Detection of Neutrons: Part II

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Recoil Detectors: Proton Telescopes
Recoil Telescopes as Reference Instruments

- Scintillation detector used as primary reference instrument?
  - Properties of the scintillators show variations: **Light output, H/C ratio**
  - Full angular distribution for **n-p scattering required**
  - Interference from \(^{12}\text{C(n,x)}\) interactions
  - Detection efficiency difficult to calculate ‘accurately’ (1-2% uncertainty)
  \(\Rightarrow\) **Calibration required!**

- **Way-out: Recoil Proton Telescopes (RPTs)**
  - Only **n-p scattering contributes**
  - Restricted range of scattering angels
    \[ E_p = E_n \cos^2 \Theta_p \]
  - ‘Localized’ response function
  - Efficiency determined by geometry, radiator mass and diff. cross section
  - Detection efficiency small: \( \varepsilon = 10^{-4} - 10^{-5} \)
  - Energy range depends of radiator thickness
Los Alamos in-beam design:
- Two CO$_2$ prop. counters: $\Delta E$
- Surface barrier detector: $E$
- Radiator – source distance: 20-35 cm
- 1 mm Ta aperture: $\phi(20.98 \pm 0.01)$ mm
- Energy range:
  - 1.2 MeV – 15 MeV using three radiators
  - up to 20 MeV with degrader foils
- Single rates: < $10^4$ s$^{-1}$
- Coincidence rate: 0.5 – 2 s$^{-1}$
  $P1 \times P2 \times SB$
- Coincidence resolution: 2 $\mu$s
- Multi-parameter DAQ
T1: Recoil Proton Spectra

- \( \text{D(d,n)}^3\text{He}, \text{D}_2 \text{ gas target, } E_{d,0} = 7.11 \text{ MeV, } \langle E_n \rangle = 10.02 \text{ MeV} \)
T1: Analysis

• Calculation of the efficiency:
  – (Semi)analytical integration
  – Monte Carlo simulation
  – Relativistic kinematics for CM → LAB
  – Anisotropic source: D(d,n)

\[
\left( \frac{d\sigma_{np}}{d\Omega_p} \right) = A(\Theta_p, E_n) \cdot \frac{\sigma_{np}(E_n)}{\pi}
\]

\[\varepsilon_{geo} = \int \int A \left( \frac{\cos \Theta_1}{d_1^2} \right) \left( \frac{\cos \Theta_2}{d_2^2} \right) dA_1 dA_2\]

\[\Rightarrow N_p = \varepsilon_{geo} n_H \sigma_{np} Y\]

• Main contributions to uncertainty
  – Counting statistics: \( u_N/N = 1\% - 2\% \)
  – Efficiency: \( u_\varepsilon/\varepsilon = 1\% \)
  – Diff. n-p cross section: \( u_A/A = 0.2\% - 1\% \)
RPT Design Exercise: 75 MeV

Test of a proton recoil telescopes for TLABS neutron beam facility:

- **Neutron Source:** \(^{\text{nat}}\text{Li} (8 \text{ mm}) + p (75 \text{ MeV})\): quasi-monoenergetic spectrum, \(<E_{n,0+1}> = 71.6 \text{ MeV} \quad (\text{FWHM} \approx 3.2 \text{ MeV})\)

- **Collimated beam** \((50 \times 50 \text{ mm})^2\)

... which one made the race?
RPT Design Exercise: Results

- Good particle discrimination with 500 µm Si-PIPS as ΔE detectors
- Less neutron induced coupling with ΔE₁-ΔE₂-E scheme
Fast Neutrons: Ionization Chambers
Fission Ionization Chambers

- Electrical field: \( E = U_0 / d \)
- Charge per unit track segment: \( q = \frac{e_0}{W} \left( \frac{dE_{ff}}{dr} \right) \)
- Voltage change induced by drift along \( dx \): \( CU_0 dU = q E dx \)
- Integration along frag. track: \( U = \frac{e_0}{C} \int_0^R \left( \frac{1}{W} \frac{dE}{dr} \right) \cdot (1 - \frac{r}{d} \cos \Theta) dr \)

Drift velocities: \( v = \mu E/p, \ v_{el} \gg v_{ion} \)
\( \Rightarrow \) Ion-induced signal suppressed by time constant of the pre-amp.

