Neutron Detection

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Content

- The neutron
- Flux (density) and Cross Sections
- Elastic Scattering and Moderation
- Neutron Detection
- Dosimetry
- Neutron Flux Measurement
- Fast Neutron Spectroscopy
- (missing – spectroscopy of thermal, cold and ultra-cold neutrons)

The Neutron (for our purposes)

- Charge $q=0$
- Mass $m_n = 1.66749 \cdot 10^{-27}\,\mathrm{kg} = 1.008665\,\mathrm{u} = 939.57\,\frac{\mathrm{MeV}}{c^2}$
- Size $r_0 = 1.2\,\mathrm{fm} = 1.2 \cdot 10^{-15}\,\mathrm{m}$
- Energy / speed relation (non relativistic) $v = \sqrt{\frac{2E}{m}} = c \cdot \sqrt{\frac{2E/MeV}{939}}$
- thermal neutron energy $E_{th} = 25\,\mathrm{meV}\,; v_{th} = 2200\,\mathrm{m/s}$
- Neutron = indirectly ionizing radiation

  It produces charged particles via

  i) reactions e.g. ${}^{10}_{5}B + n \rightarrow {}^{7}_{3}Li + {}^{4}_{2}He$

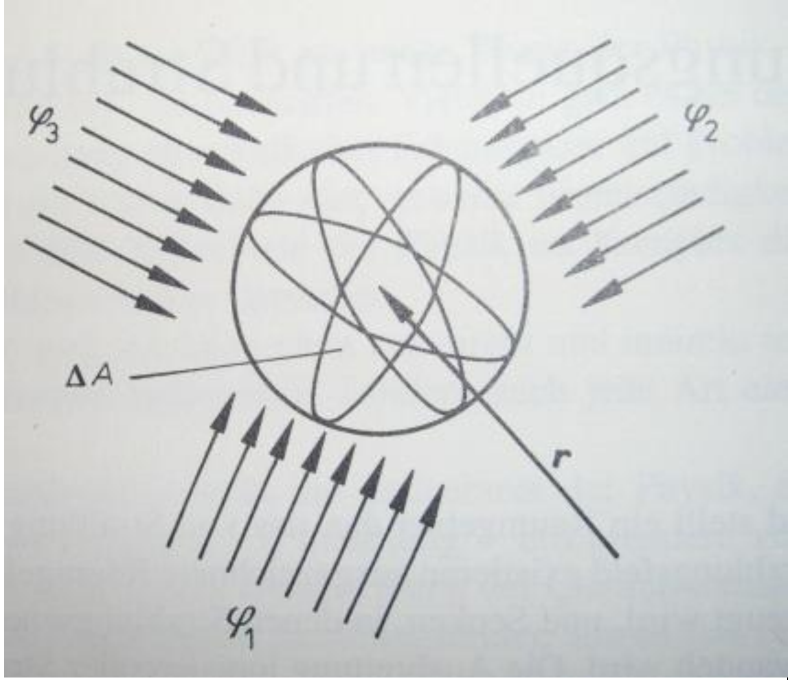
  ii) recoil (by “hitting”)

Flux

Flux density φ

- number of particles (per time) going through an arbitrarily oriented surface
- if at position $\vec{r}$ the particle density (particles per volume) for the speed $\vec{v}$ is $n\left(\vec{r}\right)$ the corresponding flux density is:

$$\varphi = n \cdot v$$



Flux density

$$\varphi(\vec{r}) = \int n(\vec{r}, v) \cdot v \, \mathrm{d}v$$

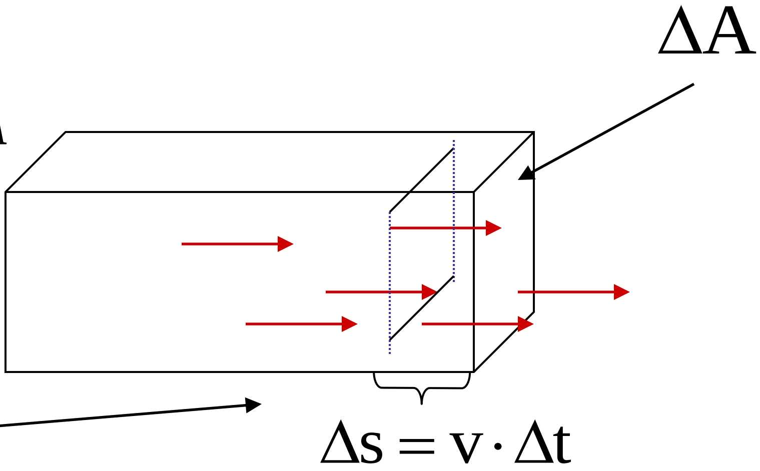
$$\varphi = n \cdot v$$

φ : particle flux density $\varphi = n \cdot v$

N_n : number of particles crossing surface ΔA

n : particle volume density projektiles

v : speed of projektiles



Particles not further away from ΔA than Δs can reach the surface in time Δt

$$\varphi = \frac{N_n}{\Delta A \cdot \Delta t} = \frac{n \cdot \Delta V}{\Delta A \cdot \Delta t} = \frac{n \cdot \Delta A \cdot \Delta s \cdot}{\Delta A \cdot \Delta t} = n \cdot v$$

Cross Section

- Event rate R of a given reaction

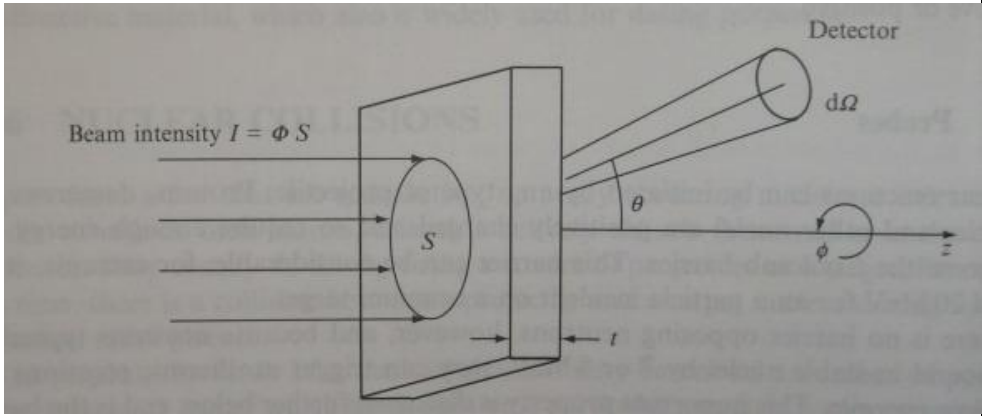
$$A(a,b)B$$

  is proportional to the **flux density** of the incident particles and the number of target nuclei $R = \sigma N \varphi$ or

