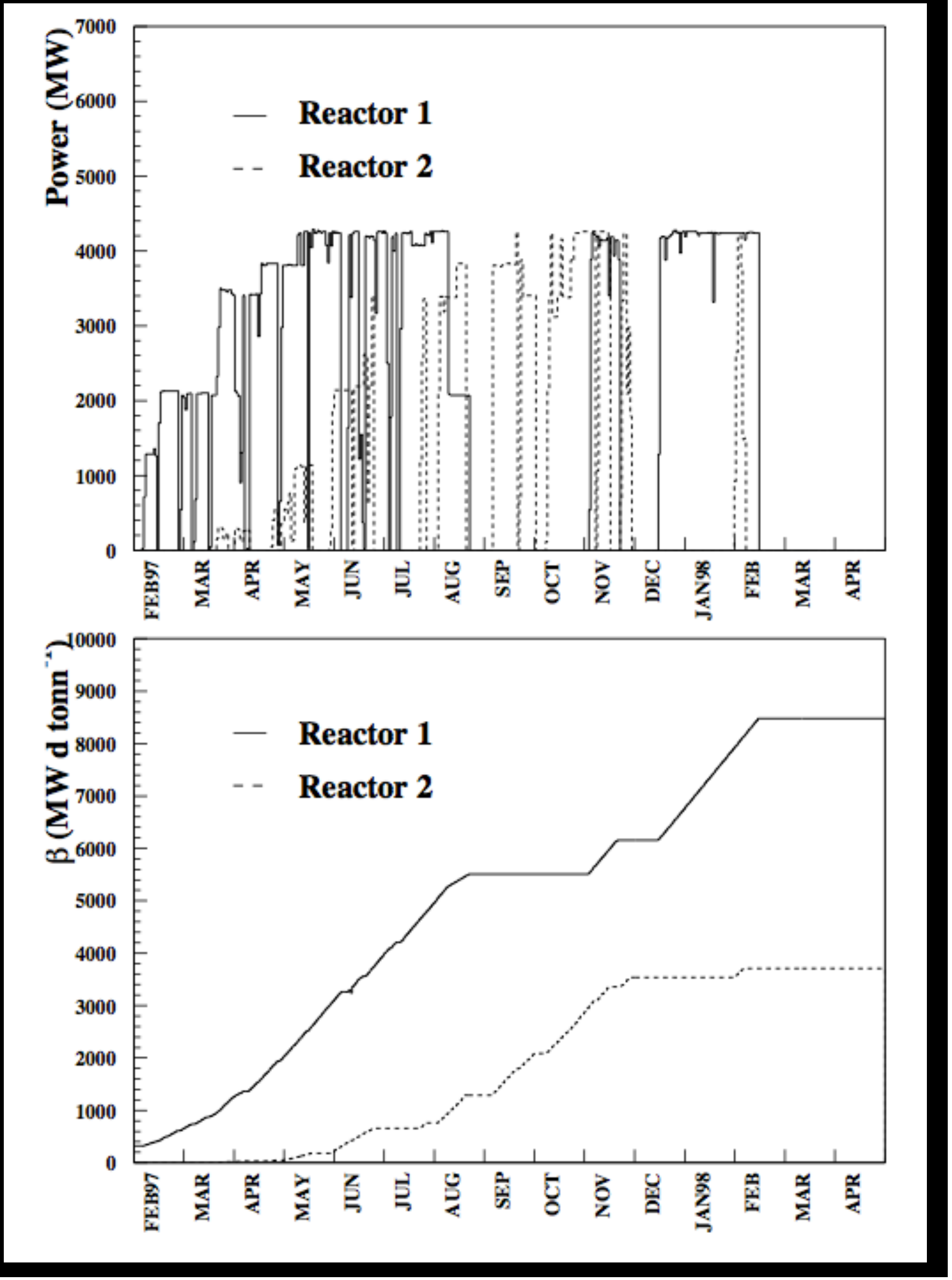
- 3-6 week shutdown every 12-18 months

- 1/4-1/3 of fuel assemblies are replaced, remaining fuel repositioned

-



- Long shutdown of 6 months every 10 years



Reactor Neutrino Flux

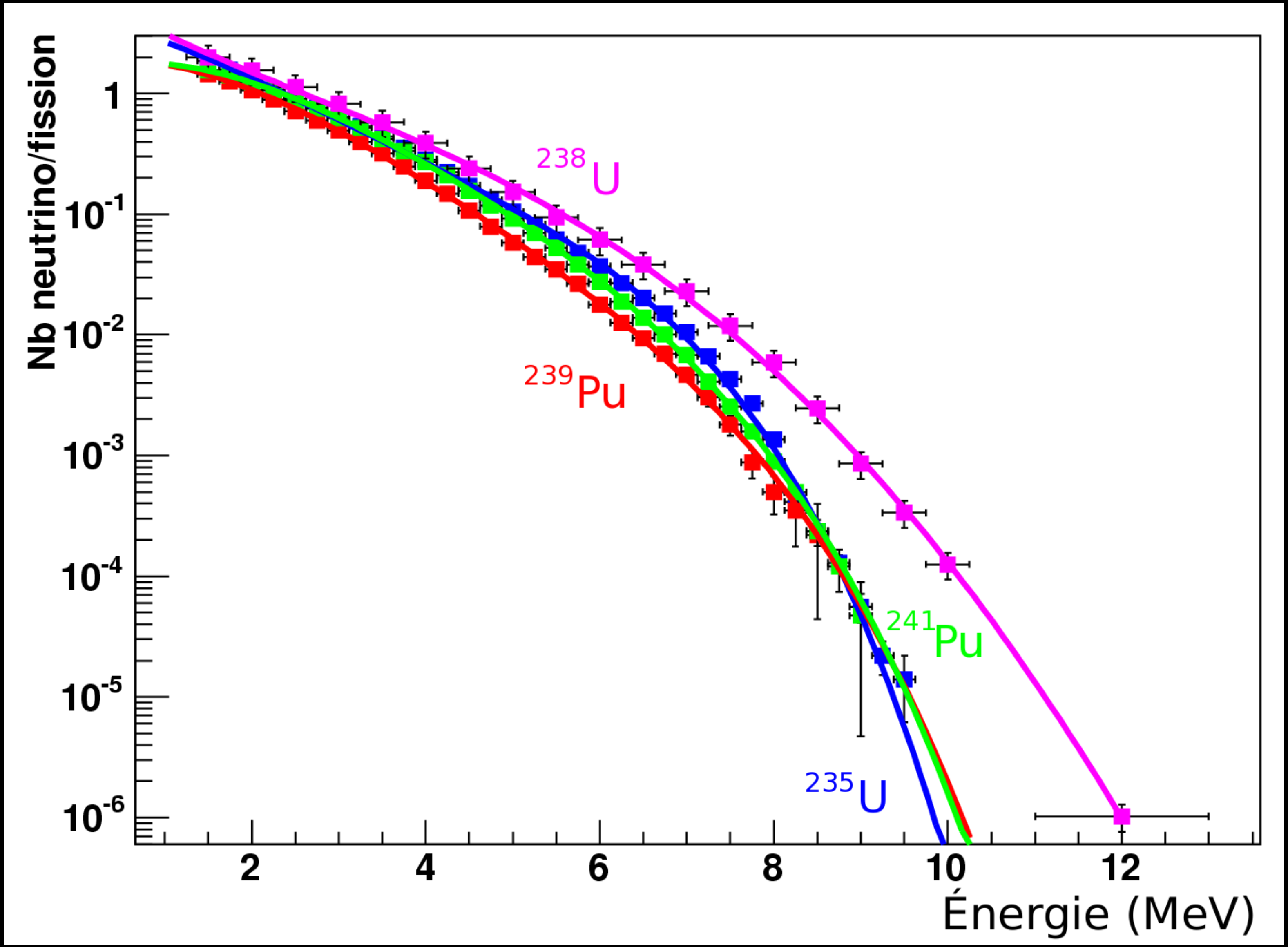
Flux & Spectrum Prediction

- **Antineutrino flux**
  - >99.9% antineutrinos produced by ^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu
  - >90% antineutrinos produced by ^{235}U, ^{239}Pu

- **^{235}U, ^{239}Pu, ^{241}Pu**
  - electron spectrum measurement (ILL reactor, 1980's)
  - electron → neutrino spectrum conversion
    - Old conversion (Schreckenbach et al., 1980's)
    - New conversion method (Mueller et al., 2011, +3%, w.r. old)

- **^{238}U**
  - Computation based on nuclear databases
    - Old computation (Vogel et al., 1980's)
    - New computation (Mueller et al., 2011, +9.6% w.r. old)

Flux & Spectrum



Reactor beta-spectrum

- **$S_{tot}(E)$: integrated neutrino spectrum**

$$S_{\text{tot}}(E) = \sum_{k={}^{235}\text{U},{}^{238}\text{U},{}^{239}\text{Pu},{}^{241}\text{Pu}} \alpha_k \times S_k(E)$$

- **$S_k(E)$: spectrum normalized to 1 fission**
  - E: electron kinetic energy
  - α_k: number of fission of the isotope k, at a given time

- **Each isotope ‘k’ undergo fission producing fission products ‘fp’**
  - $\mathcal{A}_{fp}(t)$: activity of the fpth fission product, normalized to 1 fission of isotope ‘k’

- **Each fission products decay, through N_b branches connecting the ground state of the parent nucleus to the exited states of the daughter nucleus**
  - BR_{fb}^{p} : branching ratio of the bth branch of the fpth fission product
  - $E0_{fp}^{p}$: end-point energy of the bth branch of the fpth fission product.
  - Z_f : charge of the parent nucleus.
  - A_f : atomic number of the parent nucleus.

$S_k(E)$: spectra per fission per isotopes

Sum of all fission products' activities

$$S_k(E) = \sum_{fp=1}^{N_{fp}} \mathcal{A}_{fp}(T) \times S_{fp}(E)$$

Sum of all β-branch of each fission product

$$S_{fp}(E) = \sum_{b=1}^{N_b} BR^b_{fp} \times S^b_{fp}(Z_{fp}, A_{fp}, E^b_{0fp}, E)$$

Theory of β-decay

$$\underbrace{K^b_{fp}}_{\text{Norm.}} \times \underbrace{\mathcal{F}(Z_{fp}, A_{fp}, E)}_{\text{Fermi function}} \times \underbrace{pE(E - E^b_{0fp})^2}_{\text{Phase space}}$$

$$\underbrace{C^b_{fp}(E)}_{\text{Shape factor}} \times \underbrace{\left(1 + \delta^b_{fp}(Z_{fp}, A_{fp}, E)\right)}_{\text{Correction}}$$

$$\delta^b_{fp}(Z_{fp}, A_{fp}, E) = \delta_{QED}(E) + A_C(Z_{fp}, A_{fp}) \times E + A_W \times E$$

T. Lasserre - INSS 2011

A_c & A_w corrections

- **Weak-magnetism correction (finite size of the nucleons)**
  - Approx: difference of proton and neutron magnetic mome
  - A_w>0

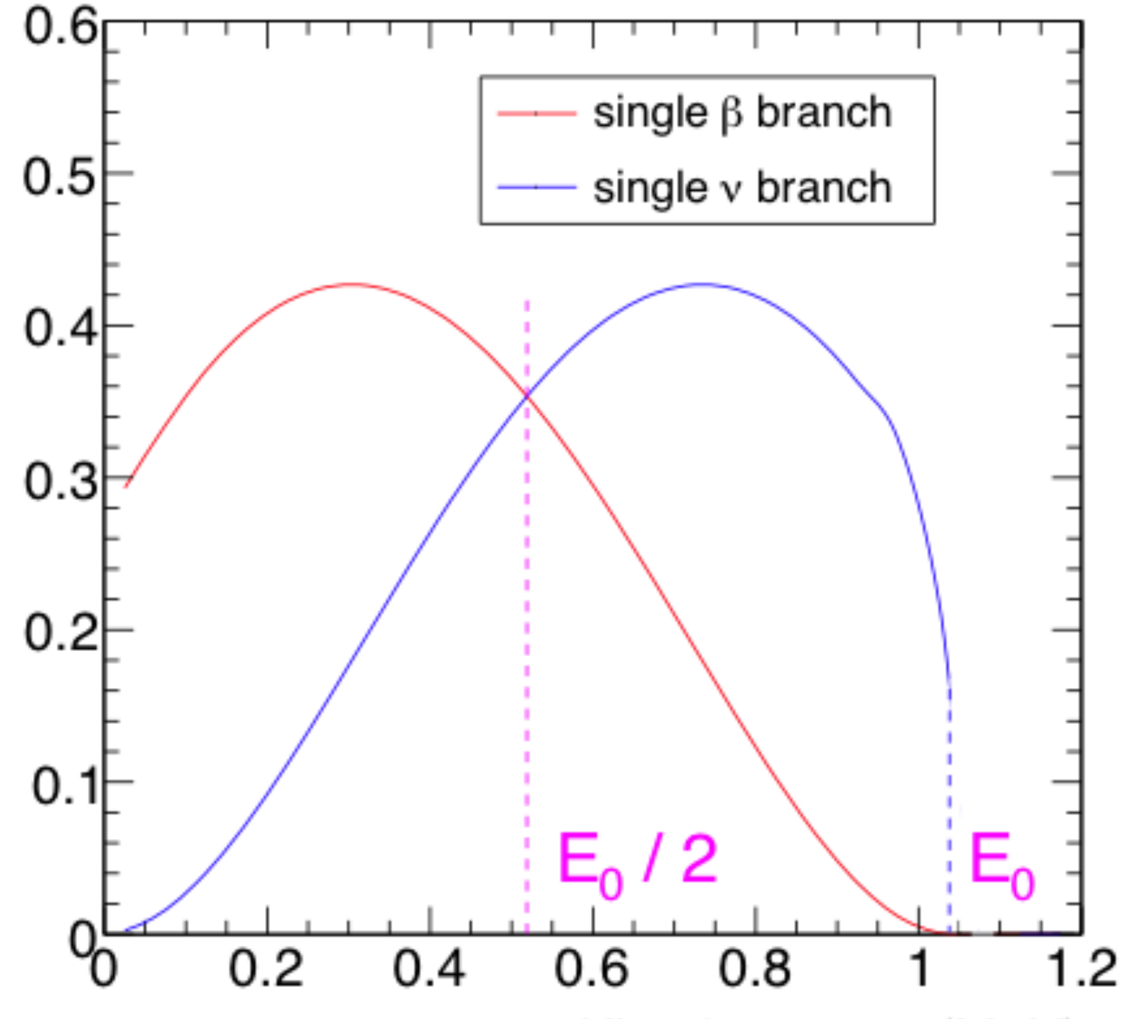
$$A_W = \frac{4}{3}\frac{\langle l + (\mu_p - \mu_n)\sigma\rangle}{m_N\langle\sigma\rangle\lambda} \approx \frac{\mu_p - \mu_n - \frac{1}{2}}{m_N\lambda} \approx 0.47\%/MeV$$

- **Coulomb correction (finite size of the decaying nucleus)**
  - electron spectrum measurement (ILL reactor, 1980's)
  - electron → neutrino spectrum conversion
    - Old conversion (Schreckenbach et al., 1980's)
    - New conversion method (Mueller et al., 2011, +3%, w.r. old)