Electron-induced signal depends on the location of the ionizing event.
Simulated Pulse-Height Spectra

Monte Carlo calculations:

- \((A, Z)\) of the fissioning system: multiple-chance fission!
- Range data for \(U_3O_8\) and \(Ar/CH_4\)
- Model for the surface roughness: \(<r_a>\)
- FF distributions: \(Y(E_n, A_{ff}, Z_{ff})\)
- FF anisotropy: \(W(\Theta^{CM}) = (1 + B \cdot \cos \Theta^{cm})/2\pi\)
- Incomplete momentum transfer
Analytical Calculation of the Detection Efficiency

Absorption of fragments in the fissile layer:

\[ \varepsilon_f = 1 - \frac{t}{2R_{ff}} + \ldots \approx 0.94 - 0.99 \]

Higher order contributions:
- Anisotropic fragment emission
- Momentum transfer

- Uncertainty: \( u_e/\varepsilon_f \approx 1\% - 2\% \)
  depends very much on sample quality

Fission Fragment Detection Efficiency

- Background at small pulse heights
  - $\alpha$ decay of fissile nuclei
  - recoil nuclei from backing materials
- Extrapolation of fission events into this region
  - thickness and ‘roughness’ of deposits
  - biasing scheme
Pu Fission Chambers for Cross Section Measurements

- $^{242}\text{Pu}$ layers produced by molecular plating (U. Mainz)
  - $m_{\text{Pu}} = 42 \text{ mg}$, $^{242}\text{Pu}$: 99.9668%
  - eight layers: 116 $\mu$g/cm$^2$
  - $A_\alpha = 6.17 \text{ MBq}$
  - $R_{sf} = 34 \text{ s}^{-1}$

- Number of fissile atoms $N_{\text{Pu}}$:
  - Spontaneous fission rate
    $t_{1/2} = (6.77 \pm 0.07) \times 10^{10} \text{ a}$
  - Narrow-geometry alpha counting

- Fast pre-amp.’s: $\alpha$ pile-up!

- Continuous P10 flow (nanofilters)
The Measurement of Neutron Energy Distributions: TOF Methods
TOF Spectrometry: Principles

• Neutron energy determined from a velocity measurement:

\[ v = \frac{d}{t} \implies E = (\gamma - 1) \cdot mc^2, \quad \gamma = \frac{1}{\sqrt{1 - (v/c)^2}} \]

• Energy resolution:

\[
\frac{\delta E}{E} = (\gamma + 1)\gamma \frac{\delta v}{v}, \quad \frac{\delta v}{v} = \sqrt{\left(\frac{\delta t}{t}\right)^2 + \left(\frac{\delta d}{d}\right)^2}
\]

Time and distance resolution contribute in same way:
⇒ express flight time \( \delta t \) by an equivalent distance \( \delta d_{eq} \)
Measurement of TOF Distributions

- Start signal: neutron detector
- Stop signal: beam pick-up
- Inverted time scale: $\text{TOF} = t_{\text{stop}} - t_{\text{start}}$
- Measured neutron flight time: $t_{m} = \text{TOF}_{\gamma} + \frac{d}{c} - \text{TOF}_{n}$

**NB:** Measured flight time $t_{m}$ includes time spent in target and detector!
Width of TOF Peaks

• Contributions to the width of TOF peaks:
  – Beam: time spread of the beam pulse \( \delta t_{\text{beam}} \)
  – Source: beam transit time
    energy-loss broadening \( \delta E_{\text{src}} = f_{\text{kin}}(E_{\text{beam}},E_n) \cdot (dE/dx) \cdot d_{\text{src}} \)
    kinematical broadening
    slowing-down time \( \delta t_{\text{slow}} \approx A/\Sigma_s v \)
  – Sample: kinematical spread \( \delta E_{\text{spl}} = f_{\text{kin}}(E_n,\Theta) \cdot \delta \Theta \)
  – Detector: transit time
    multiple scattering spread \( \delta t_{\text{det}} = d_{\text{det}}/v \)
    \( \delta t_{\text{ms}} \)

• Total TOF spread:
  \[ \delta t^2 = \sum_i \delta t_i^2 + \sum_j \left( \frac{t_j(E_{n,j},l_j)}{2E_{n,j}} \right)^2 \delta E_{n,j}^2 \]