- Taking the particle density: $r = \sigma n \varphi = \Sigma \varphi$

  With the macroscopic cross-section for the target $\Sigma = \sigma n$

- Angular differential cross section



Rate in detector covering solid angle $\mathrm{d}\Omega$

$$\mathrm{d}R(\theta,\phi) = \frac{\mathrm{d}\sigma(\theta,\phi)}{\mathrm{d}\Omega} \cdot N \cdot \varphi \cdot \mathrm{d}\Omega$$

Cross sections depend on projectile energy (excitation function)

Reactions with large cross-section are prefered

Unit:

1 barn = 10^{-24} cm^2

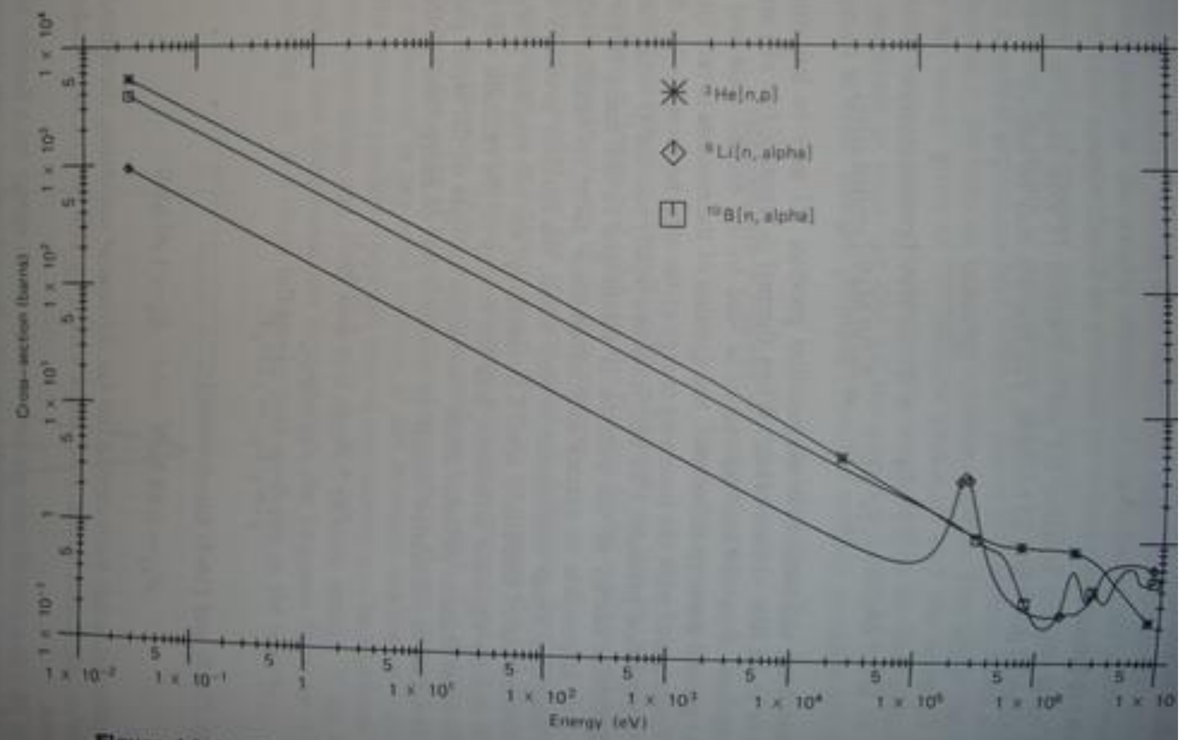
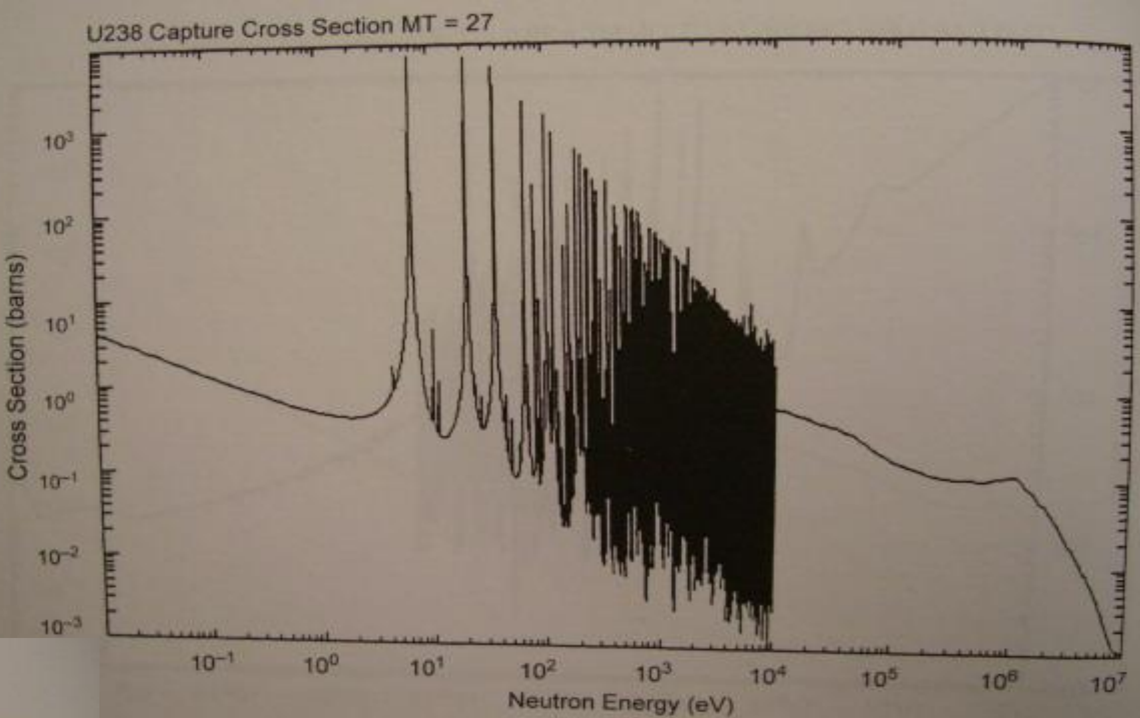
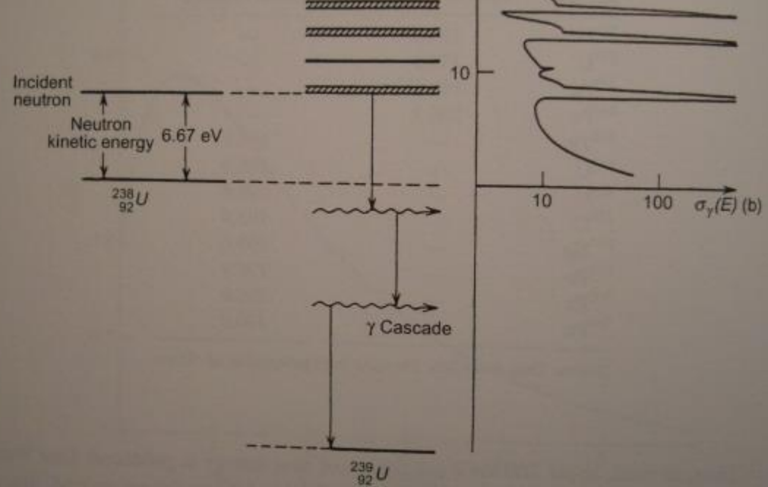