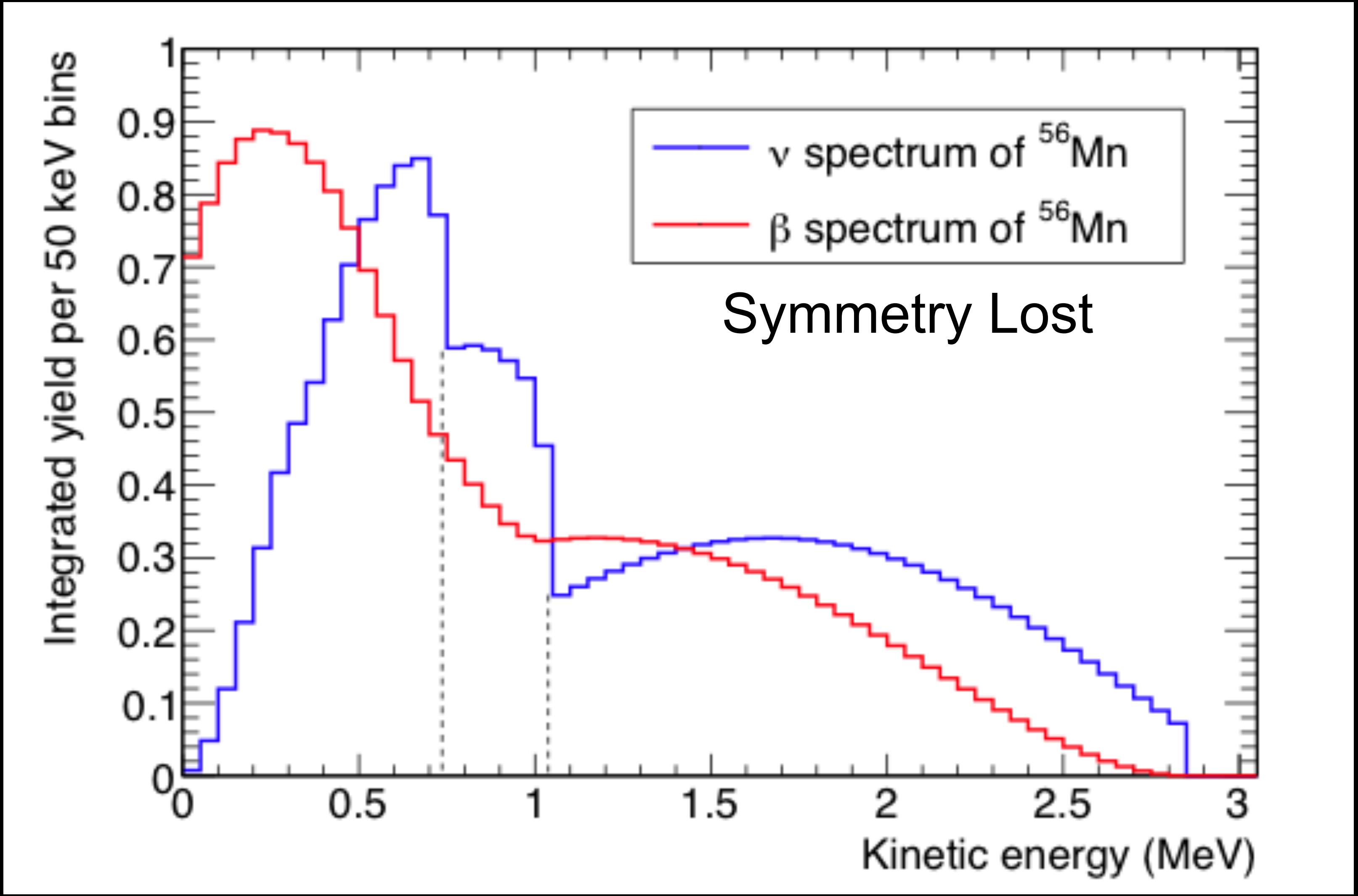
$$A_C = -\frac{10Z\alpha R}{9\hbar c}$$

From e⁻ to neutrino spectrum

Symmetry $E_\nu = E^b_{0fp} - E$



From e$^-$ to neutrino spectrum

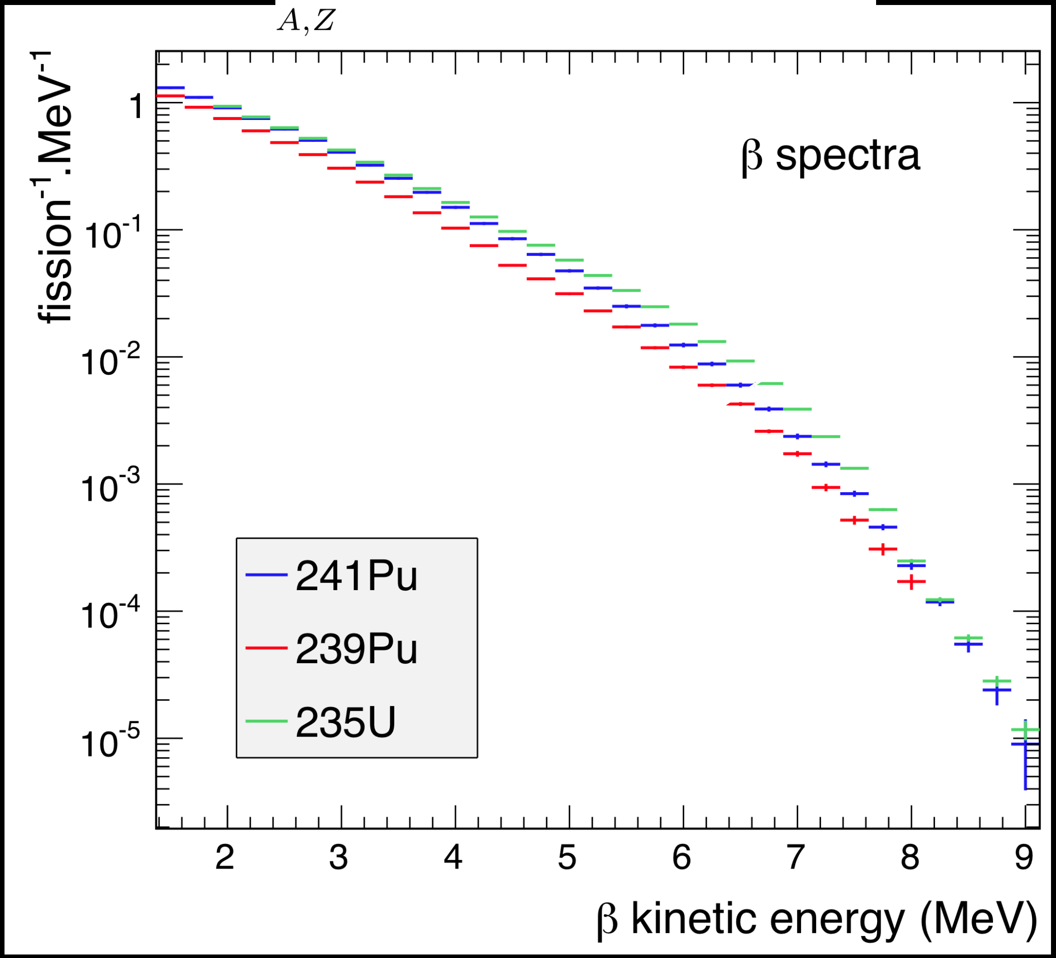


Symmetry Lost

The ILL electron Data Anchorage

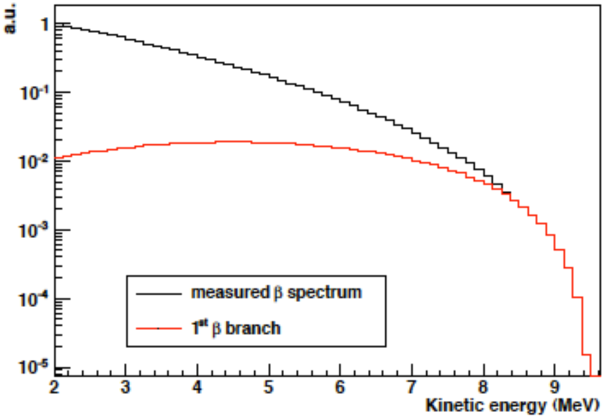
- Accurate e^- measurements @ ILL' (1980-89):
    - High resolution magn. spectrometer
    - Intense and pure thermal n spectrum from the core
    - Extensive use of reference internal conversion electron lines → Normalization (1.8%)

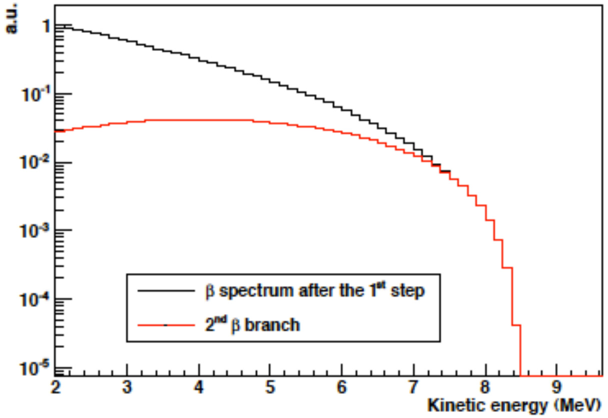
$$\sum_{A,Z}\left\{\,{}^{A}_{Z}X \longrightarrow {}_{Z+1}^{\;\;A}Y + e^{-} + \bar{\nu}_e\right\}$$

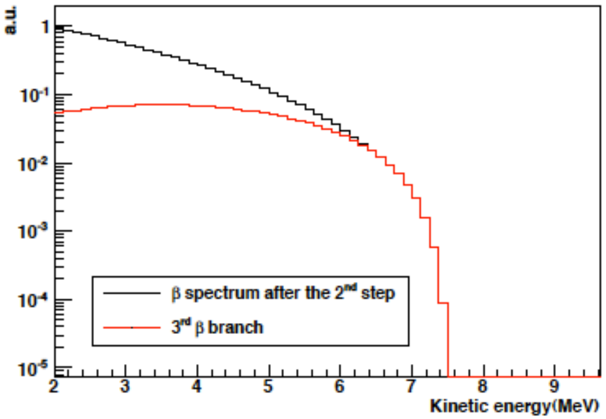


ILL data: conversion to ν spectra

- Fit e^- spectrum with a sum of 30 effective branches
- Conversion of the effective branches to ν spectra







- **All theory included in these effective branches but:**

  - What Z? : Mean fit on nuclear data *Z=f(E0)*

$$Z(E_0) \approx 49.5 - 0.7E_0 - 0.09E_0^2, \quad Z \geq 34$$

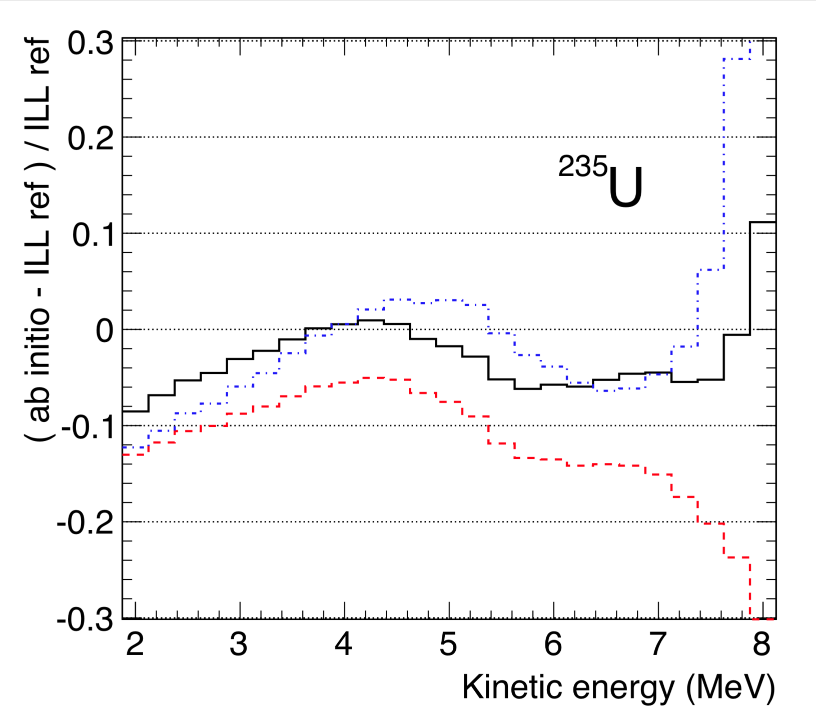
  - What A_{CW}? : effective correction on the ν-spectra

$$DN_n^{C,W}(E_n) \approx 0.65 \times (E_n - 4\mathrm{MeV}) \quad \%$$

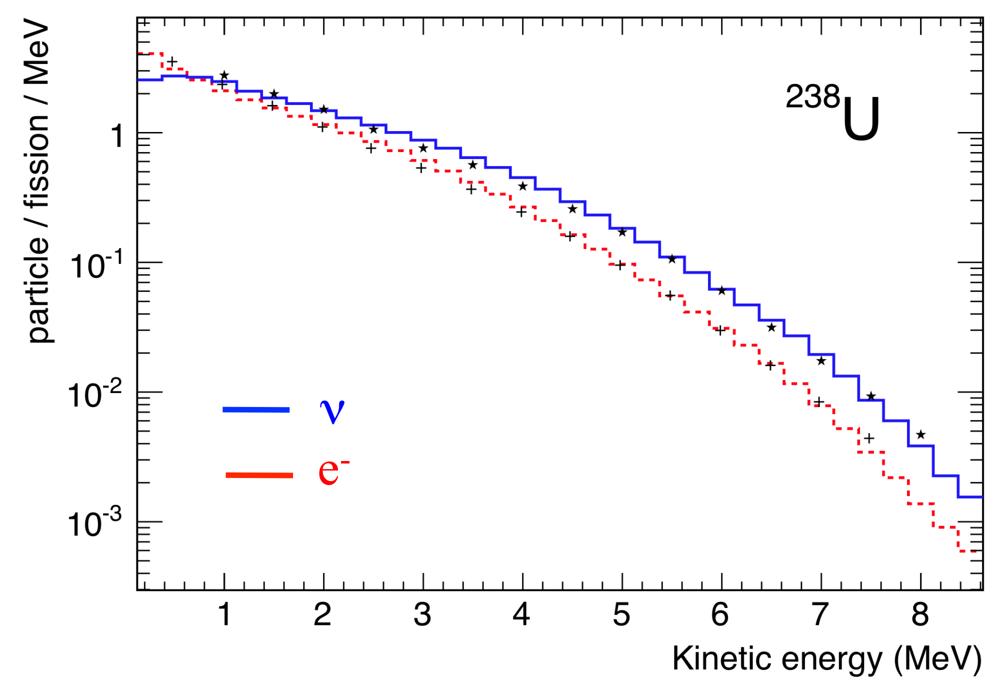
The Full ***Ab Initio*** *Attempt (electron data)*

- MURE evolution code: core composition and off equilibrium effects
- BESTIOLE code: build up database of ~800 nuclei and 10000 β-branches

Residues w.r.t. reference ILL e^- data



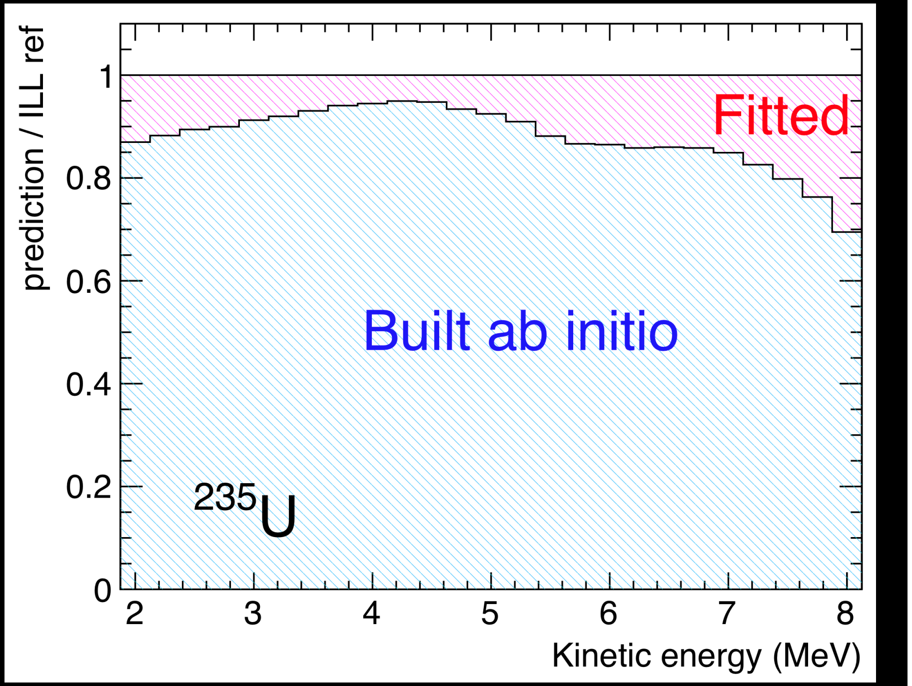
New ^{238}U spectrum prediction

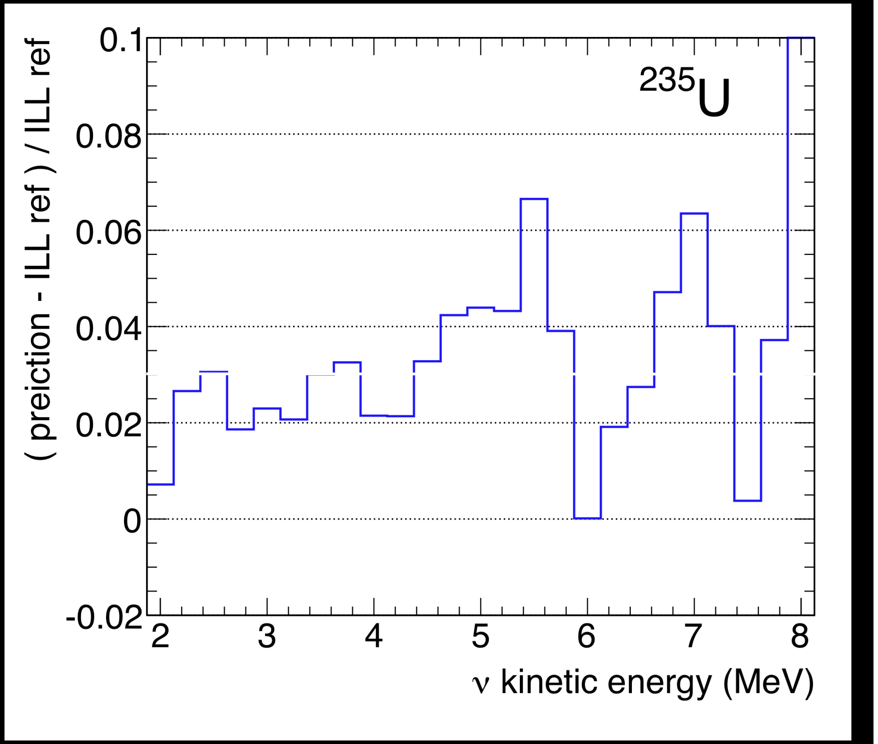


→ 95+/-5% of the spectrum reproduced but still not meeting required precision
→ Useful estimate of ^{238}U spectrum which couldn't be measured @ ILL
→ Measurement at FRMII ongoing (N. Haag & K Schreckenbach, TUM)