• Relative importance of time and energy broadening depends on the details of the setup:
  – Masses of projectiles and target nuclei: source and sample
  – Flight paths: source and sample
Time Response of Organic Scintillation Detectors

- Multiple scattering affects time response:
  - Width of the main peak: flight time through det.
  - Exponential tails for pancake-like detectors ($d \gg l$)
  - Non-Gaussian time response: $R(E,t)$
  - Modeled with Monte Carlo codes

Calc. (NRESP7)

Exp.
Example: PTB TOF Spectrometer

Parameters of the PTB's TOF spectrometer

**Projectile**
- Deuteron energy \(\approx 5–11\) MeV
- Averaged current 0.7–2.2 \(\mu\)A
- Pulse width (FWHM) 1–3 ns
- Repetition frequency \(< 1\) MHz

**Deuterium gas target**
- Length 30 mm
- Diameter 10 mm
- Gold backing 0.5 mm
- Molybdenum entrance foil 5 \(\mu\)m
- Gas pressure 0.2 Mpa
- Neutron energy \(\approx 8–14\) MeV

**Sample**
- Shape Full cylinder
- Height 50 mm
- Diameter 25 mm
- Distance from target 175 mm

**Neutron TOF spectrometer**
- 5 detectors NE-213
- Scintillator diameter
  - 10.16 cm (det. 1)
  - 25.40 cm (dets. 2–5)
- Scintillator length
  - 2.54 cm (det. 1)
  - 5.08 cm (dets. 2–5)
- Mean flight path 12.000 m

\[ E_{n,0} = 10\text{ MeV} \]
- \(\delta t_{\text{beam}} = 1.6 \text{ ns} \)
- \(\delta E_{n,\text{src}} = 106\text{ keV} \)
- \(\delta d_{\text{src}} = 17\text{ cm}, d_{\text{det}} = 12\text{ m} \)
\[ \Rightarrow \delta E_n/E_n = 1.4\% \text{ for } E_{n,\text{det}} = 2\text{ MeV} \]
\[ 1.8\% \text{ for } E_{n,\text{det}} = 10\text{ MeV} \]
Example: PTB TOF Spectrometer

**Kinematical broadening**
- Polyethylene (PE) sample
- Incident energy: $E_{n,0} = 10.21$ MeV
- Scattering angle: $\Theta = 29.3^\circ$

**Separation of TOF peaks**
- Vanadium sample
- $E_{n,0} = 10.21$ MeV
- $\Theta = 36.8^\circ$

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$12\text{C}(n,n)^{12}\text{C}$
$^{12}\text{C}(n,n')^{12}\text{C}^*$
$^1\text{H}(n,n)^{1}\text{H}$

$51\text{V}$

$Q = 0.0 +$
$Q = -0.320$ MeV
$Q = -0.929$ MeV
$Q = -1.609$ MeV
$Q = -1.812$ MeV
Self-TOF Spectrometers

- **Source of the TOF Start/Stop signal:**
  - Pulsed beam (pick-up, RF)
  - Time-correlated associated particle (TCAP)
  - Recoil particle double-scattering experiment
  \[ \Rightarrow \text{self-TOF spectrometry} \]

- **Example: TOFOR spectrometer at JET**
  - Designed for DD plasmas: \( <E_n> = 2.5 \text{ MeV} \)
  - Energy resolution: \( \Delta E / E \approx 7\% \)
  - Dynamic range: \( 10^5 \)

\[ E_{n'} = E_n \cos^2(\alpha) \Rightarrow E_n = 2m \left( \frac{R}{t} \right)^2 \]

TOF Spectrometry of Incompletely Pulsed Beams

Pulsed beams with rep. frequency $f$ and flight path $d$

⇒ Frame-overlap threshold: ‘only one pulse at a time’

\[ n_c = d \cdot f \Rightarrow E_c = (\gamma_c - 1) \cdot mc^2 \approx \frac{1}{2}mv_c^2 \]

Possible workarounds:

- Spectrometry using recoil detectors
- Bonner Sphere spectrometry

⇔ Spectral fluence $\Phi_E$ for $E > E_c$ from TOF measurement

- Combination of measurements at different flight paths $d$ and Monte Carlo calculations for very low energies
Lead Slowing-Down Spectrometer (LSDS)