Figure 14-1 Cross section versus neutron energy for some reactions of interest in neutron detection

There can be resonances

“Not so good for the reactor”





If the target + the neutron energy match a level in the Comp0und nucleus

Example for prediction of reaction rate

Example: Reaction rate for production of ^{56}Mn , using 5g ^{55}Mn in neutron flux of $\varphi = 10^8 \cdot 1/\mathrm{cm}^2\mathrm{s}$

$$R = \sigma N_1 \varphi = \sigma \frac{m}{M} N_A \varphi =$$

$$= 1.33 \cdot 10^{-23}\,\mathrm{cm}^2 \cdot \frac{5\mathrm{g}}{55\,\frac{\mathrm{g}}{\mathrm{mol}}} \cdot 6.022 \cdot 10^{23}\,\frac{1}{\mathrm{mol}} \cdot 10^8\,\frac{1}{\mathrm{cm}^2\mathrm{s}} =$$

$$= 0.8 \cdot 10^8\,\frac{1}{\mathrm{s}}$$

Kinematics (Test it on a Snooker table)

Laboratory

Target at rest

CM in motion

2 coordinates $\vec{r}_p$ *and* $\vec{r}_T$

2 angles θ_L *and* φ_L

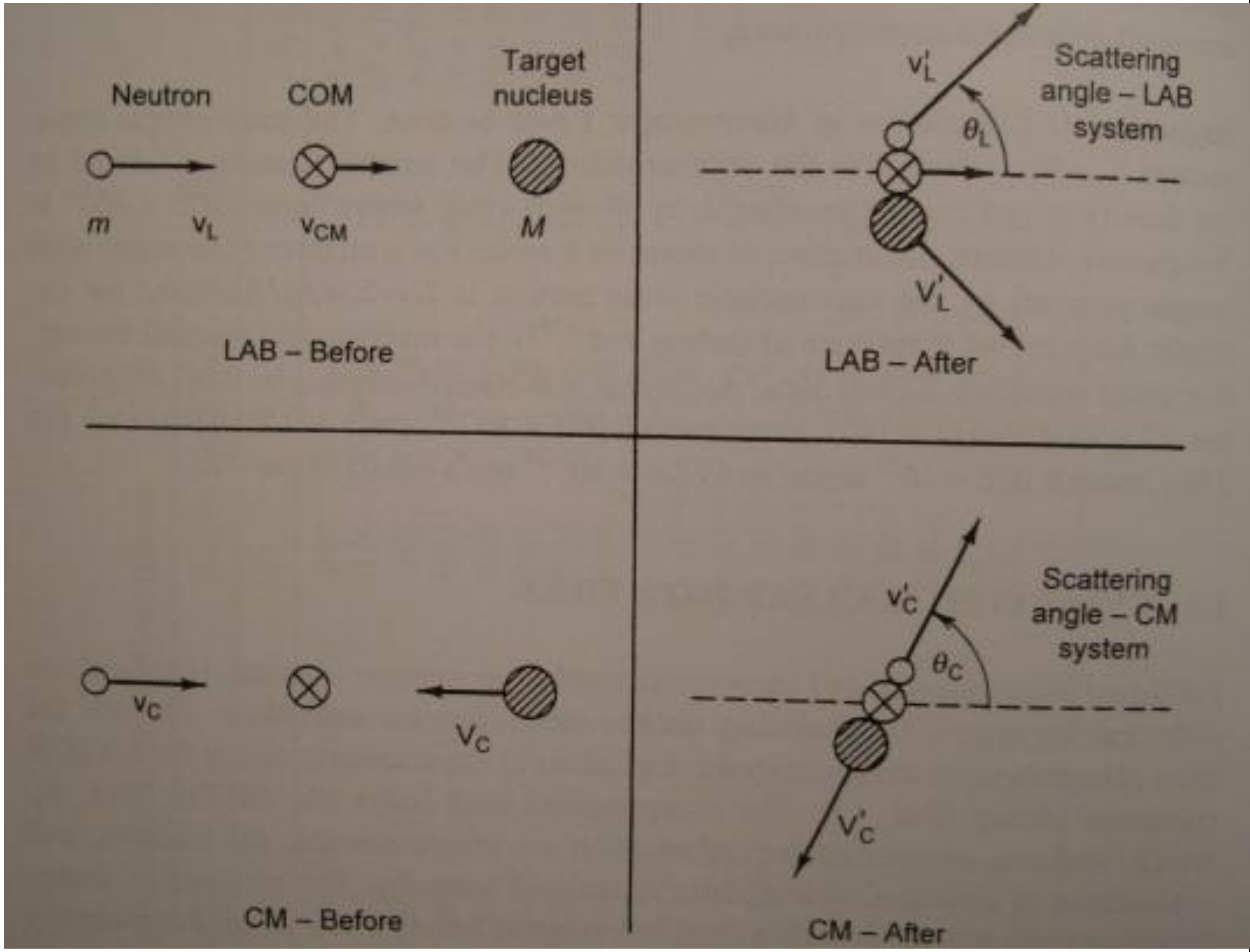
CM-System

Target and projectile move