The New Mixed Conversion Approach

1. **SAME** ILL e- data Anchorage
2. Ab-Initio: “true” distribution of β-branches reproduces >90% of ILL e^- data
3. Old-procedure: five effective anchorage-branches to the remaining 10%

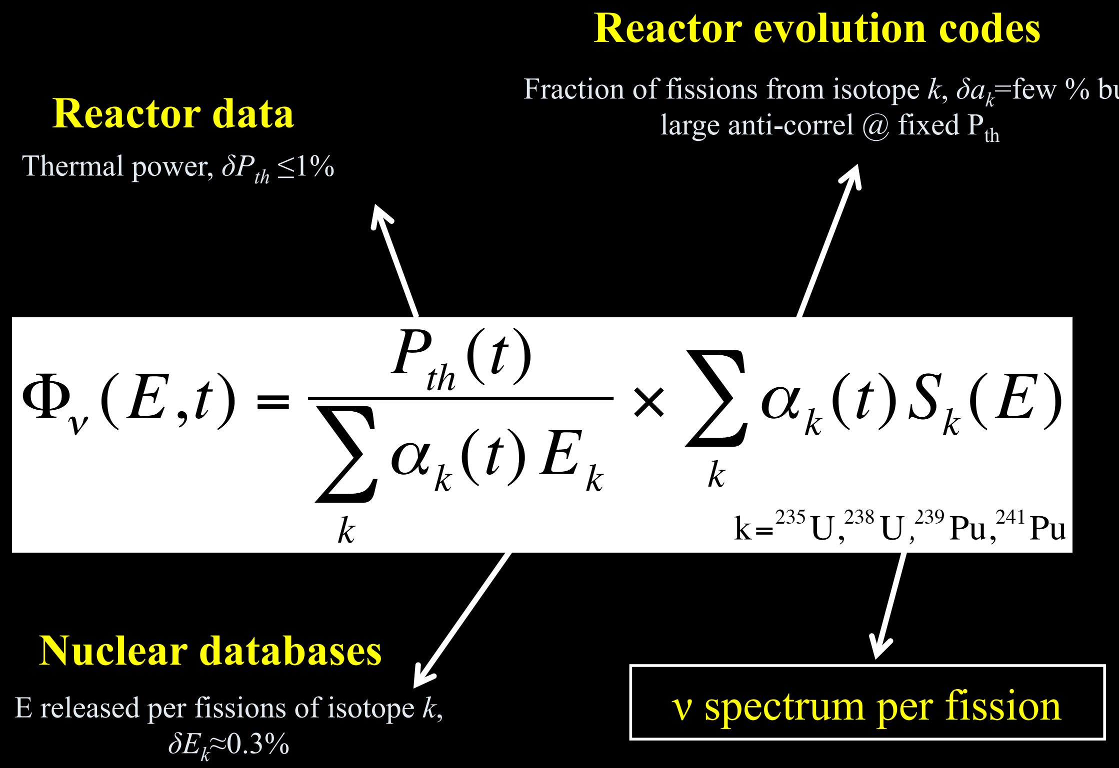




- **+3% normalization shift with respect to old ν spectrum**
- **Similar result for all isotopes (^{235}U, ^{239}Pu, ^{241}Pu)**
- **Stringent Test Performed – Origin of the bias identified**

Reactor ν spectrum

The prediction of reactor ν spectrum is the dominant source of systematic error for single detector reactor neutrino experiments



Reactor evolution codes

Fraction of fissions from isotope k, δa_k=few % but large anti-correl @ fixed P_{th}

Reactor data

Thermal power, $\delta P_{th} \leq 1\%$

$$\Phi_\nu(E,t) = \frac{P_{th}(t)}{\sum_k \alpha_k(t)\, E_k} \times \sum_k \alpha_k(t)\, S_k(E)$$

k = ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

Nuclear databases

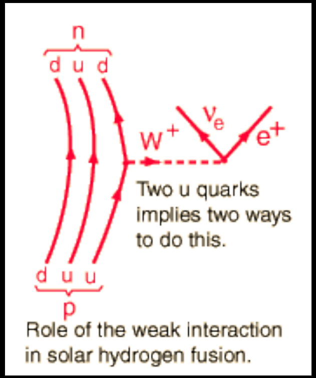
E released per fissions of isotope k, $\delta E_k \approx 0.3\%$

ν spectrum per fission

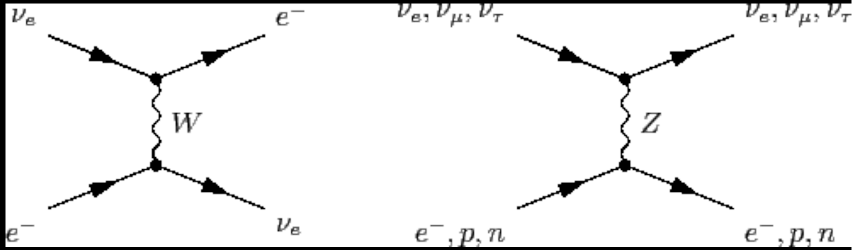
Reactor Antineutrino Detection

Reactor Neutrino Detection

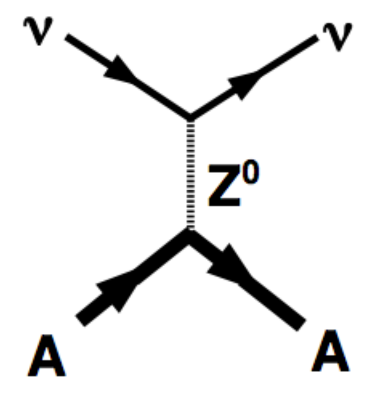
- **Inverse Beta Decay**
  - p + anti-$v_e \rightarrow e^+ + n$
  - cross section @2 MeV : 5 10^{-43} cm^2
  - scale as E^2



- **Neutrino-Electron Scattering**
  - e^- + anti-$v_e \rightarrow e^-$ + anti-v_e
  - cross section @0.8 MeV : 5 10^{-45} cm^2
  - scale as E



- **Neutrino-Nucleus Coherent Scattering**
  - A + anti-$v_e \rightarrow$ A + anti-v_e
  - cross section @2 MeV > 10^{-41} cm^2
  - scale as E^2
  - scale as N^2



IDB: Basics Kinematics

- Inverse beta-decay: $\overline{\nu_e} + p \rightarrow e^+ + n$

- Momentum conservation:

$$\overrightarrow{p_{\nu_e}} + \overrightarrow{p_p} = \overrightarrow{p_{e^+}} + \overrightarrow{p_n}$$

$$\text{Most of the time } \overrightarrow{p_p} = \vec{0} \text{ (lab frame)}$$

- Energy conservation:

$$E_{\nu_e} + E_p = E_{e^+} + E_n$$

neglecting neutron recoil

$$E_{\nu_e} + m_p c^2 = E_{e^+} + m_n c^2$$

$$E_{\nu_e} = E_{e^+} + (m_n - m_p)c^2 = E_{e^+} + \Delta$$

$$E_{e^+} = T_{e^+} + m_e c^2$$

$$E_{\nu_e} = T_{e^+} + m_e c^2 + \Delta$$

- Energy threshold:

$$\Delta \approx 1.293 \text{ MeV}$$

$$m_e c^2 \approx 0.5 \text{ MeV}$$

$$T_{e^+} = \Delta + m_e c^2 - E_{\nu_e}$$

$$T_{e^+} = 0 \rightarrow E_{\nu_e} = 1.804 \text{ MeV} = \mathrm{E}_{\mathrm{th,approx}}$$

But exact threshold given by :

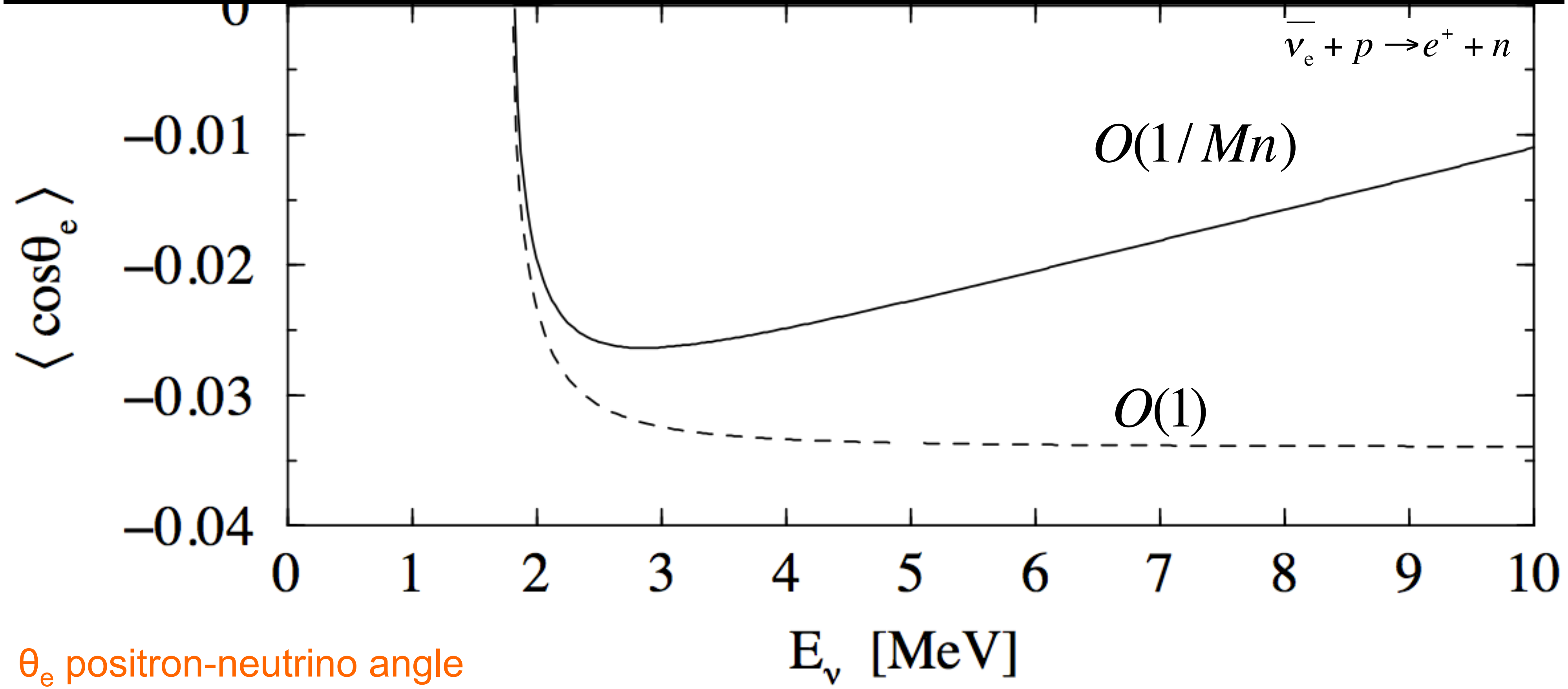
$$\mathrm{E}_{\mathrm{th,true}} = \frac{(m_n + m_e)^2 - m_p^2}{2m_p} = 1.806 \text{ MeV}$$

IDB: positron angular distribution

- Inverse beta-decay: $\overline{\nu}_e + p \rightarrow e^+ + n$
- Positron angular distribution given by (Vogel-Beacom 1999) $\frac{d\sigma}{d\cos\theta} \approx 1 + velocity_{e^+} a(E_\nu)\cos\theta$
- θ positron-neutrino angle
- Valid for reactor neutrino energies
- Average <cos θ > : $\langle\cos\theta\rangle \approx \frac{velocity_{e^+} a(E_\nu)}{3} \approx -0.03$
  - velocity = 1 (but near to the threshold)
  - Infinite nucleon mass approximation a(E)=a
  - Fermi/Gamow-Teller transitions competition → a=-0.1
- Angular distribution of the positron is slightly backward
- Rarely accessible…

IDB: positron angular distribution

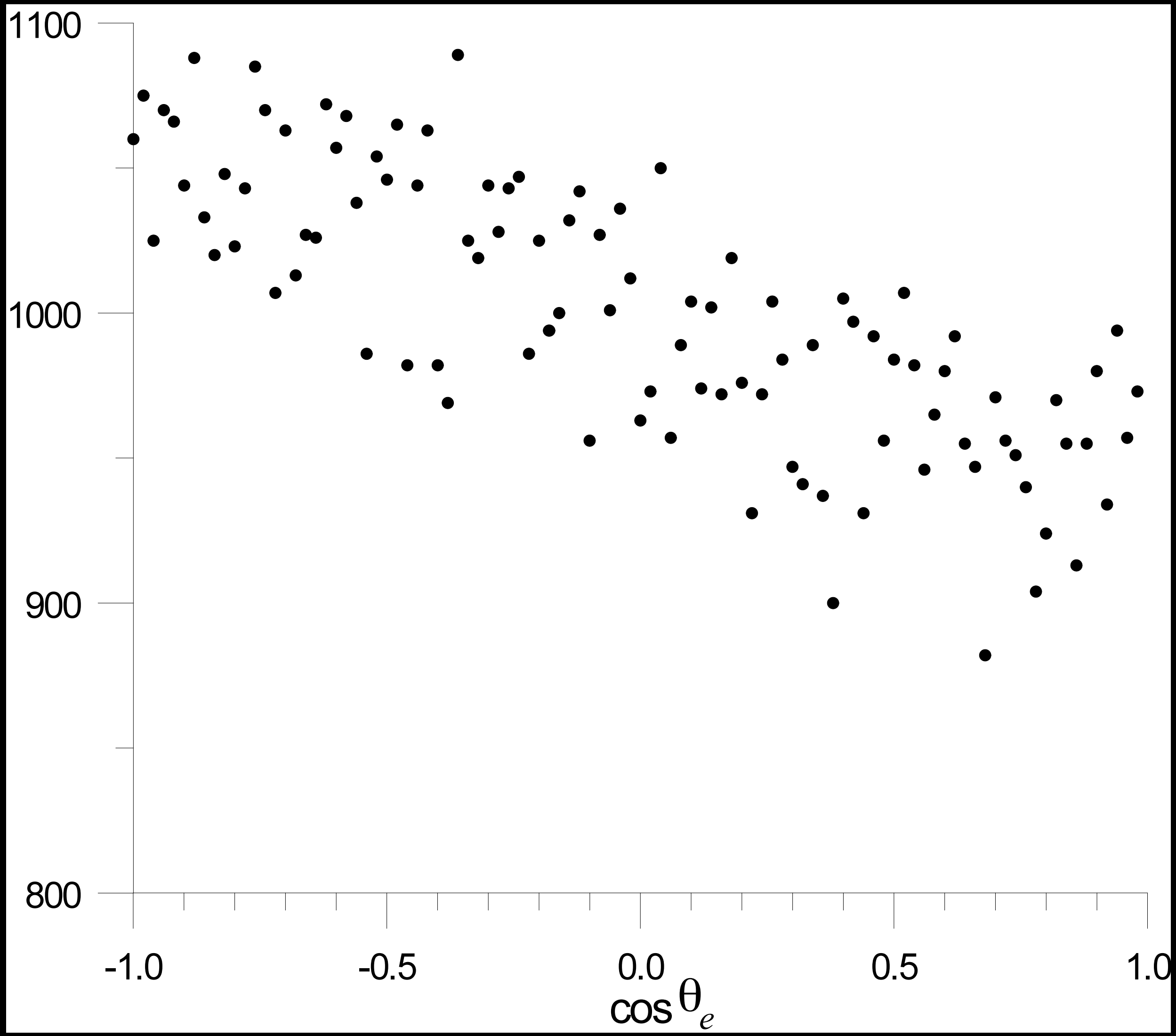
$$\langle \cos\theta \rangle \approx \frac{velocity_{e^+}\, a(E_\nu)}{3} \approx -0.03$$



θ_e positron-neutrino angle

IDB: positron angular distribution

IBD generated events: neutrino/positron angle (θ_e)



IDB: neutron kinetic energy

- Finite Neutron Mass → 1/M terms dev.