- Semi-empirical relation between energy $\bar{E}$ and slowing-down time $t$:

$$\bar{E}(t) = \frac{K}{(t - t_0)^2}$$

- $K$ and $t_0$:
  - MC simulations
  - resonance analysis

- Very high neutron flux

- Energy range $0.1 - 100$ eV

- Application:
  - Reactions with rare isotopes
  - Fission of very radioactive isotopes
  - Fission of isomers

Detectors inserted in the moderator:
  - Compensated fission chambers
  - Solar cells with fissile layers
  - …
Neutron Detectors for TOF Measurements

- **$^6$LiGlas Detectors:**
  - Suitable for neutron range $E_n < 1$ MeV
  - Strong photon sensitivity, strong energy dependence around 250 keV res.
  - Complicated time response due to 250 keV resonance: $\delta t \approx 3 - 4$ ns
  - Sensitive to (epi)thermal background neutrons: $\sigma \propto 1/v$

- **Fission Chambers**
  - Secondary standard cross sections: $^{235,238}$U(n,f)
  - Low but calculable detection efficiency: reference instrument
  - Slow time response requires long flight paths: $\delta t \approx 3 - 6$ ns

- **Organic scintillation detectors:** working horses for TOF meas.
  - Fast response: $\delta t \approx 1 - 2$ ns, often limited by PMT‘s
  - High detection efficiency: $\varepsilon \approx 10 - 20\%$
  - Many sizes and shapes possible: 1 cm - 1 m
  - Diff. n-p cross section is primary standard
  - Discrimination of photon background by PSD
  - Quenching requires low pulse-height thresholds for $E_n < 1$-2 MeV
The Measurement of Neutron Energy Distributions: Unfolding Methods
Need for ‘Non-TOF’ Spectrometry

• There are situations where TOF cannot be used:
  – Accelerators based sources with high rep. rates: \( f > 0.1 - 1 \text{ MHz} \)
  – Neutron diagnostics at nuclear fusion experiments
  – Sources without well-defined flight paths:
    Transmission through shields, fusion benchmarks
  – Neutrons in the environment
  – …

• But there is a way-out:

  The spectral neutron distribution \((d\Phi/dE)\) is related to the distribution of ‘events’ \((dN/dL)\) in the detector:

  \[
  N_L = \int R(L, E) \cdot \Phi_E \, dE \rightarrow N_i \approx \sum_j R_{i,j} \Phi_j
  \]

  (Fredholm integral equation of the first kind)

  The attempt to solve this equation is called ‘spectrometry’
Spectrometric Methods

• High-resolution spectrometry
  – Spectrometry of recoil nuclei:
    organic scintillation detectors
    recoil telescopes
  – Spectrometry using reaction products:
    $^3$He counters and ionization chambers
    sandwich spectrometers
    diamond detectors
  – Capture-Gated spectrometry

$\leftrightarrow$ Make response matrix $R$ as diagonal as possible!

• Low-resolution spectrometry
  – Multi-sphere spectrometry
  – Spectrometry using threshold activation foils
Unfolding Problem

- **Unfolding problem:**
  How to get from $N_j$ (data space) to $\Phi_j$ (space of possible solutions)

- **Problem of unfolding:**
  - There is a multitude of solutions $\Phi_j$ which produce the same $N_j$
  - The response $R_{j,i}$ is not exactly known
  - The $N_j$ have uncertainties $u_i$

  \[ N_j + u_i = \sum_j R_{i,j} \Phi_j \]

**Nota bene:**

- There is no exact solution!
- What is needed is a consistent approximate solution
- Usually prior information is available and must be included
Technical Approaches to Unfolding

• Direct matrix inversion: \( N \approx R \cdot \Phi \Rightarrow \Phi \approx (R^T \cdot R)^{-1} \cdot R^T \cdot N \)

but: \( (R^T \cdot R)^{-1} \) is usually ill-conditioned if it exists at all:
\[
(R^T \cdot R)^{-1} = V \cdot \Sigma^{-1} \cdot U^T \quad \text{with } U, V \text{ orth, } \Sigma = \text{diag}(\gamma_i), \gamma_1 \geq \gamma_2 \geq ... \geq 0
\]
⇒ ‘noise’ is amplified, \( \Phi_j < 0 \) possible!