CM – at rest

Only 1 nontrivial coordinate $\boxed{\vec{r}\,' = \vec{r}\,'_p - \vec{r}\,'_T}$

and 1 angle θ_C

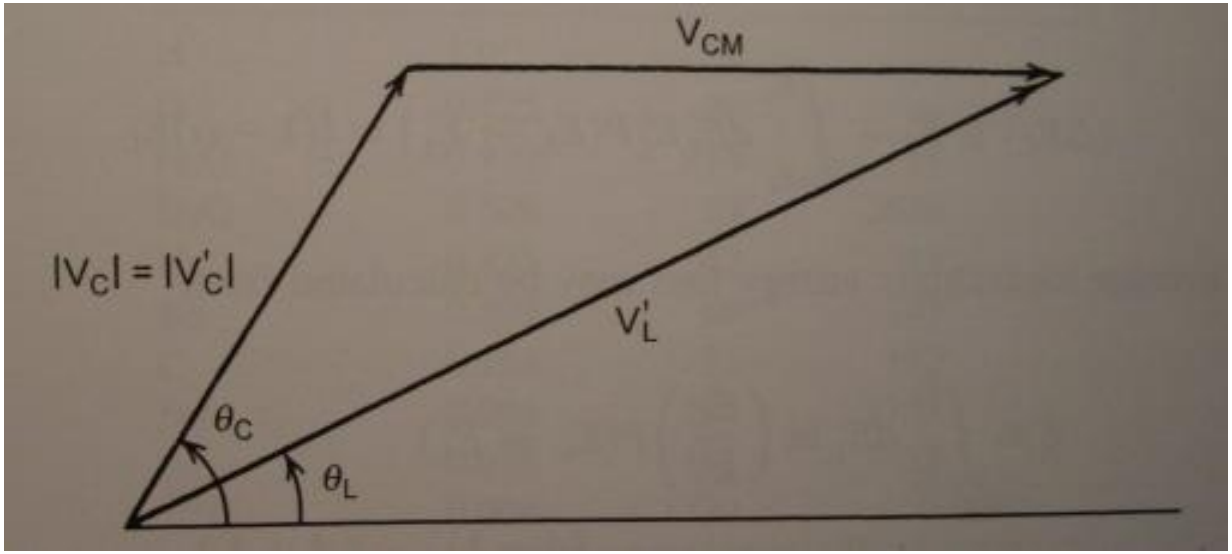


Transformation LAB - CM

To go from one system to the other: add / subtract v_{cm}

This implies:

Angles change, solid angles change …



Formula for the energy of the scattered particle in elastic scattering:

$A(a,a)A$

$$E' = E \cdot \frac{m_a^2}{(m_A + m_a)^2} \cdot \left[\cos\theta_L + \sqrt{\cos^2\theta_L + \left(\frac{m_A}{m_a}\right)^2 - 1} \right]^2$$

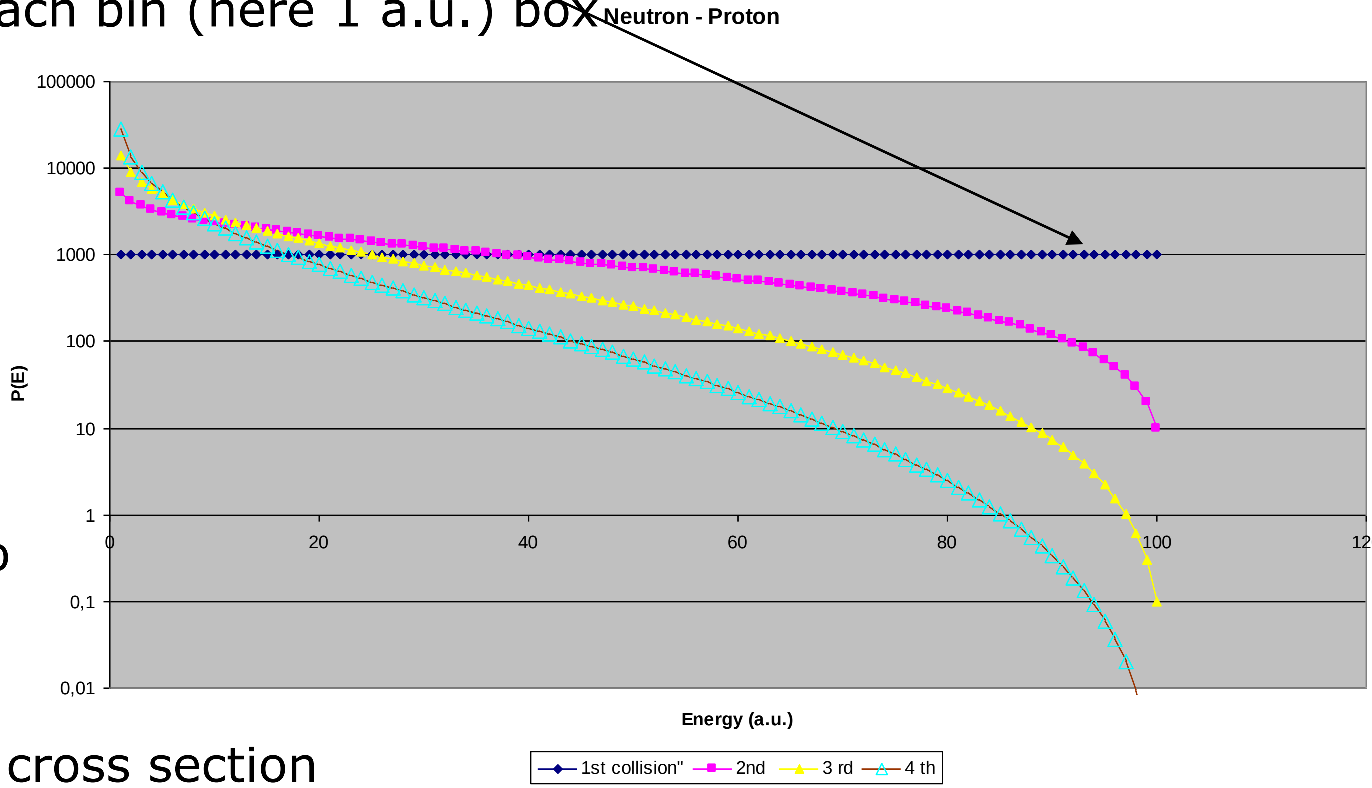
“Moderation” (here proton neutron)

Assume mono-energetic neutrons (E=100a.u., 100000 neutrons)

After 1st collision distribution = box

After 2nd collision each bin (here 1 a.u.) box

And so on…



Only few collision needed to concentrate intensity at low energies

(18 from 3 MeV to 25 meV)

More complicated if cross section non isotropic

Neutron Detection

Neutrons are indirectly ionizing radiation!