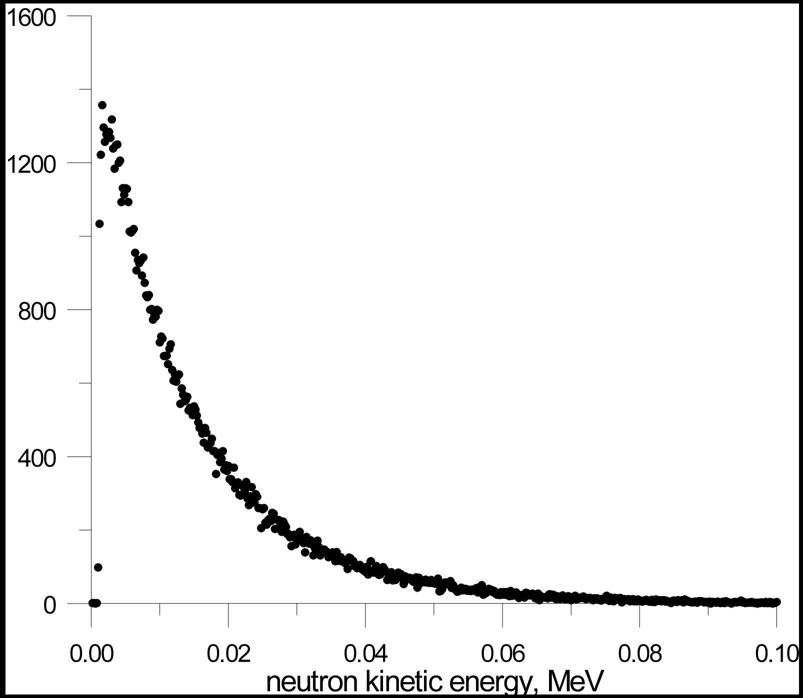
$$E_e^{(1)} = (E_\nu - \Delta)\left(1 - \frac{E_\nu}{M}(1 - \cos\theta)\right) - \frac{\Delta^2 - m_e^2}{2M}$$

$$T_n = \frac{E_\nu (E_\nu - \Delta)}{M}\left(1 - \cos\theta\right) + \frac{\Delta^2 - m_e^2}{2M}$$

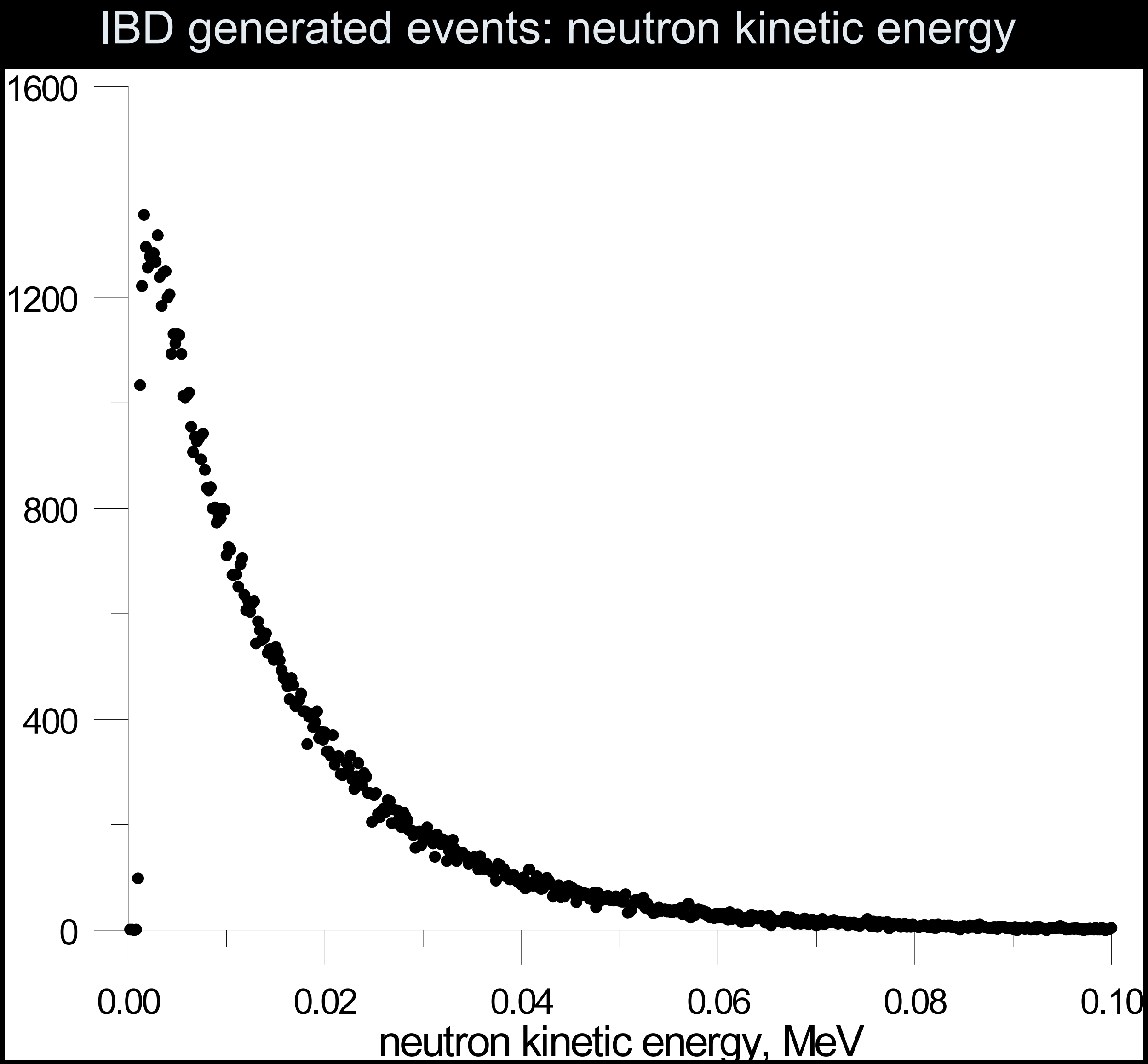
- $E_\nu = 3.5$ MeV
- $E_e = E_\nu - \Delta = 3.5 - 1.3 = 2.2$ MeV
- velocity=1
- assuming cos θ = 0
- M=938 MeV

→ $T_n = 1/938\ (3.5 \times 2.2 + 0.7) = 10$ keV
(relevant for the detector calibration)

IBD generated events



IDB: neutron kinetic energy



IDB: neutron angular distribution

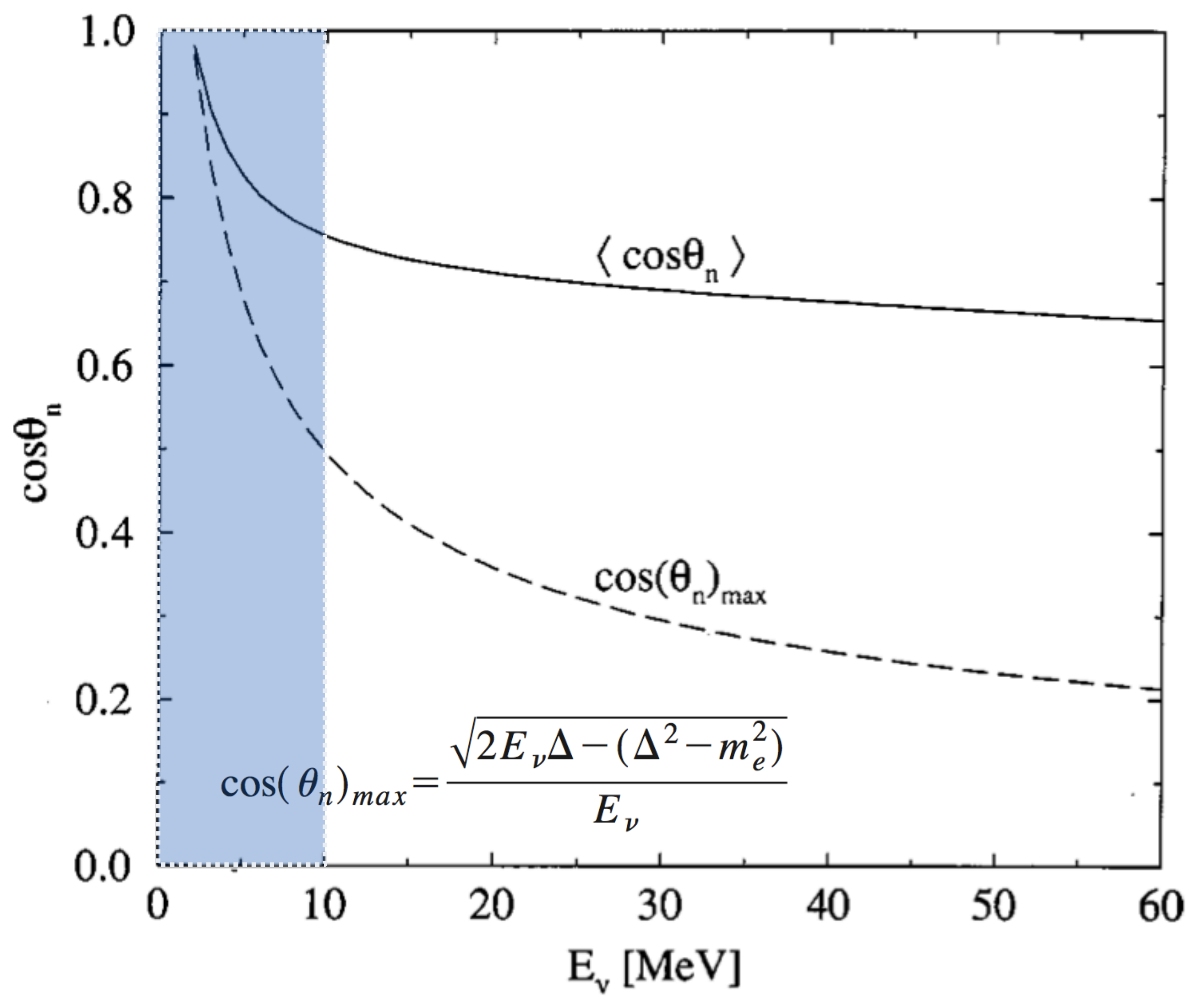
- **IDB reaction**
  - Positron emission (no position information): vertex reconstruction
  - First neutron step in the forward direction → directionality information
  - Then neutron thermalization → random walk → loose directionality
  - Finally neutron capture → vertex localization possible (γ emission)

- After vertex reconstruction: (e^+,n) vertex vector reconstructed for all events and statistically studied → 1.5-2 cm displacement in the antineutrino direction

- **Experimentally**
  - Observed in the Goesgen experiment (10 sigmas)
    - Segmented detector
  - Observed in the Bugey-3 experiment
    - Segmented detector
  - Observed in the CHOOZ experiment
    - Unsegmented detector

- **Future Goal: Could directionality be used for background rejection?**

IDB: neutron angular distribution



$$\cos(\theta_n)_{max} = \frac{\sqrt{2E_\nu\Delta - (\Delta^2 - m_e^2)}}{E_\nu}$$

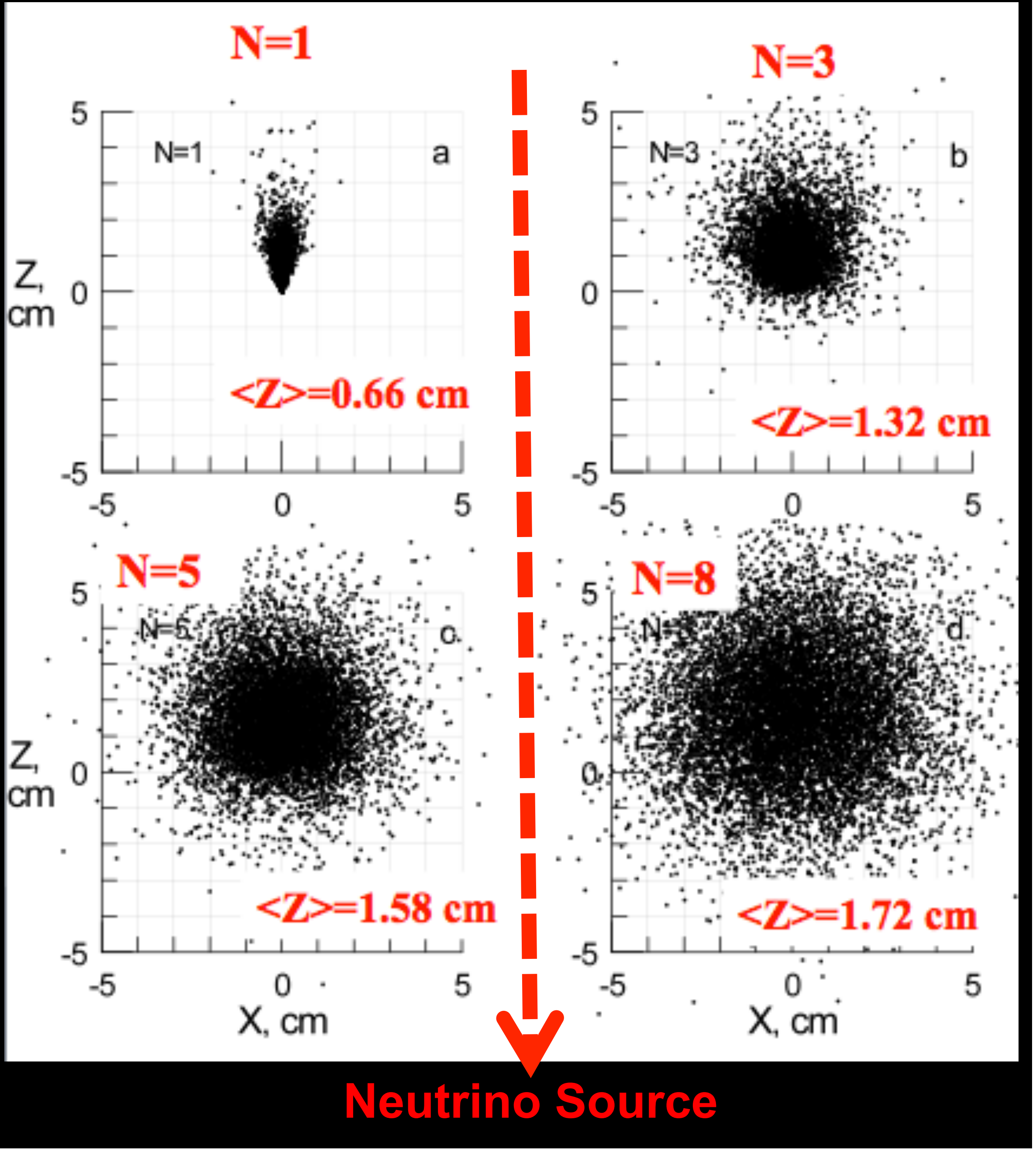
IDB: Toy MC Simulation

- First neutron step before collision: very clear forward emission

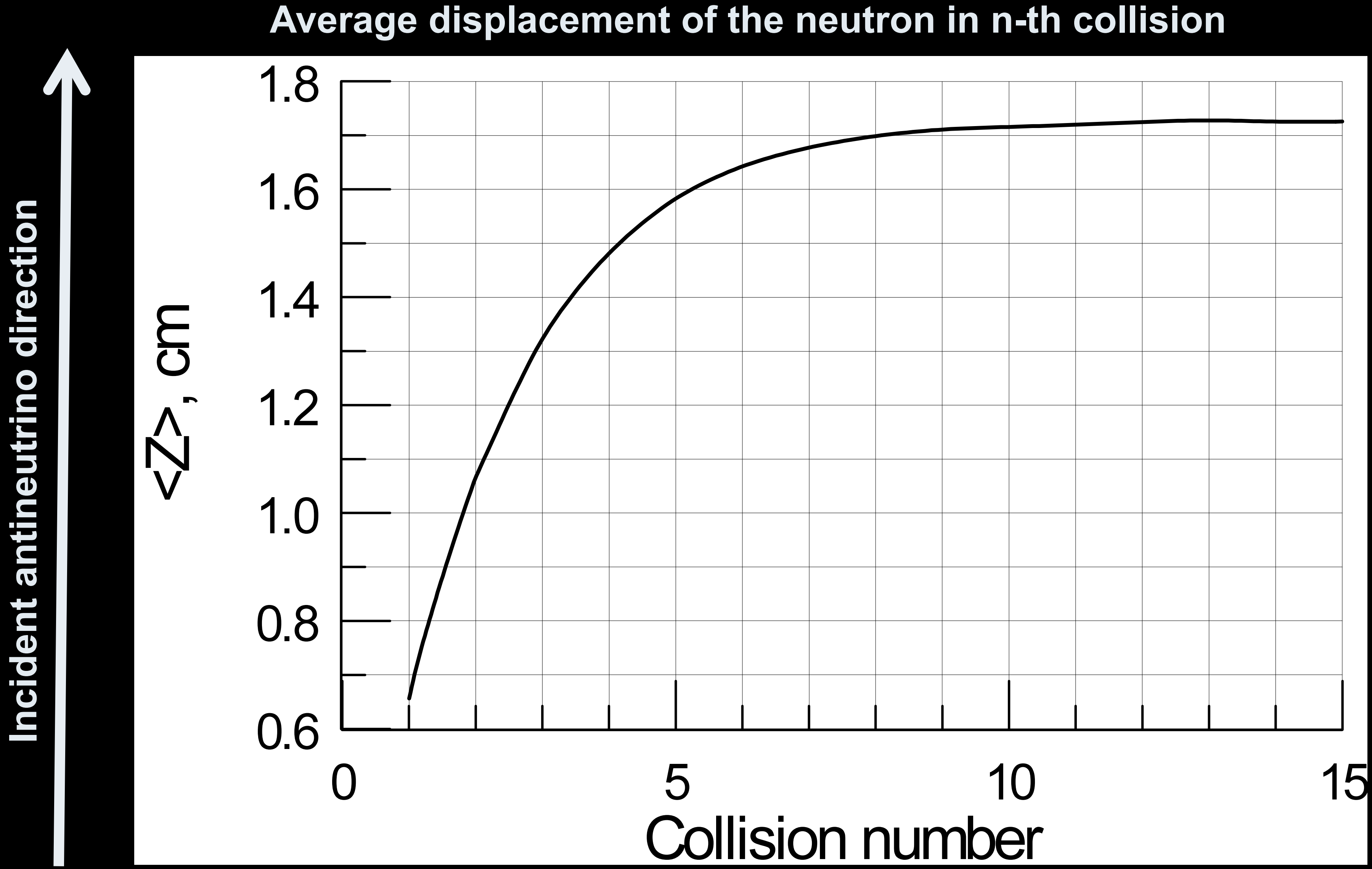
- First few collisions with scintillator atoms the memory is partially conserved and neutron is displaced from the reaction point in +Z direction