⇒ More suitable methods are required:
  – Iterative procedures: usually black-magic recipes!
  – Stochastic methods: Monte Carlo, genetic algorithms, ...
  – Regularisation: add constraints to enforce smoothness
  – Least-squares adjustment: usually linearization required
  – Bayesian parameter estimation: requires an analytical model
  – Maximum entropy principle: justifiable from information theory
    consistent treatment of prior information and uncertainties

The PTB scintillation spectrometer: Response Matrix

2” x 2”
BC501A cell

Figure 3: Response functions of the NE213 scintillation detector for 9 neutron energies selected between 2.5 MeV and 16 MeV by time-of-flight slices. The experimental spectra (black histogram) are compared with and normalized to responses calculated with the NRESP7 code (red lines).

Measurements at JET
Ohmic and NBI Heated JET Discharges (DD)

- Passive (offline) gain stabilization: $f_{\text{LED}} \approx 1 \text{ kHz}$
- Unfolding with MAXED using a flat (uninformative) prior

The Dark Side of Unfolding: Artefacts

\[ T(d,n), \ E_d = 643 \text{ keV}, \ \Theta = 0^\circ: \ 2''\times2'' \ \text{BC501A detector with } A = 7.2\%, \ B = 10.5\% \]

Artefacts result from imperfect response function:

- **Calc. response matrix**: cross sections, e.g. \(^{12}\text{C}(n,n'3\alpha )\), light yield \(L(E_n)\), resolution \(\Delta L/L\)
- **Exp. response matrix**: imperfect CFD timing (walk effect), imperfect satellite subtraction
Few-Channel Unfolding: Multi-Sphere Spectrometry

BS spectrometer NEMUS
- $^3$He detector inside moderators
- bare counter: (epi)thermal
- 12 PE spheres (3"-18"): $E_n < 20$ MeV
- 4 PE/(Pb,Cu) spheres: $E_n < 1$ GeV

- Response matrix: MCNPX
- Precise dimensions
- Measured PE densities
- Calibrated $^3$He pressures
- Regular stability checks
- Background studied in UDO underground laboratory
Analysis: Bayesian Parameter Estimation

- Response functions are very similar
- Components of neutron spectra known
  - Thermal peak: \(\approx 25\) meV
  - Slowing-down cont.: \(\approx \text{flat}\)
  - Evaporation peak: \(\approx 2-3\) MeV
  - ‘Spallation’ peak: \(\approx 100\) MeV

\[ \Rightarrow \text{Analytical model and Bayesian parameter estimation} \]

\[ \Rightarrow \text{The ‘spallation’ peak (\(\approx 100\) MeV) cannot determined only from the data!} \]
Capture-Gated Spectrometry

- Full-energy events in doped organic scintillators ‘tagged’ by capture signal $\Rightarrow$ response ‘more diagonal’

- Triggers: $^{10}\text{B}(n,\alpha)^{7}\text{Li}$ $Q = 2.79$ MeV
  $^{6}\text{Li}(n,t)^{4}\text{He}$ $Q = 4.78$ MeV (preferred!)

- PH signal only from fast recoils: $t_{\text{int}} << t_{\text{life}}$
  $\Rightarrow$ Total pulse height $L(E_{n})$ not prop. to $E_{n}$!

Example: 5" × 3 boron-loaded detector (BC454)

Radiation detectors on NASA Mars Rover:

- Charged Particle Detector (CPD)
- Capture-Gated Fast Neutron Detector (FND):
  - EJ254XL $^{10}$B-loaded scintillator
  - Calibration: LED + Diode
  - PMT readout
  - $E_n = 0.5 - 8$ MeV

Courtesy: C. Zeitlin, Southwest Research Institute, Boulder (Colorado)
Modern Spectrometry with RTPs: Proton Tracking

Recoil telescope with track reconstruction:

- $E$ detectors: $E_p$
- $\Delta E$ detector: track reconstruction, $\theta_p$

$\Rightarrow \quad E_n = E_p / \cos^2 \theta_p$

- Example: TPR-CMOS (IRSN Cadarache)

Ref.: J. Taforeau: Un spectromètre à pixels actifs pour la métrologie des champs neutroniques, Thèse, Université de Strasbourg 2013
Spectrometry using Exothermic Reactions

- $^6\text{Li}(n,t)^4\text{He}$, $Q = 4.78$ MeV,
  $^3\text{He}(n,p)^4\text{T}$, $Q = 0.76$ MeV

- High thermal cross section: $\sigma = \sigma_0 \cdot \left( \frac{v_0}{v} \right)$ for $E_n < 100$ keV

⇒ Spectrometry by detection of both reaction products:
  - (epi)thermal peak: $c_{th}$
  - fast peak: $c_f$
  - zero bias: $c_0$

\[
E_n = \frac{c_f - c_{th}}{c_{th} - c_0} Q
\]

NB: constant $W$-value assumed!