Detection uses interaction of neutrons with detector material

Thermal neutrons

$$\left.\begin{array}{l} {}^{10}B(n_{th},\alpha)^{7}Li^{*} \quad Q=2.31\,\mathrm{MeV} \;\; exc.state\,96\% \\ {}^{10}B(n_{th},\alpha)^{7}Li \quad Q=2.79\,\mathrm{MeV} \;\; g.s.4\% \end{array}\right\} \sigma = 3840\,\mathrm{b}$$

Some usefull reactions:

$${}^{6}Li(n_{th},\alpha)T \quad Q=4.78\,\mathrm{MeV} \qquad \sigma=940\,\mathrm{b}$$

$${}^{3}He(n_{th},p)T \quad Q=0.764\,\mathrm{MeV} \qquad \sigma=5330\,\mathrm{b}$$

$${}^{nat}Cd(n_{th},\gamma) \;\; (\gamma + conversion\,electrons) \qquad \sigma=2520\,\mathrm{b}$$

$${}^{235}U(n_{th},\,fission) \qquad \sigma=525\,\mathrm{b}$$

Detectors must discriminate against other radiation (Gammas!)

Thermal neutrons

Ionization (fission) chambers – walls with ^{235}U

Proportional counters – walls loaded with material
- counting gas $^{3}He,\ BF_3$

Scintillators e.g. CdTe, Li-glass = up to 8% Li content

Solid state (Li-sandwiched)

Gamma Discrimination due to pulse height:

Energy of fission products	around 100 MeV
Energy of heavy ions	around 1 MeV
Energy deposition of Gammas	some keV!

Fast neutrons

Mainly the recoiling nuclei are detected

Proportional counters – counter gas: Hydrogen, Helium..

Scintillators mostly plastic scint. for recoiling protons

Gamma discrimination more serious:

Prop. counter

- recoil protons – high efficiency requires measurement of low energy protons – low threshold in energy

Scintillators

- as above + light ouput low for heavy ions / compared to electrons

Solution – Pulse shape discrimination

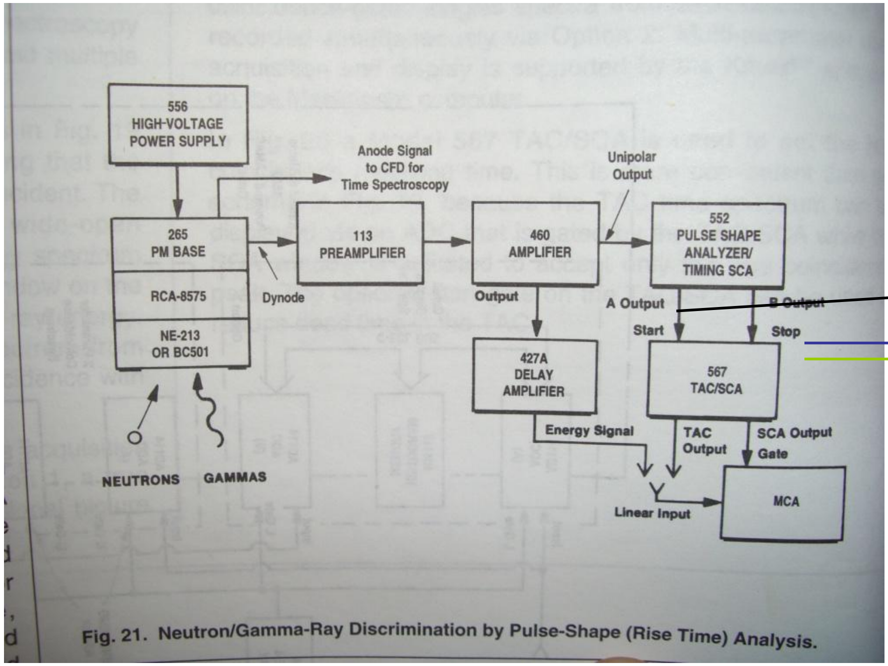
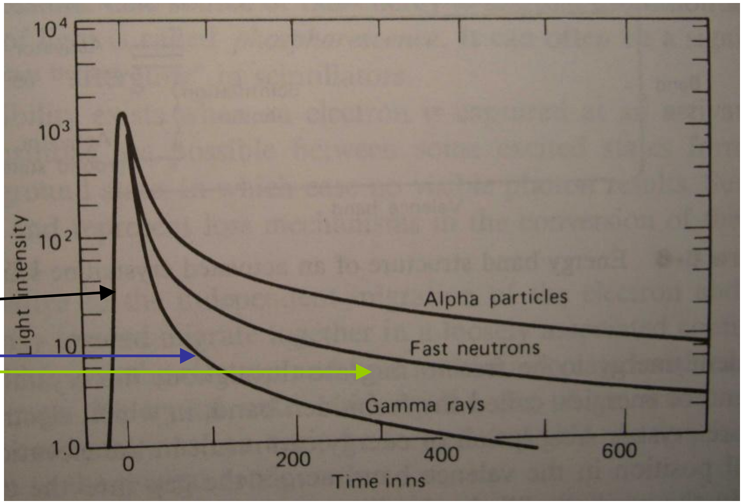
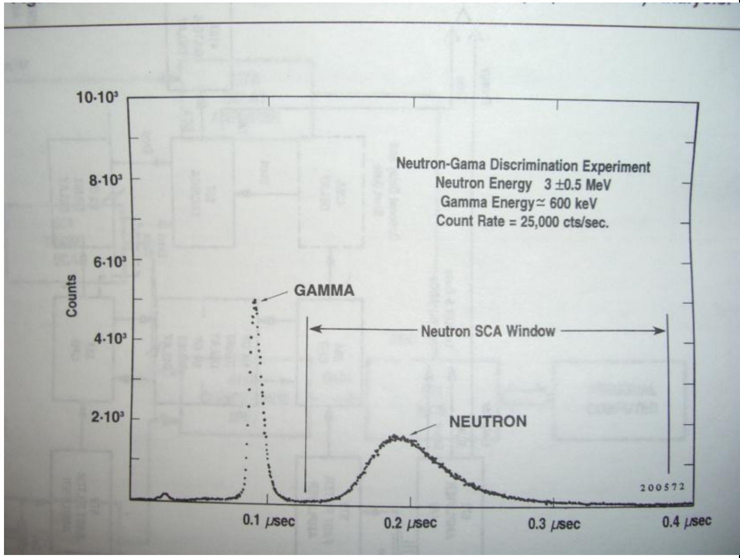


Fig. 21. Neutron/Gamma-Ray Discrimination by Pulse-Shape (Rise Time) Analysis.