- After 8 collisions the memory is lost and neutrons slow down and diffuse symmetrically around the displaced center

- After 20 collisions the neutron is thermalized (0.025 eV) and captured (in oil or water)



IDB: Toy MC Simulation



IDB: Cross Section

- Vogel: cross-section with corrections (Phys Rev D29 p1918, 1984)
- Fayans 1985: very close to Vogel 84 (Sov J Nucl Phys 42, Oct 85)

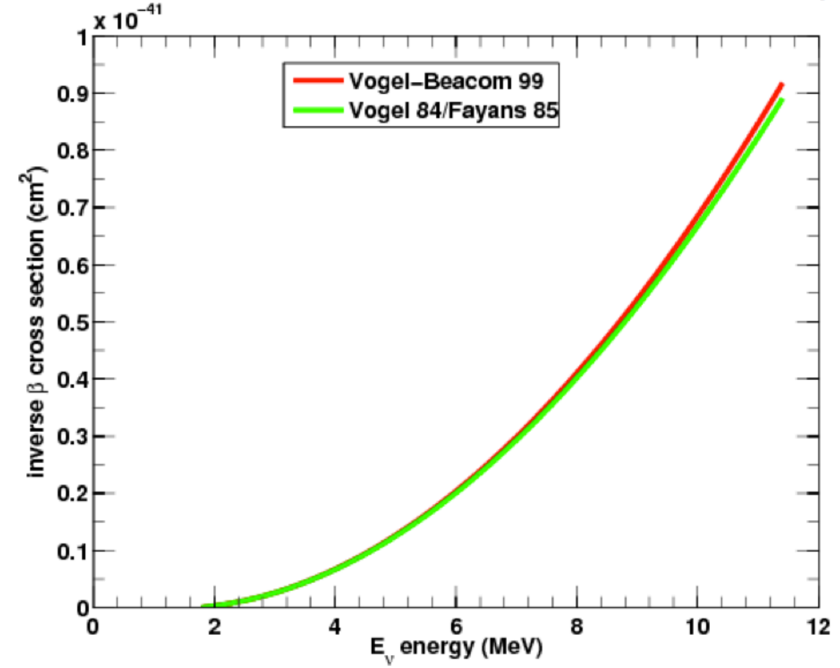
- Order 0 cross-section: $\sigma_0 = K\, p_e E_e$

- K = prefactor (cm^2 MeV^{-2})

- Need extra corrections:

$$\sigma_1 = \sigma_0 (1 + \delta_{rec} + \delta_{wm} + \delta_{rad})$$

  - neutron recoil,
  - weak-magnetism,
  - outer radiative corrections:



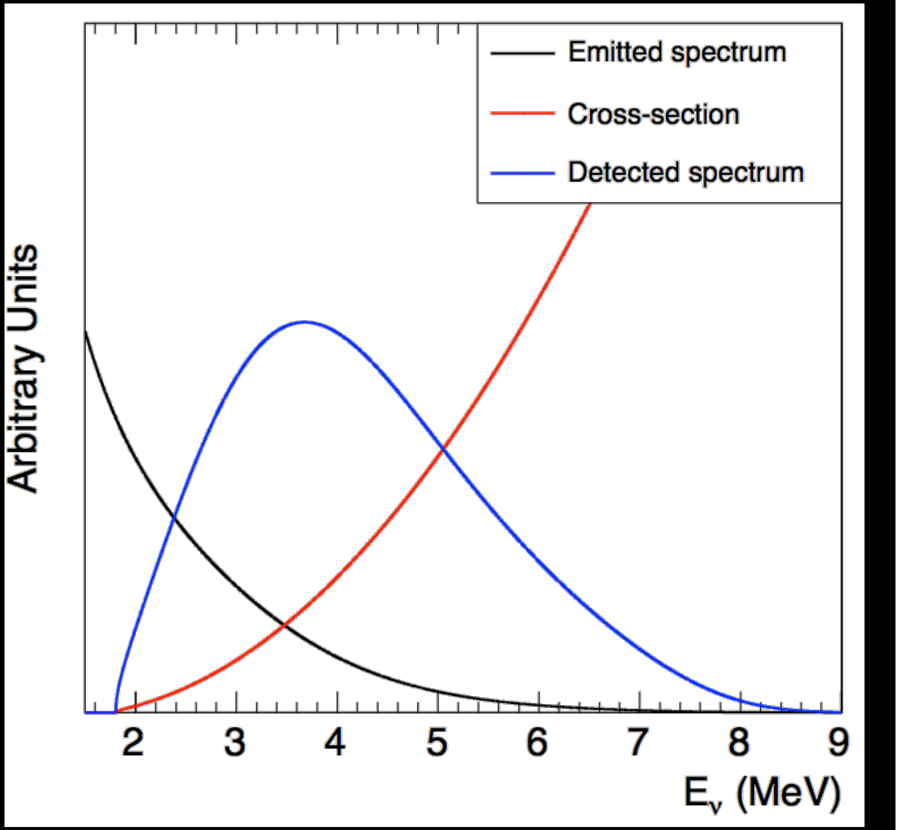
- Vogel-Beacom 99: “supersedes” Vogel 84 (Phys Prev D60 053003)
Full development to order 1/M. Complicated formula, numerical integration

Positron Yield Calculation

- For fixed positron energy E_e only a narrow interval of neutrino energies contribute to the yield, centered around :

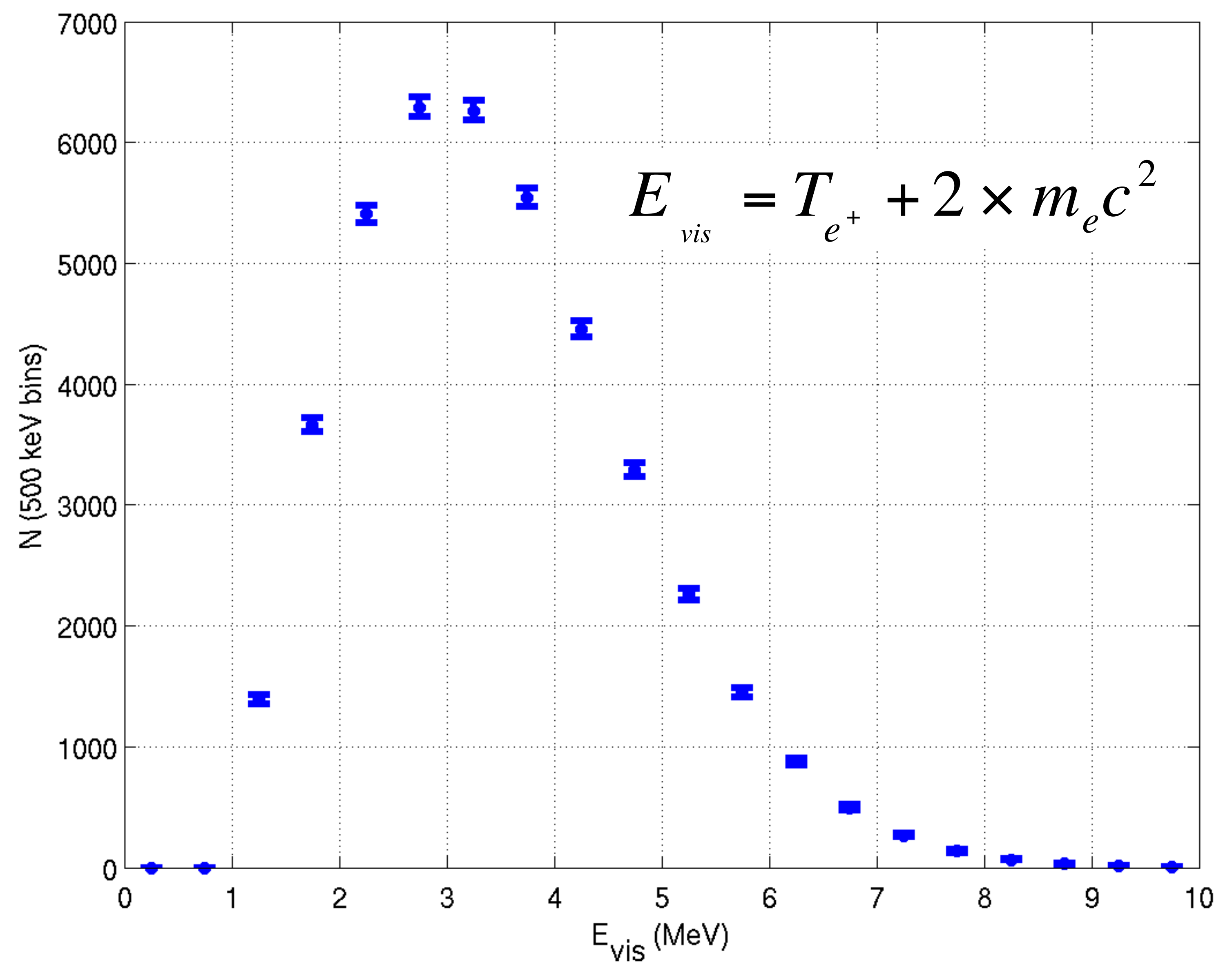
$$\overline{E_\nu} = E_e + \Delta + \frac{2E_e(E_e+\Delta)+\Delta^2-m_e^2}{2M_p}$$

- Therefore : $n(E_e) \approx \phi(\overline{E_\nu})\sigma_1(E_e)$



- For σ_1 Vogel-Beacom99 should be used
- cross-section accurate to +/-0.2%

Visible Energy Spectrum



$$E_{vis} = T_{e^+} + 2 \times m_e c^2$$

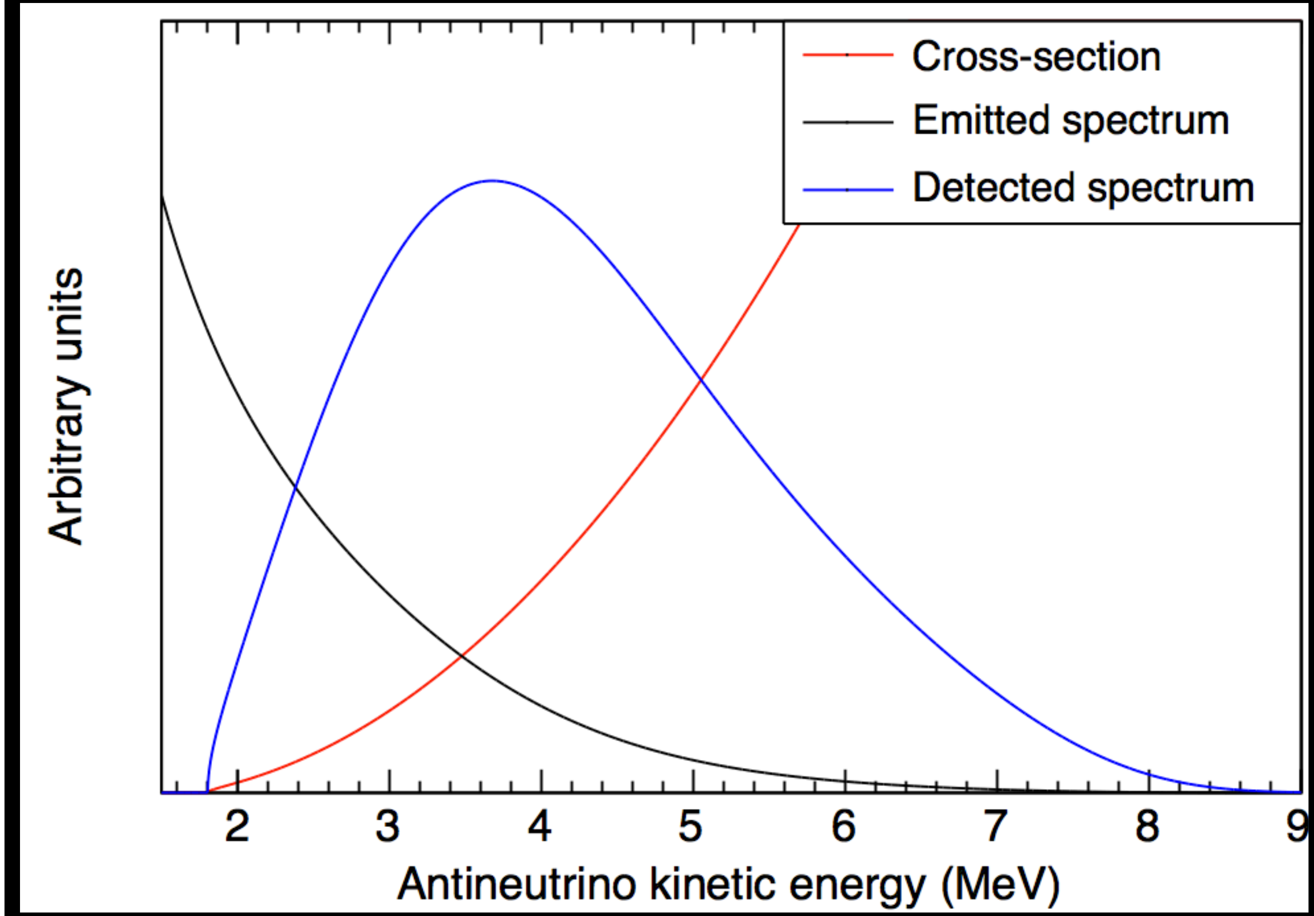
IBD Prefactor

- $$\kappa = \frac{G_F^2 \cos^2\theta_C}{\pi}(1+\Delta^R_{\text{inner}})(1+3\lambda^2) = \frac{2\pi^2}{m_e^5 f^R \tau_n} \qquad \lambda = |\frac{g_A}{g_V}|$$
- **The “prefactor” requires experimental inputs (dominant errors):**
  - Either the neutron lifetime
  - Or the axial-to-vector coupling ratio $\lambda = |\frac{g_A}{g_V}|$
- According to Vogel & Beacom, K = 9.52 10^{-44} cm^2/MeV^2
- Based on PDG 2010: K = 9.56 10^{-44} cm^2/MeV^2
- **τ and λ are accessible through different kinds of experiments**
  - τ = 885.7 s (PDG 2010)
  - BUT: recent measurements (Serebrov, confirmed by MAMBO-II) will have the average fall to 881.4 s (Schreckenbach, private com)
  - λ=1.2694 (PDG2010) or even ~1.275 (more recent measurements)
  - All point to a forthcoming revision of K = 9.61 10^{-44} cm^2/MeV^2

Cross Section Per Fission

$$\sigma_f^{\text{pred}} = \int_0^{+\infty} S_{\text{tot}}(E_\nu)\sigma_{\text{V-A}}(E_\nu)dE_\nu = \sum_k f_k \sigma_{f,k}^{\text{pred}}$$

Ex: ^{235}U→ 6.6(1)10^{-43} cm^2



Detected Spectrum

- Threshold : 1.8 MeV (neutrino energy)
- Mean Energy : 3.6 MeV
- Disappearance experiment
- No matter effect to be considered for < 1000 km baseline experiments

Cross Section Measurement

- **Inverse Beta Decay:** $\bar{\nu}_e + p \to e^+ + n$
- **Anti-ν_e interaction rate**

$$n_\nu = \frac{1}{4\pi R^2} \frac{P_{\text{th}}}{\langle E_f \rangle} N_p \varepsilon \sigma_f$$

- **Experimental cross section per fission:** σ_f

$$\sigma_f^{\text{meas.}} = \frac{4\pi R^2 n_\nu^{\text{meas.}}}{N_p \varepsilon} \frac{\langle E_f \rangle}{P_{\text{th}}}$$

- **Predicted cross section per fission:** σ_{pred}

$$\sigma_f^{\text{pred.}} = \int_0^\infty \phi_f^{\text{pred.}}(E_\nu)\sigma_{\text{V-A}}(E_\nu)\mathrm{d}E_\nu$$

Expected Event Rate

- **Inverse Beta Decay – No oscillation**

- **Anti-ν_e interaction rate:**

$$n_\nu = \frac{1}{4\pi R^2} \frac{P_{\rm th}}{\langle E_f \rangle} N_p \varepsilon \sigma_f$$

  - P = 2 x 4.3 GW_{th}
  - R = 1000 meters
  - E_f = 204 MeV
  - N_p= 10 m^3 x 6.6 10^{28} H/m^3 = 6.6 10^{29} H
  - σ_f = 6 10^{-43} cm^2 $fission^{-1}$
  - ε = 0.8
  - 1 day = 86400 s

  → **2*4.3*1e9 / (204*1e6*1.6e-19)*6.6e29*6e-43/4/pi/(1e5)^2*86400*0.8**

  → **57 interactions detected per day**

- **Anti-ν_e flux (above 1.8 MeV):**
  - Fission number x 1.5 neutrinos/sec
  - 4 10^{20} neutrinos/sec emitted by the plant & 3 10^9 neutrinos/cm^2/sec at 1 km
  - @1 km, for a detector section of 6,25 m^2 (target) : 1.7 10^{19} neutrinos crossing the target of the detector each day

The Neutrino Discovery

Discovering Neutrinos from Nuclear Explosion

- **Inverse Beta-decay Cross Section**
  - $\sigma_{IBD} < 10^{-37}$ cm^2 (H.R. Crane, 1948)
  - Theoretical prediction: $\sigma IBD = 10^{-44}$ cm^2
  - Experiment sensitivity: $\sigma_{IBD} > 10^{-40}$ cm^2

  → experiment approved!