- Proportional counters
- Ionization chambers with Frisch grid
\textbf{3He and \textsuperscript{6}Li Sandwich Spectrometers}

\textbf{3He spectrometer}
- Small recoil energies
- \( n/\gamma \) interference
- High efficiency
- Small energy loss

\textbf{\textsuperscript{6}Li spectrometer:}
- High recoil energies
- Good \( \gamma \) suppression
- Resolution depends on radiator thickness
- \( E_{n,\text{min}} = 100 - 500 \) keV

\textsuperscript{3}He Prop. Counter

\textsuperscript{3}He Spectrometer

Ref.: H. Bluhm et al., NIM115 (1974) 325-337
Spectrometry using scCVD Diamond Detectors


Single-crystal chemical vapor deposition diamond detectors (scCVD):

• Neutron detection via $^{12}$C($n,\alpha$)$^9$Be: full-energy peak
• Large displacement energy (42 eV/atom) ⇒ high radiation hardness
• High thermal conductivity ⇒ operation at elevated temperature
• But: large band gap (5.5 eV) ⇒ resolution not as good as silicon (1.11 eV)

⇒ Very attractive material for neutron spectrometers
The Measurement of Spatial Neutron Distributions
The Micromegas Beam Imager for n_TOF

- Neutron detection:
  - $^6\text{Li}$, $^{10}\text{B}$ converter
  - Counting gas: p, He recoil
- Energy-resolved images: 10 eV – 20 MeV
- Several 1-dim. and 2-dim. (strips or pixels) read-out schemes
- Spatial resolution: $\approx 0.5$ mm

Ref: J. Pancin et al. NIMA 524 (2004) 102-114
Micromegas Results


- Profile of the n_TOF neutron beam:
  - Converter: LiF, $^{10}$B$_4$C
  - Readout anode: 6 cm × 6 cm with 106 x and y strips, Gassiplex readout chip

- Determination of beam coverage factors for large sample
Absolute Methods, Key Comparisons
Stability and Consistency of Neutron Measurements

- Ref. detectors depend on ref. materials
  - Purity of gases (H\textsubscript{2}, CH\textsubscript{4}, C\textsubscript{3}H\textsubscript{8}): RPPC
  - Tristearin (C\textsubscript{57}H\textsubscript{110}O\textsubscript{6}) radiators: RPT
  - 235,238\textsuperscript{U} deposits: FC

⇒ Test of stability and consistency
⇒ Comparison with ‘absolute methods’
Standards: Absolute Methods

Traceability of detector calibrations to the SI requires ‘Absolute’ methods for neutron production:

- **Manganese bath:** $^{56}\text{Mn}(n,\gamma)$ in a saturated MnSO$_4$ solution
  - only for radionuclide sources
  - 50% correction for capture and leakage
  - 0.5% uncertainty of the emission rate

- **Time-correlated associated particles** (‘tagged neutrons’):
  - $^{252}\text{Cf(s.f.)}$: standard technique, relies on $<\nu>$ ✓
  - D(d,n)$^3\text{He}$: standard technique, difficult ✓
  - T(d,n)$^4\text{He}$: standard technique ✓
  - H(n,n)p: low count rates ✓
  - D($\gamma,n$)p: requires a tagged bremsstrahlung beam
  - D(p,n)2p: very difficult

- **Uncertainty of (TC)AP method**: 1% - 1.6% for T(d,n)$^4\text{He}$, $E_n \approx 14.2$ MeV
$^{252}$Cf(s.f.) Ionization Chamber

- Low-mass parallel-plate IC with $^{252}$Cf source: $A_a = 4.5$ MBq $\Rightarrow R_{sf} = 1.4 \times 10^5$ s$^{-1}$
  time resolution: $\approx 1$ ns

- Neutron ‘tagged’ by fission fragments

- Prerequisites:
  - Evaluated $^{252}$Cf neutron spectrum and $\bar{\nu}$
  - Corrections:
    - deadtime and uncorrelated stops
    - fragment detection efficiency
    - neutron emission anisotropy
    - neutron transport, air scattering
TCAP: $T(d,n)^4He$, $D(d,n)^3He$