Gamma Discrimination using the time behavior of the scintillation process.

For same pulse height gamma pulse shorter!



Dosimetry

Mostly thermal Neutrons are detected

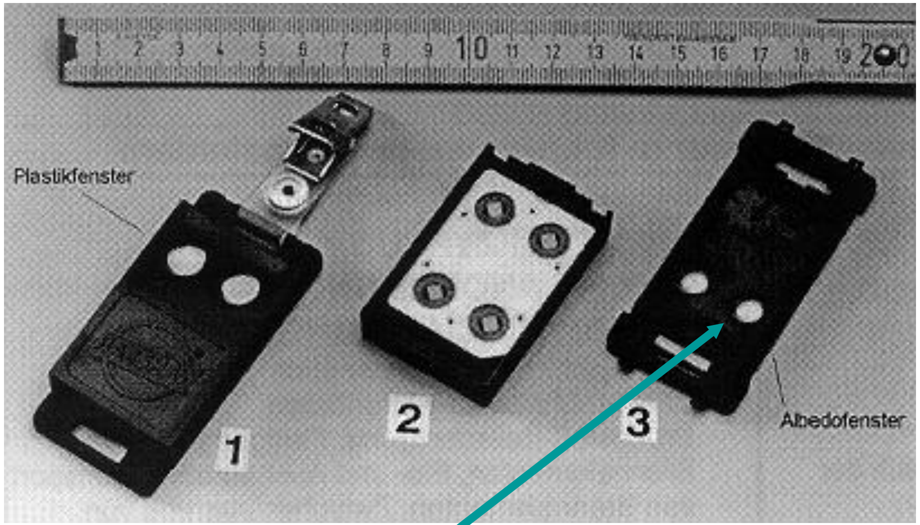
In many dosimeters proportional counters are used (^{3}He and BF$_3$):

$$ {}^{10}_{5}B + n \rightarrow {}^{7}_{3}Li + {}^{4}_{2}He $$

$$ {}^{3}_{2}He + n \rightarrow {}^{3}_{1}H + p $$

Sometimes counter walls loaded with ^{6}Li, Gd or ^{235}U

Personal Dose using Albedo Dosimeters (TLD)



Germany

If neutrons contribute to effective dose more than 10% the use of Albedo dosimeters is recommended

1 Front View, 2 casette with 4-TLD , 3 Rear view with albedo window

Detector measures $H_p(10)$ from Photons and *Neutrons*

Bor plastic - shields TLD from thermal neutrons

Photon detection

TLD pairs of ^{6}LiF and $\overbrace{^7\text{LiF}}$ material

Thermal neutrons: $^6Li + n \longrightarrow \alpha + {}^3H$

Thermal neutrons:

Are detected using the front window

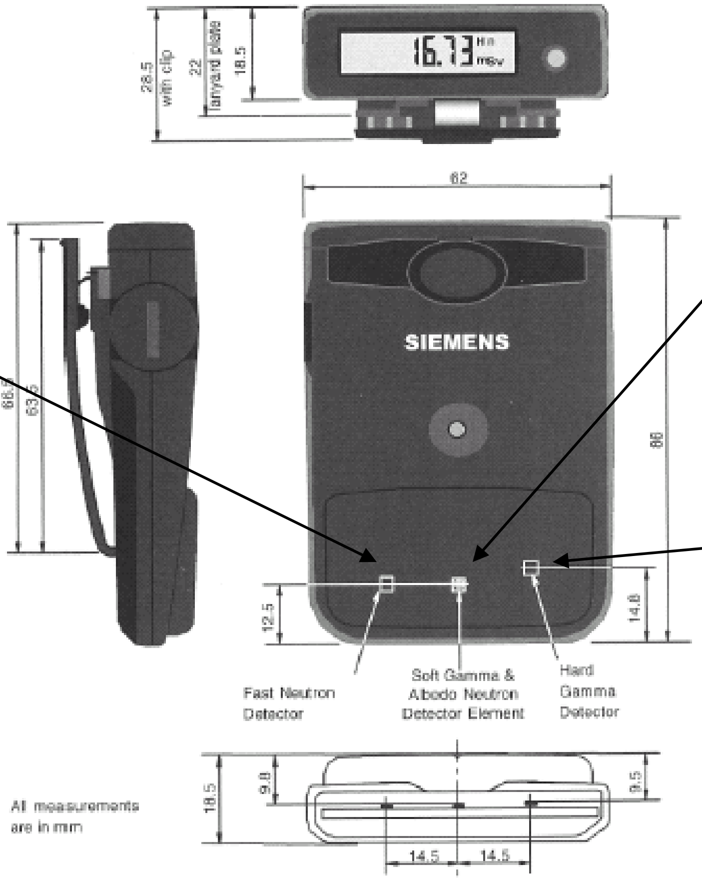
Fast neutrons:

Are moderated in the body. Thermal neutrons emerging from the body (Albedo) are detected at the rear window

Electronic Dosimeter EP D2 Can be used for measurement of $H_p(10)$ from neutrons