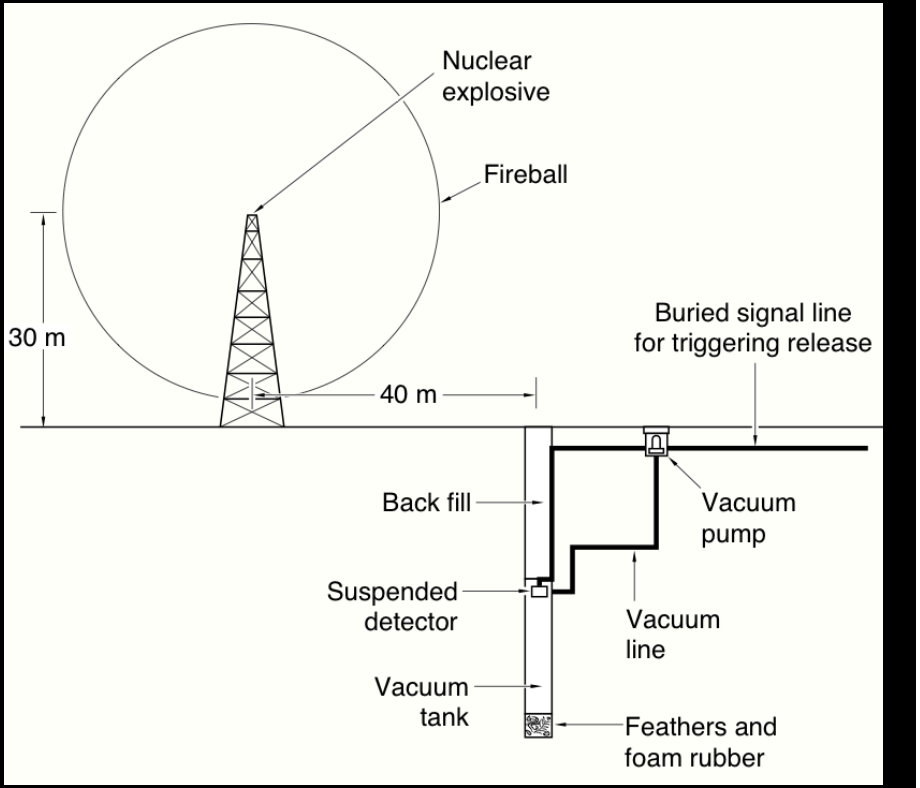
- Pyramidal **ton scale toluene/teraphenyl liquid scintillator** coupled to 4 PMTs: ‘a giant liquid scintillation device’ called ‘El Monstro’

- 2 second free-fall in a vacuum shaft detector in coincidence with the nuclear blast → several interactions at 50 meters from the tower-based explosion of a 20-kiloton bomb

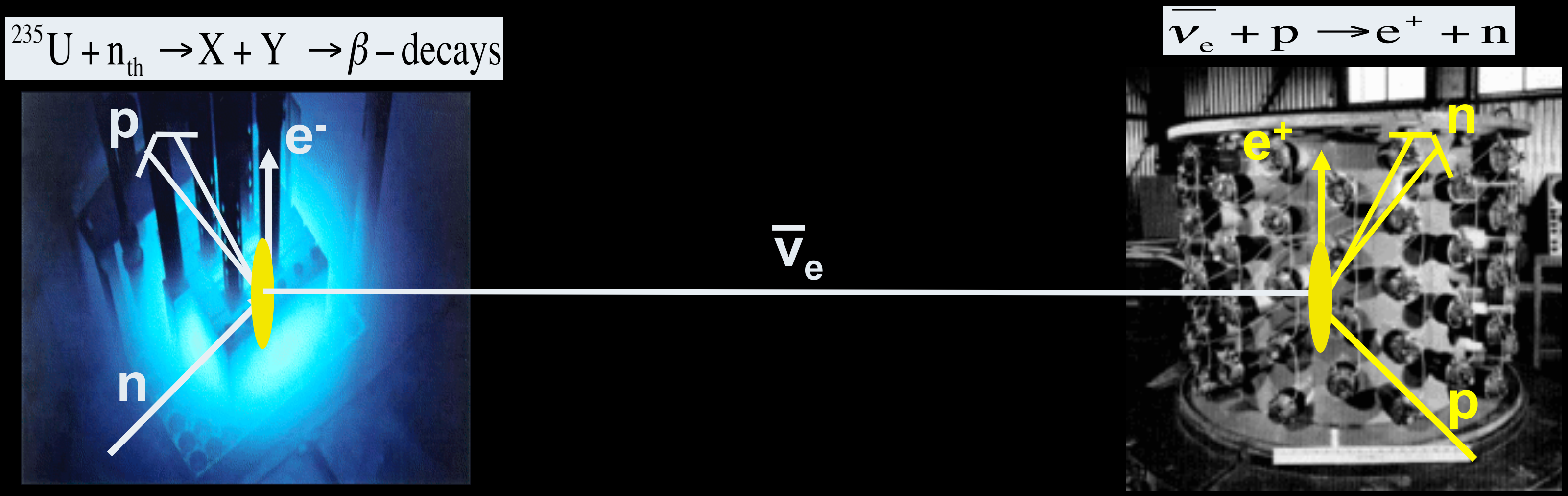
- But J. M. B. Keylogg pushed for an experiment close to a fission reactor & Reines & Cowan considered (e+,n) coincidence detection → **project canceled**

Approved experiment (early 1950’s)

Reines & Cowan’s Group



Towards Neutrino Discovery



$^{235}\mathrm{U} + \mathrm{n}_{\mathrm{th}} \rightarrow \mathrm{X} + \mathrm{Y} \rightarrow \beta - \mathrm{decays}$

$\overline{\nu_e} + \mathrm{p} \longrightarrow \mathrm{e}^+ + \mathrm{n}$

Production

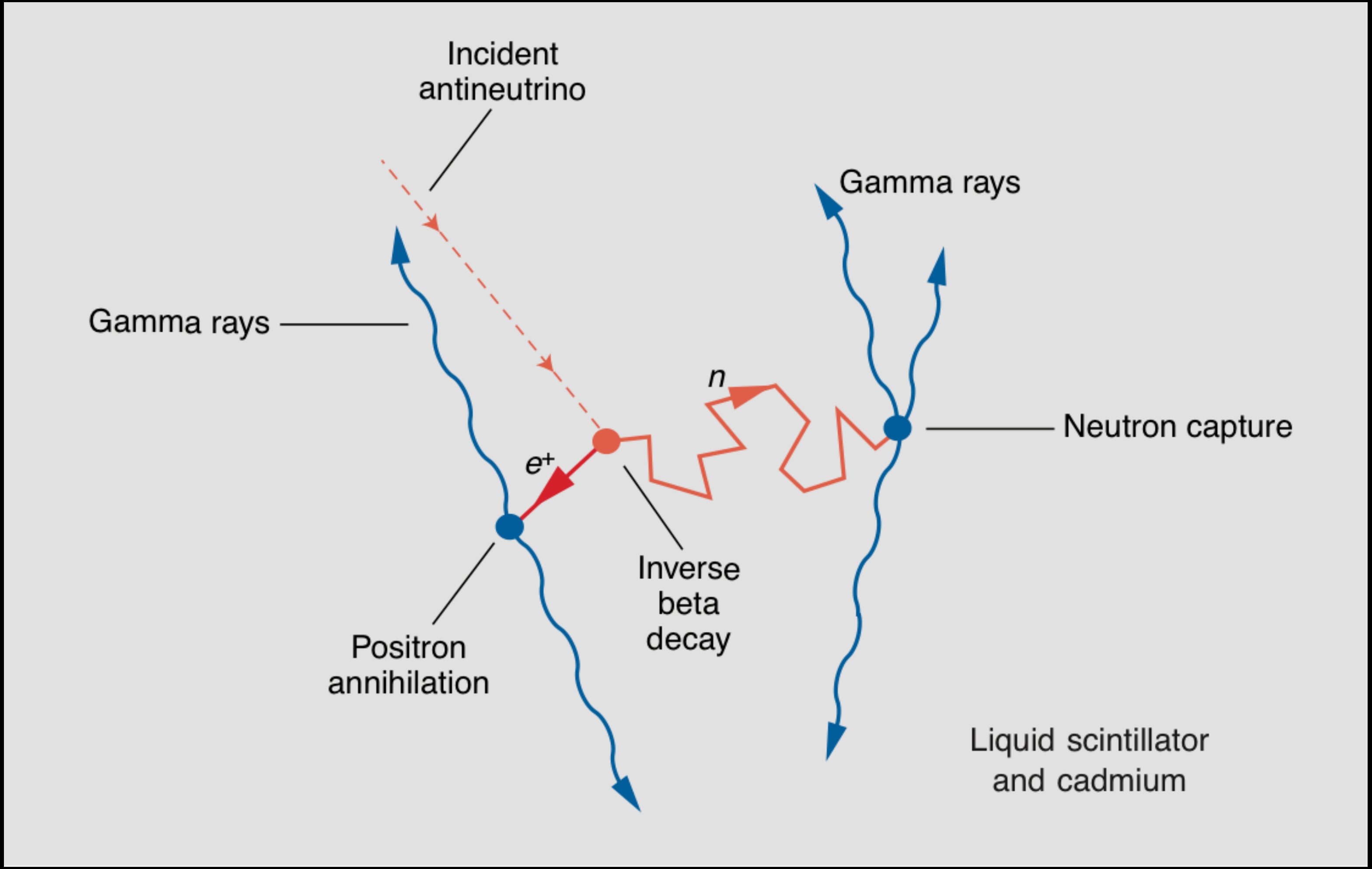
Detection

$t_{\mathrm{creation}} \longrightarrow t_{\mathrm{detection}}$

Time (Neutrino Proper Time)

The Poltergest Project

Electron antineutrino detection



Positron Detection

- **Positron:**
  - m_n = 0.511 MeV, +1 electric charge

- **Energy Loss**
  - Collision/Scattering with nuclei
    - Bethe-Bloch dE/dx formula
    - Multiple-scattering complicates the analytical computation → MC
  - Bremsstrahlung
    - Emission of atomic radiation as e^+ scatter in the electric field of the nucleus
    - A few % of the total loss for MeV e^+
  - **Total dE/dx = $(dE/dx)_{coll} + (dE/dx)_{rad}$**
  - Mean free path is on the mm to cm scale

- **Annihilation**
  - Positron looses its kinetic energy and start ‘diffusing’
  - Annihilation with electron : $e^+ + e^- \rightarrow \gamma + \gamma$
    - Prompt signal simultaneously with dE/dx
    - Gamma energy : E_g=1.022 MeV
    - Back-to-back gammas (momentum conservation)
    - Attenuation length in oil is about 10 cm at 511 keV

Neutron Physics Basics

- **Neutron:**
  - m_n = 938.27 MeV
  - no electric charge, main interaction through strong interaction
  - Must path close to nucleus to interact (10^{-11} cm) → penetrating particle

- **Interactions**
  - Elastic scattering (main): A + n → A + n’
  - Inelastic scattering: $A + n \rightarrow A^* + n$; A + n → B + n’ + n”
  - Radiative neutron capture: $n + (Z,A) \rightarrow (Z,A+1) + \gamma$
    - cross section ∞ 1/v ; resonances
  - Others: (n,p), (n,d), (n,α), …

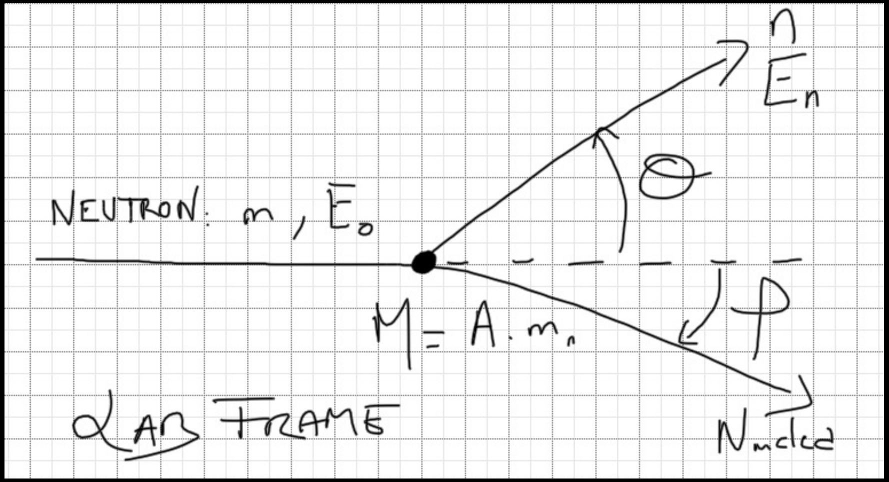
- **Energy & terminology**
  - Fast n: E > 100 keV - ten’s of MeV
  - Slow n: E = 0.025 eV - 1 eV

Epithermal n: E = 1 eV - 100 keV
Thermal n: E = 0.025 eV

- **Mean free path length**
  - $1/\lambda\ (\mathrm{cm}^{-1}) = n\ (\mathrm{cm}^{-3})\ .\ \sigma\ (\mathrm{cm}^2)$
  - collimated n beam : $N=N_0 \exp(-x/\lambda)$

Neutron Physics Basics

- **Moderation:**
  - Fast neutrons scatter loosing their energy until thermal equilibrium
  - Then neutrons diffuse until they are captured
- **Elastic scattering**



- **Energy of the scattered neutron**
  - $\mathbf{(A-1)^2/(A+1)^2 E_0 < E_n < E}$ (with A the atomic mass of the target nuclei)
- **Implication for neutron shielding**
  - The lighter the target nucleus, the more recoil energy is absorbed by the neutron
  - Low-Z material are being used to slow down neutrons
    - Water, Paraffin (CH_2), Oil

Neutron Moderation

- **How many collisions before thermalization?**
  - Depends on the target material atomic number

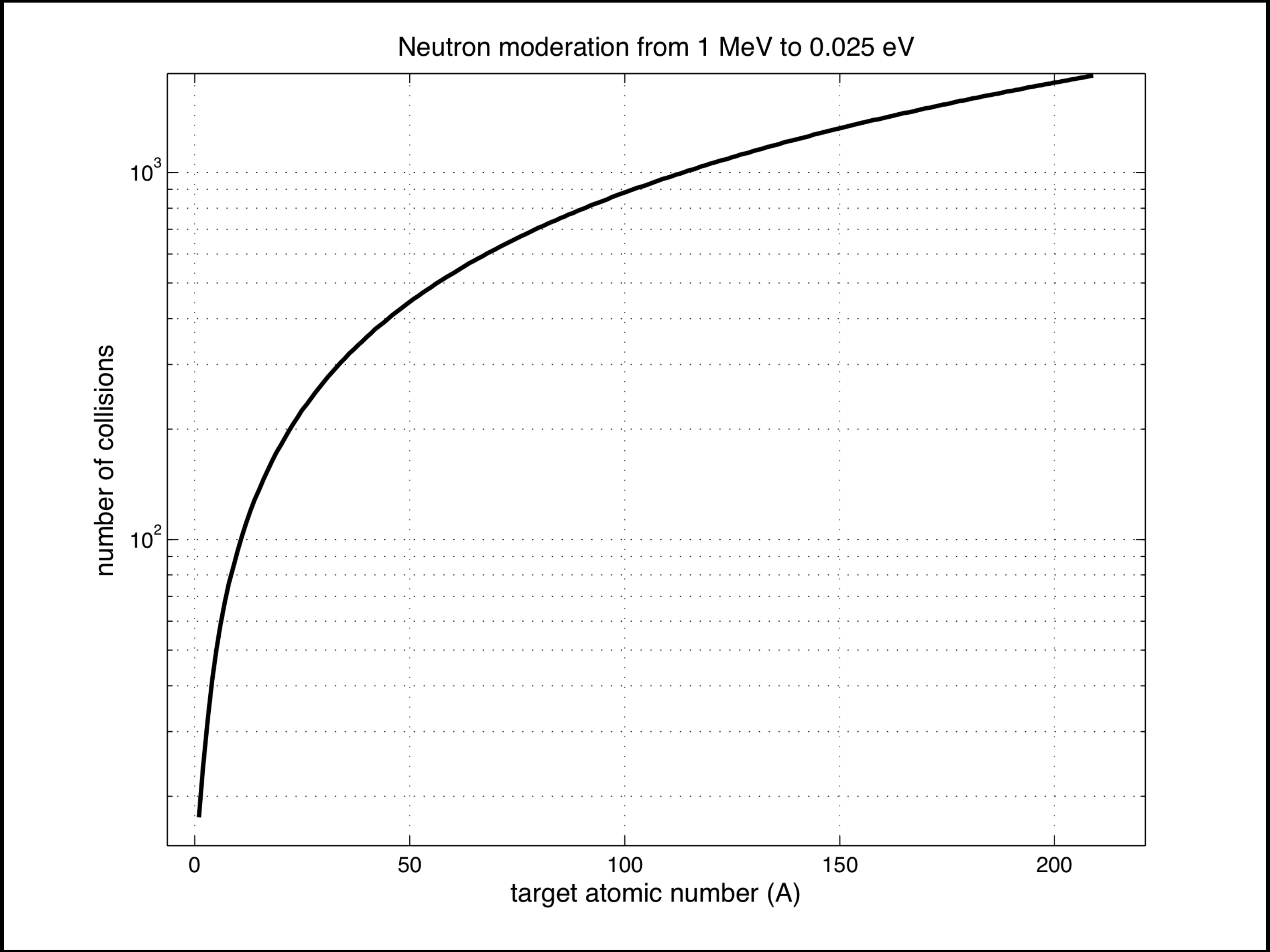
- **Lethargy change**
  - Neutron initial energy : Ei
  - Neutron final energy : Ef
  - lethargy u = ln (Ei/Ef)
  - $Ef/Ei = (A^2+1+2A\cos\theta)/(A+1)^2$ (center of mass)