‘Tagging’ of neutrons by the associated charged particle

- $T(d,n)^4He$, $E_d = 150$ keV
  - $\Theta_n = 26.5^\circ$, $\Theta_\alpha = -150^\circ$
  - $E_n = 14.48$ MeV, $E_\alpha = 2.46$ MeV
  - no (d,d) background
  - $^3He(d,p)^4He$ can be a problem
  - ‘routine’ 14 MeV standard

- $D(d,n)^3He$, $E_d = 4$ MeV
  - $\Theta_n = 40^\circ$, $\Theta_{^3He} = -59.8^\circ$
  - $E_n = 6.13$ MeV, $E_{^3He} = 1.14$ MeV
  - strong (d,d) and (d,p) background requires $\Delta E-E$ separation of $^3He$

- Problem of all TCAP experiments:
  Loss of correlation due to angular straggling!
TCAP with $T(d,n)$ at $E_{d,0} = 150$ keV

- Shape of the associated neutron cone:
  - Tritium depth profile in Ti(T) target
  - Position of the beam spot

- Modeling of the transport of 150 keV d in Ti(T) is a challenge!
Metrological Cooperation: Key Comparisons

- Organized within the CCRI(III) of the BIPM
- Regular Key Comparisons (every 10 years)
- Results go into the KCDB: www.bipm.org
- the ‘usual suspects’:
  - CIAE (PR China)
  - LNE / IRSN (France)
  - IRMM (EU)
  - NPL (UK)
  - NMIJ (Japan)
  - NIST (USA)
  - PTB (Germany)
  - VNIIM (Russia)
- Typical uncertainties:
  - KCRV: 1 – 1.5 %
  - Standard deviation: 2 – 4 %
Summary:

Neutron detection means conversion to charged particles:
- Products of two-particle reactions with high $Q$ value
- Recoil particles
- Fission fragments

Measurements techniques:
- Time-of-flight spectrometry
- Unfolding of signal distributions

Normalization:
- relative to cross sections standards
- ‘absolute’ neutron counting
Tributes

Frank Brooks
1931-2012

Horst Klein
Thank you for your attention!
Additional Material
High-Energy Telescopes

Neutron energies above 20 MeV pose special challenges:

- Large proton ranges: degraders, thick stopping detectors
- Charged particles from n+\(^{12}\)C: high-resolution \(\Delta E-E\) particle discrimination
- Neutron induced coincidences: more coincidence conditions
- ‘Grey’ apertures: active collimation by veto detectors (\(E_n > 100\) MeV)

Proton recoil telescope T2: \(E_n = 20 - 60\) MeV
TOF Variants: Slowing-Down Spectrometry

Heavy ($A = 208$) non-absorbing moderator with constant isotropic scattering cross section:

- Small mean log. energy loss per collision:
- Rel. std. deviation of slowing-down time: $\sqrt{\frac{\sigma^2_{iE}}{t^2_E}} \approx \sqrt{\frac{2}{3A}} = 5.7 \times 10^{-2}$, mean energy: $\sqrt{\frac{\sigma^2_E}{E^2}} \approx \sqrt{\frac{8}{3A}} = 0.11$

$\Rightarrow$ Time dependence of the velocity $v$:

$$v(t) = \frac{2}{\xi \Sigma_s} t \quad (v \ll v_0)$$
Lead Slowing-Down Spectrometer (LSDS)

- Semi-empirical relation between energy $\bar{E}$ and slowing-down time $t$:

$$\bar{E}(t) = \frac{K}{(t - t_0)^2}$$

- $K$ and $t_0$:
  - MC simulations
  - resonance analysis

- Very high neutron flux

- Energy range 0.1 – 100 eV

- Application:
  - Reactions with rare isotopes
  - Fission of very radioactive isotopes
  - Fission of isomers

Detectors inserted in the moderator:
- Compensated fission chambers
- Solar cells with fissile layers
- …
The LANSCE Slowing-Down Spectrometer

- High-purity lead cube: $V = (1.2 \text{ m})^3$
- WNR beam (800 MeV p), tungsten target
- Resolution: $\Delta E/E \approx 0.29$

Resolution broadening

Ref.: D. Rochman et al., NIMA 550 (2005) 397-413