fast neutrons

Albedo and low energy photons

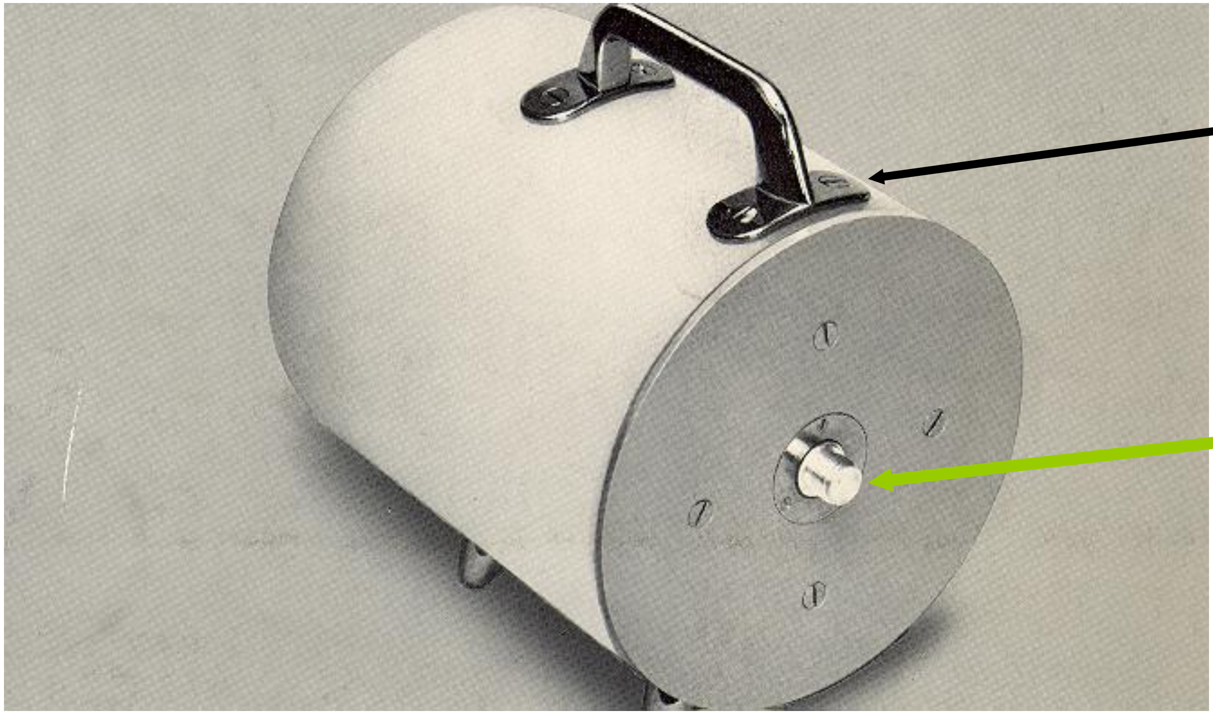


High energetic photons

3 Si-diode detectors

Abb.10: Technische Zeichnung aus dem englischen Benutzerhandbuch der Firma Siemens

Ambient Dose from Neutrons

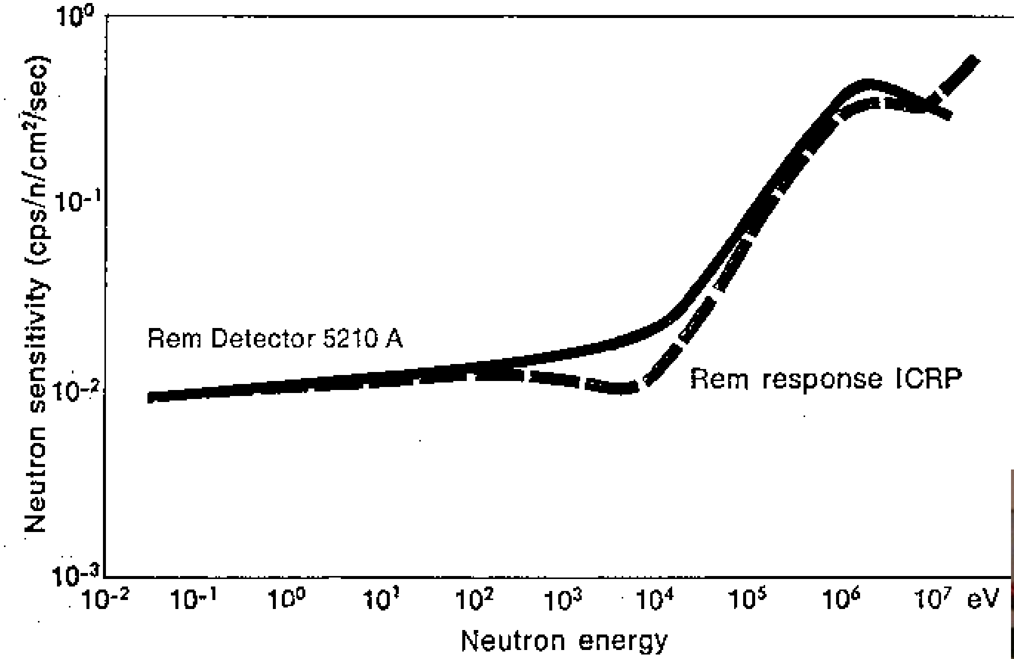


Moderator

BF3- prop-counter in the center

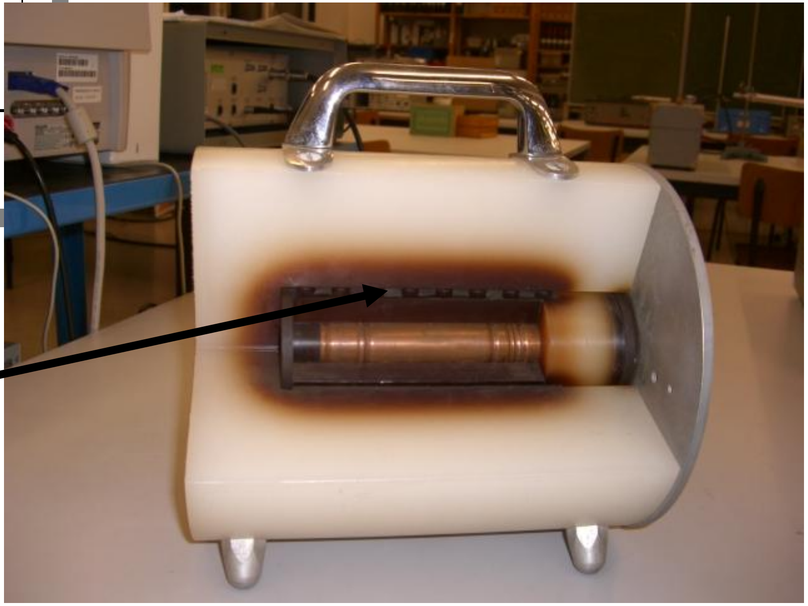
Response of the detector must be proportional to the neutron dose rate

„Remcounter“



Quality factor of n-radiation rises steeply between 10 keV and 10 MeV

Sensitivity of the rem-counter follows this curve due to Boron absorbers reducing the response to thermal neutrons