  - Average lethargy change by collision :
    - $\xi = 1 + (A-1)^2/2A \ln (A-1)(1+1) = cte(A)$
    - independent of the initial energy

- **Number of collisions before thermalization**
  - $N_c = \ln (Ei/Ef) / \xi$

- **Application**
  - A=1 (hydrogen): 18 collisions
  - A=12 (carbon): 111 collisions
  - A=207 (lead) : 1818 collisions

Neutron Moderation

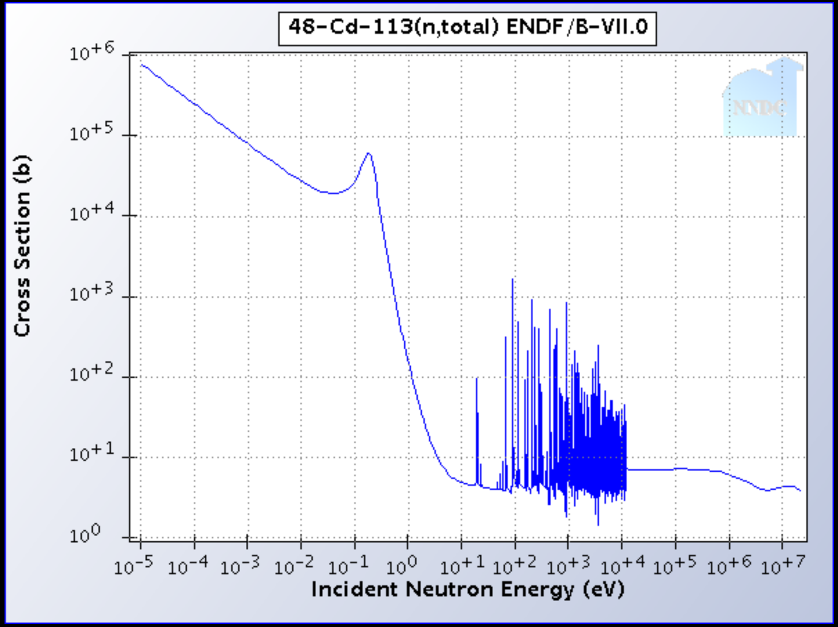


Detecting the neutron capture

- **Few tens of keV neutrons emitted in inverse beta decay**

- **Oil (or toluene) acts as a moderator**
    - neutron collides with hydrogen nuclei
    - ½ of its energy lost at each collision
    - Takes about 20 collisions to thermalize

- **Cadmium enhancing neutron capture**
    - 12.2% of ^{113}Cd
    - ^{113}Cd+n→^{114}Cd→^{114}Cd+γ's
    - ^{113}Cd, high neutron capture cross section of >10^4 barns for E<0.5 eV
    - Emission 9.21 MeV gamma's on average, well above any natural radioactive gamma ray emission



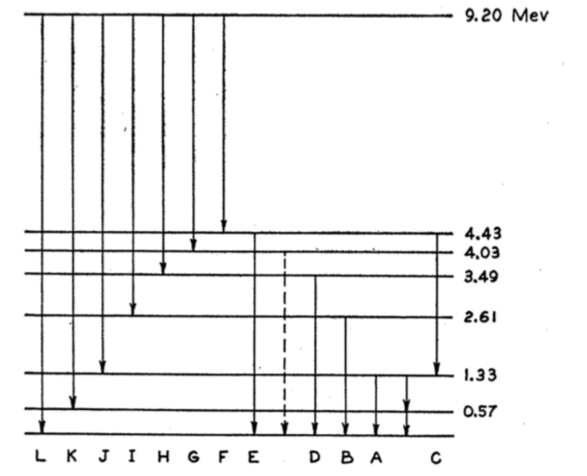


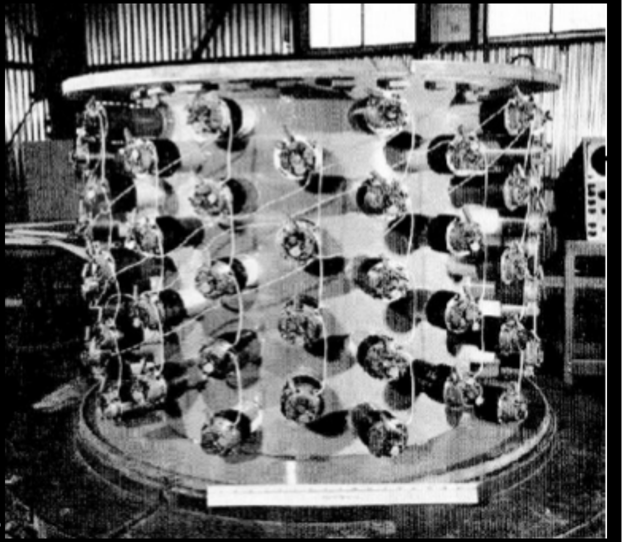
FIG. 2. Level scheme for Cd^{114} proposed on the basis of the Fig. 1 results.

The Hanford Experiment (1953)

- **‘Herr Auge’ Detector**
  - 283 liter of toluene based liquid scintillator (largest detector at that time)
  - 90 PMTs (two inches)

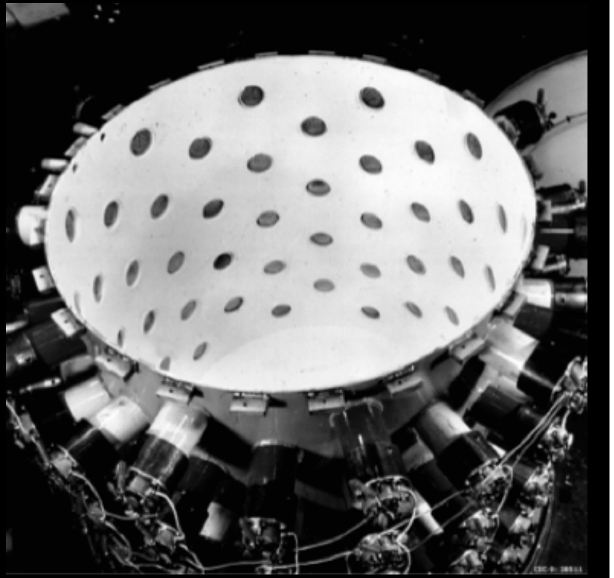
- Deployed at to the Hanford plutonium producing reactor

- **Electronics & DAQ**
  - Two gates accepting prompt-like & delayed-like signals
  - < 9 μs coincidence gate



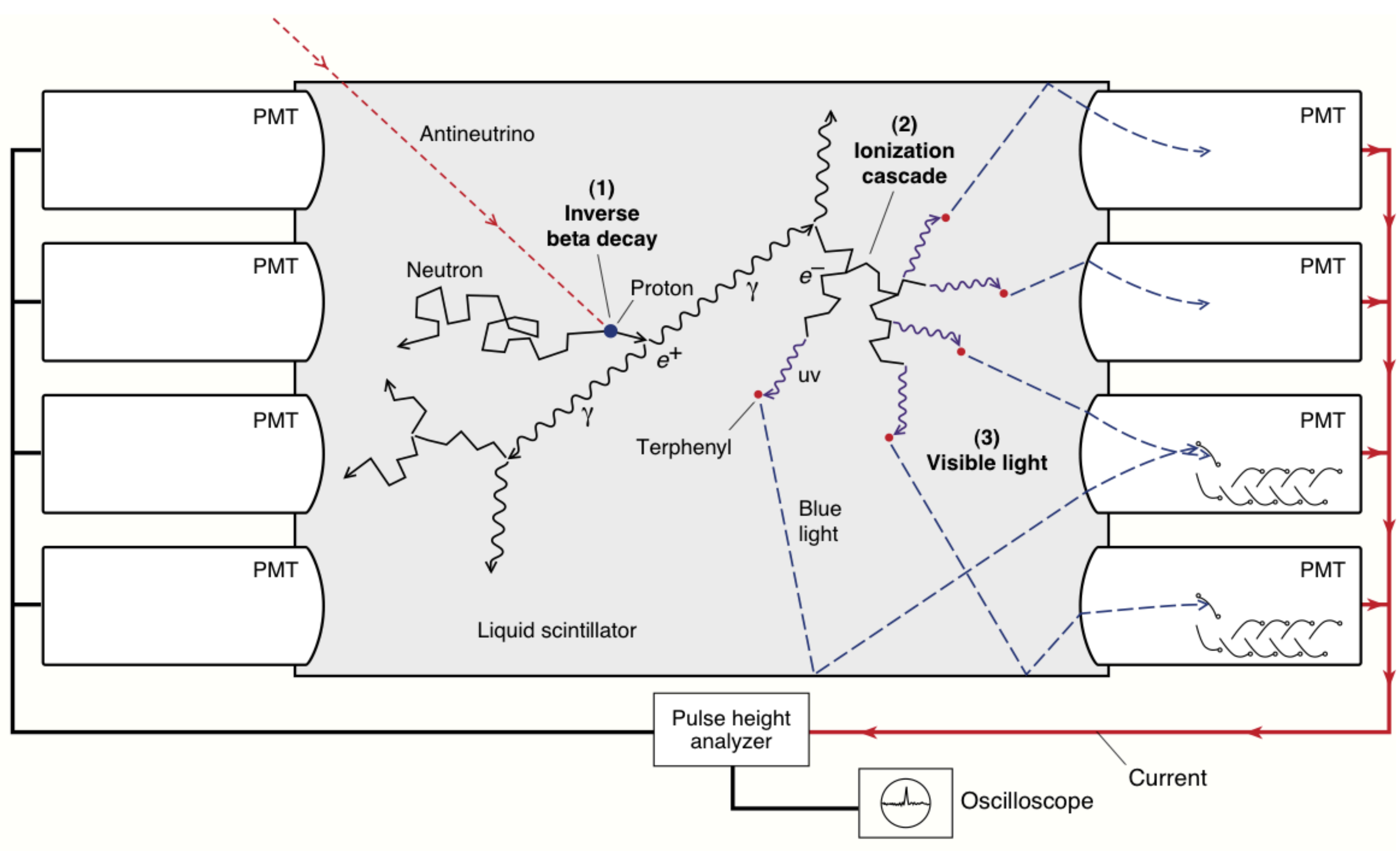
- **Backgrounds not know at that time**
  - **Surface detector**
  - 1.2-1.8 m boron-paraffin shielding (neutrons)
  - 10-20 cm lead (gammas)

- No neutrino detection, but background…
  - Expected rate: 0.1-0.3 counts per minute
  - Measured rate: 5 counts per minute…



The Hanford experiment concept

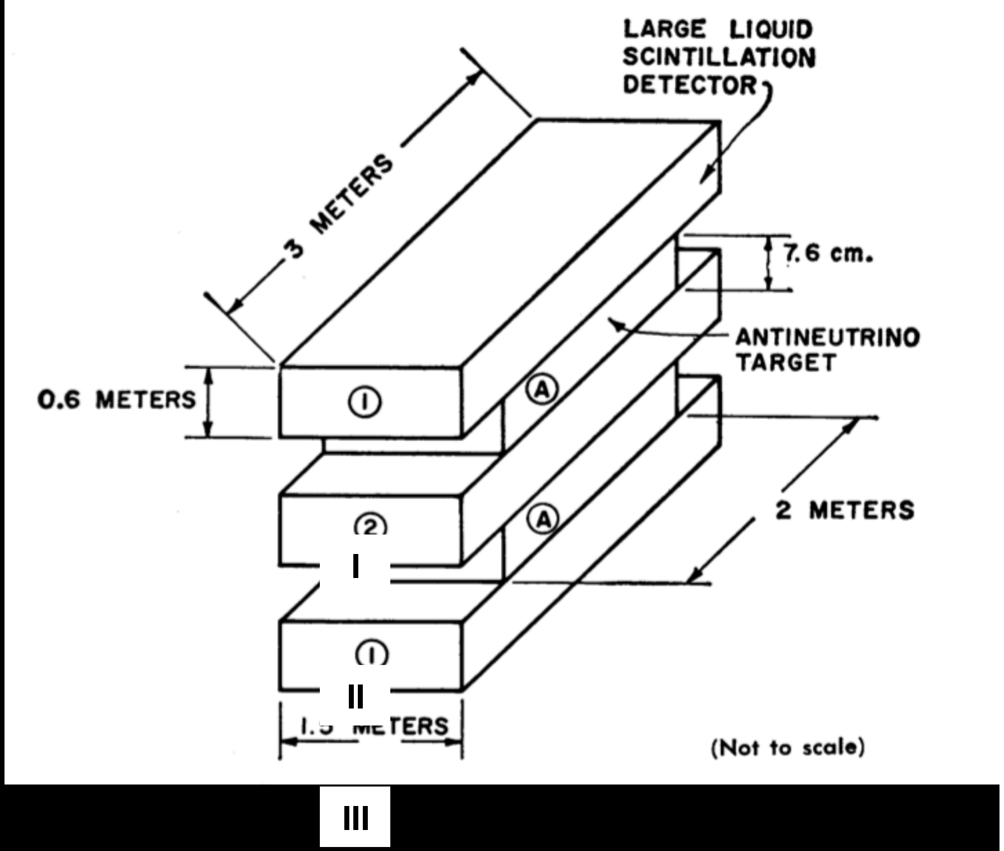
- Target protons transparent medium : toluene liquid scintillator
- Terphenyl+PPO as the wavelenght shifter
- Cadmium phopionate mixed with methanol as neutron eater



The Savannah River Experiment

- **Identification of the cosmic rays as major source of background**

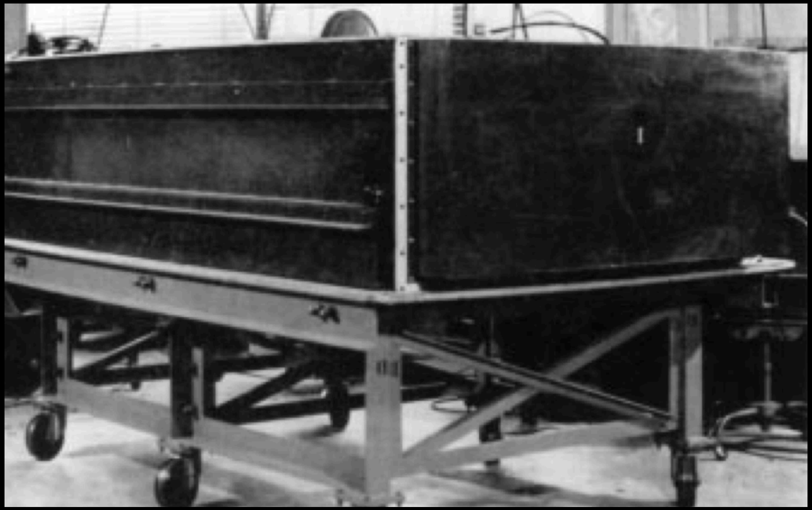
- **New detector (ready by 1955)**
  - Two large 200 l plastic tanks filled with water acting as target H medium (A & B)
  - Cadmium salt dissolved in water
  - I, II, III large 1,400 l purified triethylbenzene solution of terphenyland POPOP liquid scintillator
  - each tank is viewed by 110 PMTs
  - Scintillator tank coated with epoxy inside to preserve the scintillator purity
  - 10 tons detector (without the shieldings)
  - Whole detector wrapped with fiberglass insulating material for temperature control



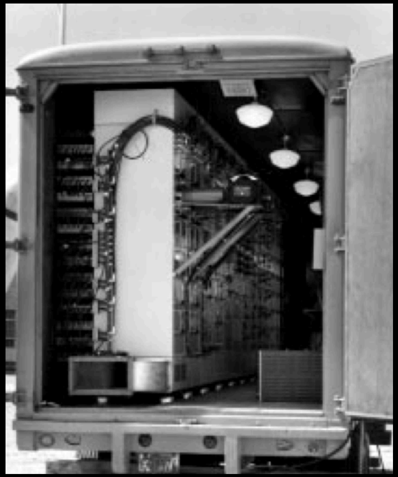
- **New site:** Savahnnah River Plant (SC, US)
  - Basement of the reactor building - ON-OFF cycles for background measurements
  - 11 meters of concrete from the core - 12 meter overburden to shield from cosmic rays

The Savannah River Experiment

liquid scintillator tank (I, II, III)

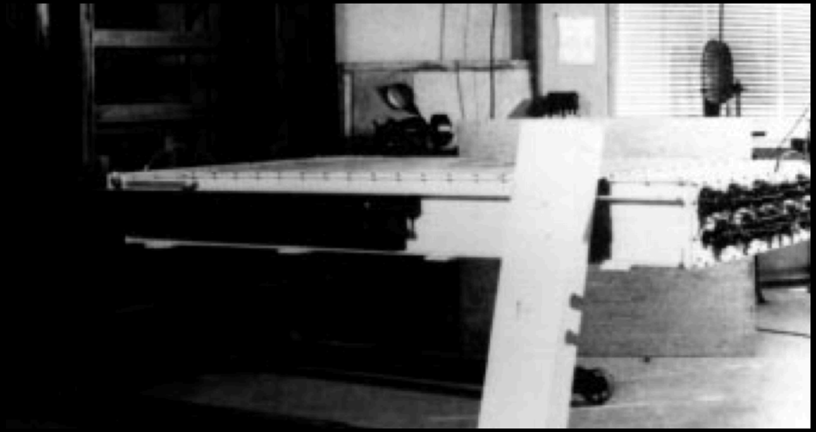


electronics truck

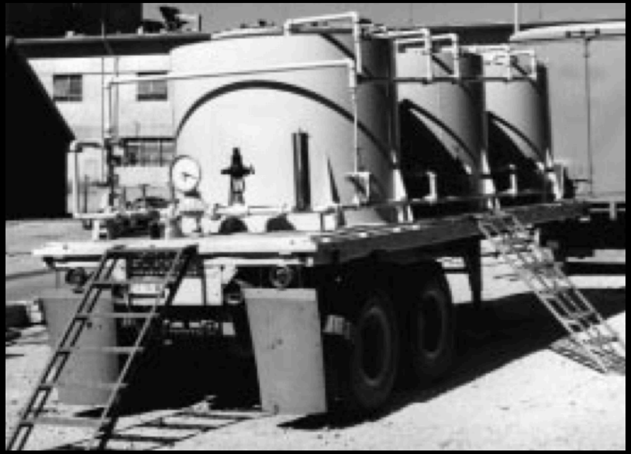


water soaked sawdust (d=0.5)

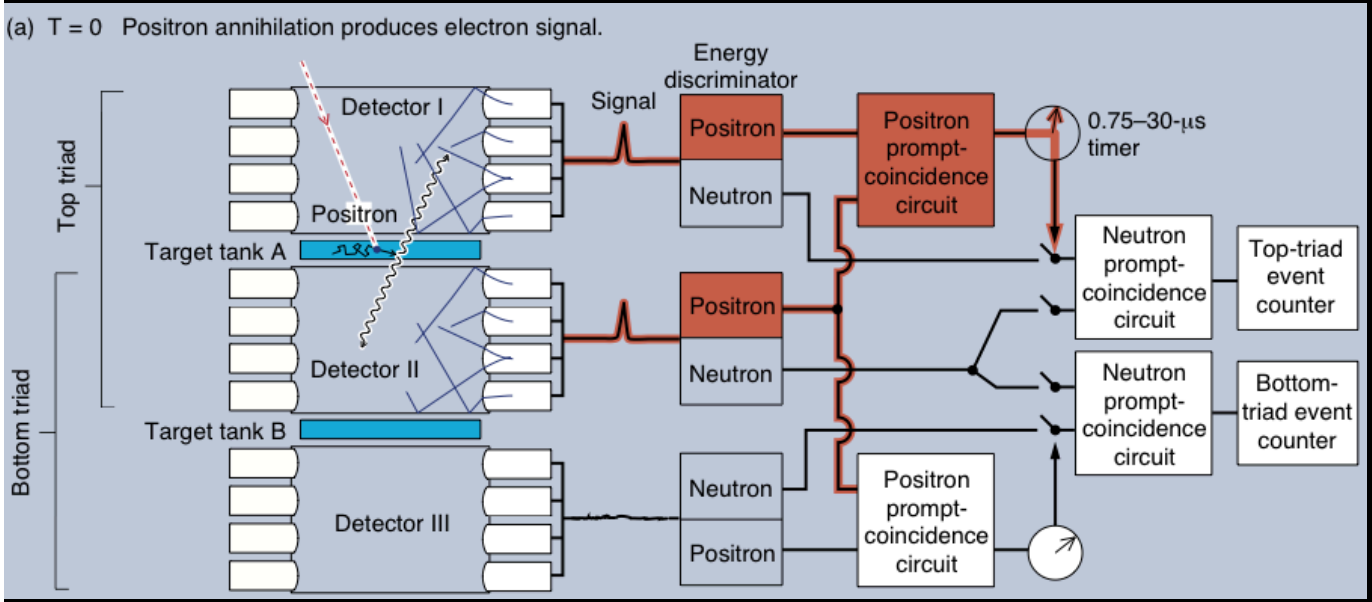
cadmium doped water tank (A, B)

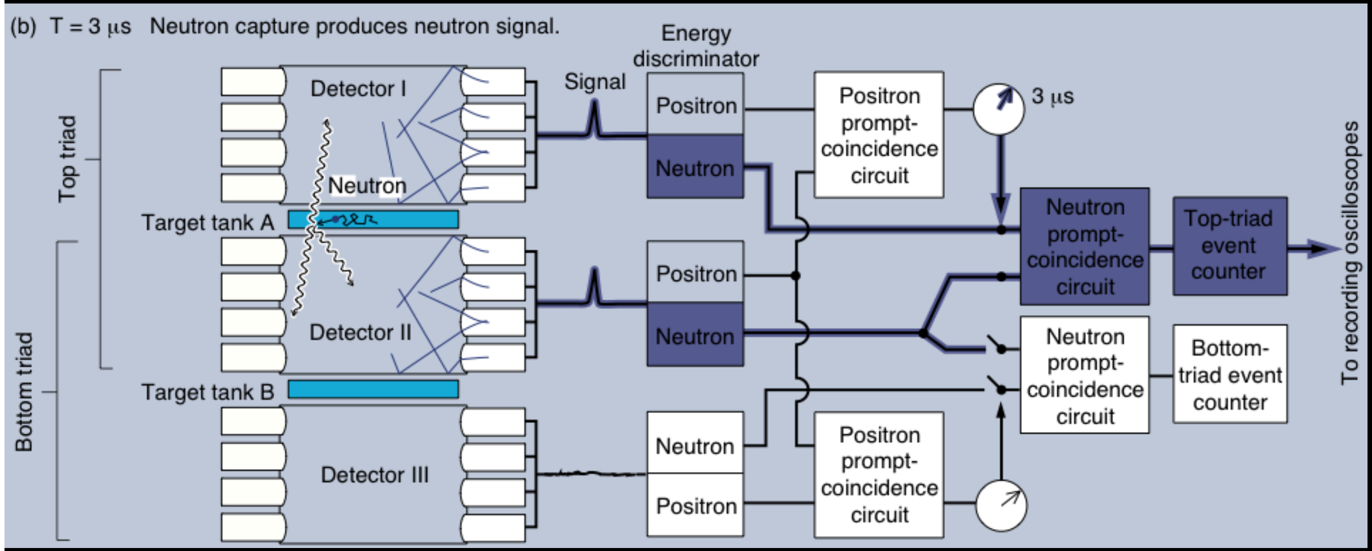


fluid handling system (4,500 l steel tanks)



Delayed Coincidence Signal Tagging


(a) T = 0 Positron annihilation produces electron signal.


(b) T = 3 μs Neutron capture produces neutron signal.

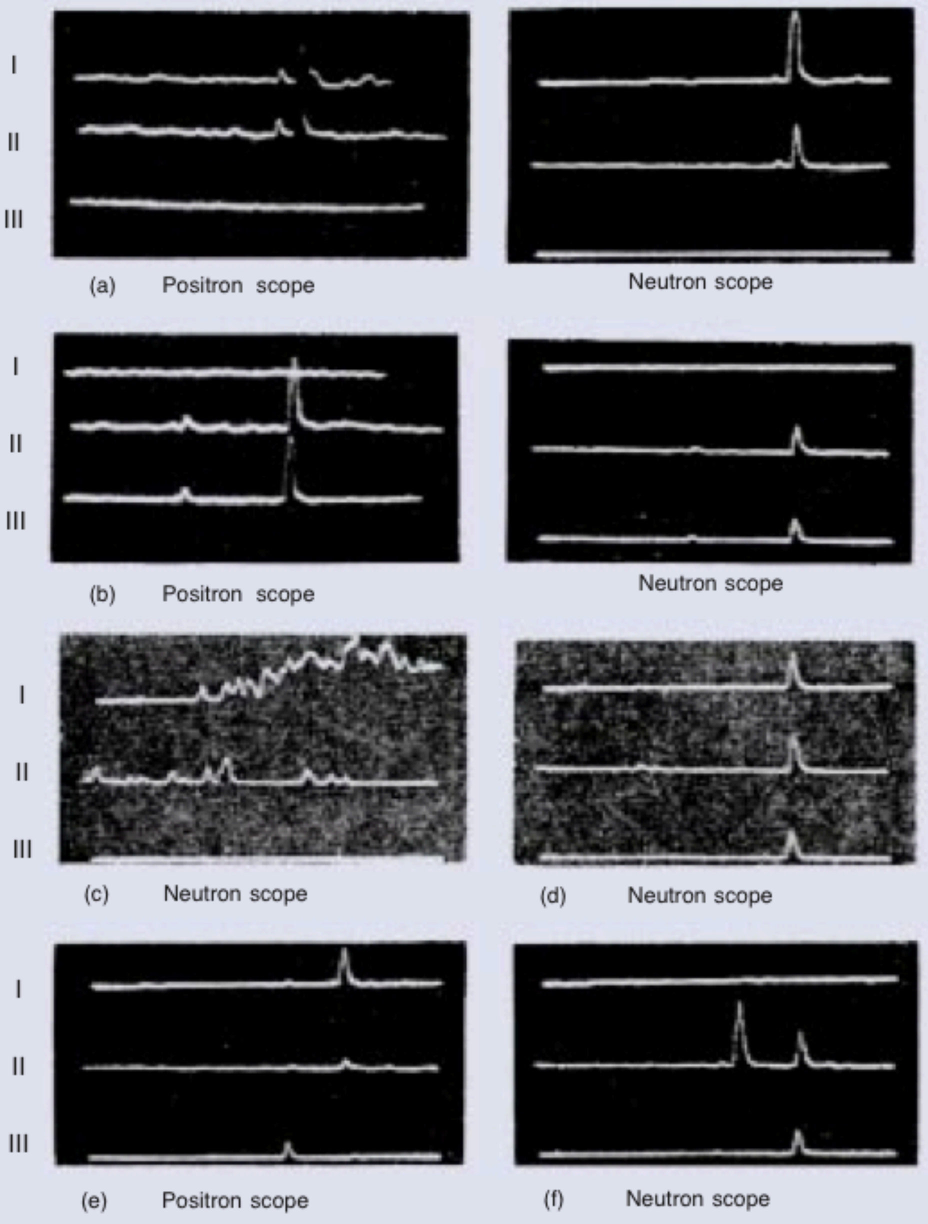
- **Positron-like**

- Two energy depositions in I,II or II,III
- No energy deposition in the farthest tank
- 0.2 < E < 0.6 MeV, each
- Within 200 ns
- Start neutron-prompt coincidence timer

- **Neutron-like**

-Two energy depositions in I,II or II,III
- No energy deposition in the farthest tank
- E > 0.2 MeV each
- 3< E_{tot} < 11 MeV
- within 200 ns
- less than 30 microsecond after the prompt signal trigger

True Signals (from Reines, Cowan, Harisson, et al. 1960)



- **a) neutrino-like signal**

- e^+ scope (I,II): E_I=0.3 MeV, E_{II}=0.35 MeV, $\Delta t<0.2$ μs
- n scope (I,II): E_I=5.8 MeV, E_{II}=3.3 MeV, $\Delta t<0.2$ μs
- 2.5 μs coincidence time

- **b) neutrino-like signal**

- e^+ scope (II,III): E_{II}=0.3 MeV, E_{III}=0.35 MeV, $\Delta t<0.2$ μs
- n scope (II,III): E_I=2.0 MeV, E_{II}=1.7 MeV, $\Delta t<0.2$ μs
- 13.5 μs coincidence time

- **c) electrical noise signal (PSD)**

- e^+ scope (I,II): strange non physical pulse shape
- n scope (I,II,II): cosmic ray induced event

- **d) background signal**

- e^+ scope (I,II,III): cosmic ray event
- n scope (I,II): ? but rejected since extra-pulse in II

Announcement of the discovery

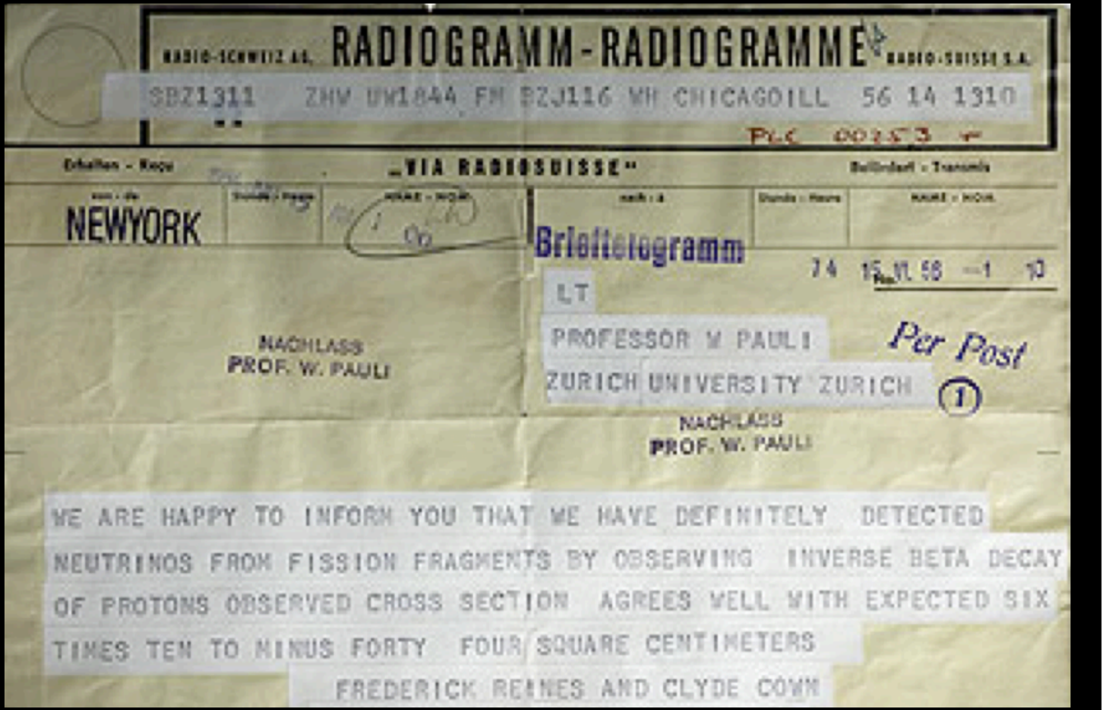
- **Signal**

- Reactor-power dependent
- 1371 hours running time
- 2.88+/-0.22 events per hours

- **Backgrounds**

- Signal to background ratio : 3 /1
- Reactor background : 1/20 of the signal
- check with reactor on-off periods

telegram send to Pauli on June 14th 1956



RADIO-SCHWEIZ AG. RADIOGRAMM - RADIOGRAMME RADIO-SUISSE S.A.

SBZ1311 ZHV UW1844 FM BZJ116 WH CHICAGOILL 56 14 1310

PLC 00253

„VIA RADIOSUISSE"

NEWYORK

Brieftelegramm

74 15.VI.56 -1 10

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

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NACHLASS
PROF. W. PAULI

NACHLASS
PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

- **Consistency checks**

- ½ dilution with D_2O to reduce the target proton density
- proton signal calibrated using ^{64}Cu 0.3 MeV source dissolved in water
- neutron detection efficiency measured with a plutonium-beryllium source
- Doubling of the cadmium concentration
- Increase of the 'neutron' shield

IDB Cross Section

- **Measured neutrino rates depends on:**
    - Neutrino flux (10^{13}/cm^2/sec at the Savannah River experiment site)
    - Target Proton number (10^{28} for the Savannah River detector)
    - IDB cross section (parity non-conservation no yet discovered by June 1956)
    - Cross section per fission (>25% uncertainty on reactor neutrino spectrum in 1956)
    - Detector efficiency

- **Savannah River Cross Section per fission, 1956**
    - Predicted: 6.3+/-1.6 10^{-44} cm^2
    - Reines et al. article in Science (20 July 1956, Volume 124, Number 3212) reported a cross section in agreement with the predicted value, within 5%

- **Parity non-conservation was found soon after neutrino discovery**
    - Two component neutrino (instread of four). Prediction increased by a factor of 2

- **Savannah River Cross Section per fission revisited, 1960**
    - Reines et al. in Physical Review 117 (159) 1960 reported 12^{+7}_{-4} 10^{-44} cm^2

- **In 1995 Reines was awarded by the Nobel price for the neutrino discovery**