ESM
BIOREM

Neutron Flux Measurement

Most methods rely on activation: $^{A}X\,(n,\gamma)\,^{A+1}X$

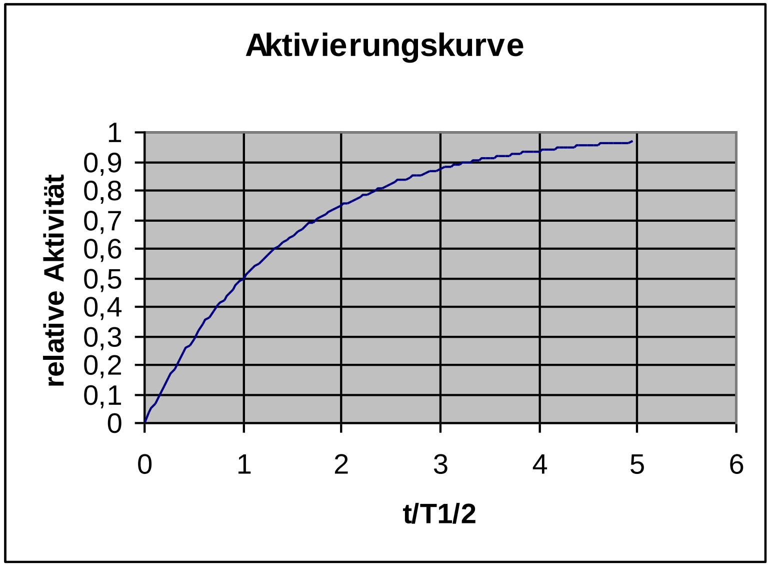
If flux not too high (and/or cross section not too big)

Production rate is nearly constant:

$$R = \sigma \cdot N \cdot \varphi$$

Resulting activity of radioactive product nucleus

$$\frac{dN_2}{dt}(t) = R - \lambda N_2(t)$$



$$A(t) = \lambda \cdot N_2(t) = R \cdot (1 - e^{-\lambda t})$$

Activation curve

After 3 Half-Lifes roughly 90% of maximal attainable activity is reached

Very common choice of reaction for thermal flux

$$^{197}Au(n,\gamma)^{198}Au,\ \sigma_{th} = 98.5\text{b},\ T_{1/2} = 2.7\text{d},\ E_{\gamma} = 411{,}79\,\text{keV}, I_{\gamma} = 95.5\%$$

“Cadmium ratio”: Measure the activiation with bare foil and foil covered with Cadmium (thick enough to absorb all neutrons with E<0.4 eV)

- measure of the thermalization of the neutron spectrum

Other probes, to cover other energy ranges

Threshold reactions for fast neutrons:

e.g. $^{23}Na(n,\alpha)^{20}F,\ T_{1/2} = 11s,\ E_{\gamma} = 1{,}63\,\text{MeV}, E_{threshold} \approx 7\,\text{MeV},$

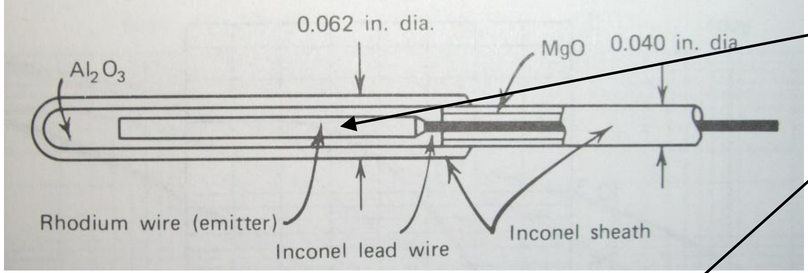
(n,γ) on Na has been used in Tokaimura

In reactor-instrumentation: Chain with Hf (or In) spheres along the fuel elements. Measures vertical flux distribution

Not useful for transients since long delay

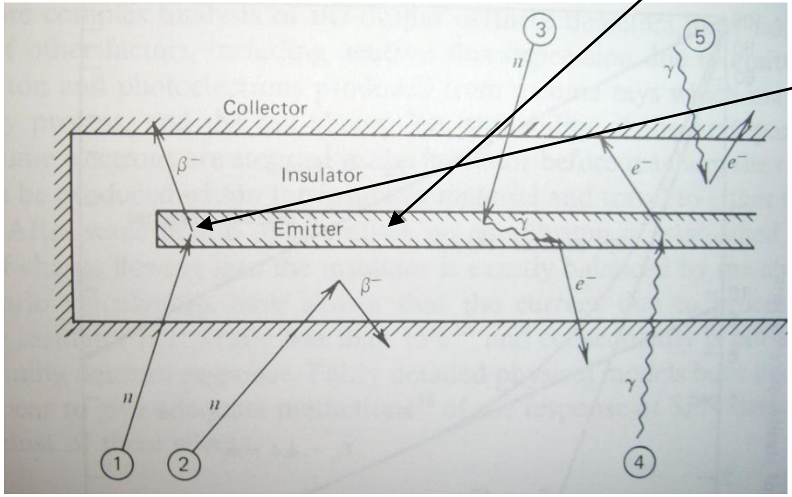
Continuous flux measurement using SPN – detectors

(SPN – self powered neutron detector)



β-from emitter reach collector

– current between emitter and collector

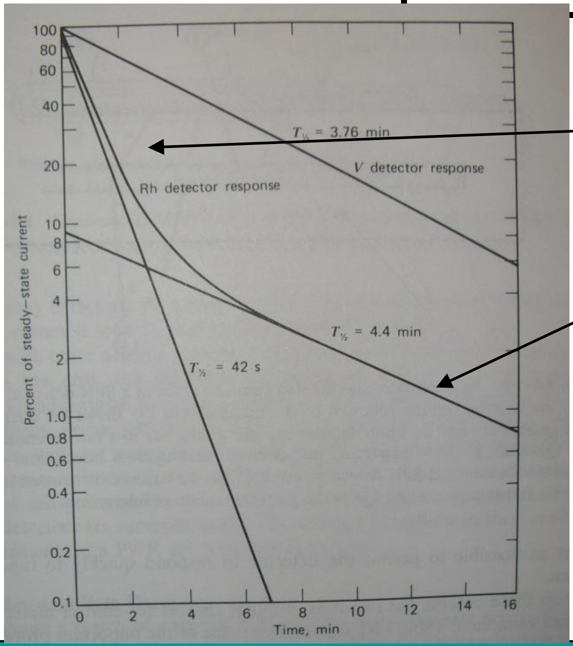


Standard event for operation with thermal neutrons

Used in reactor instrumentation

Emitter materials:

Material	Cross section/ barn	Half-Life/s	Typical currents/ A/(n/cm²s)
Vanadium	4.9	225	$5\text{x}10^{-23}$
Rhodium	139 and 11	44 265	$1\text{x}10^{-21}$



Time behavior after "shutdown"

- response time depends on half-life of activation product

Using Rh: Flux of 10^{13} n/cm²s gives current of I = 10 nA

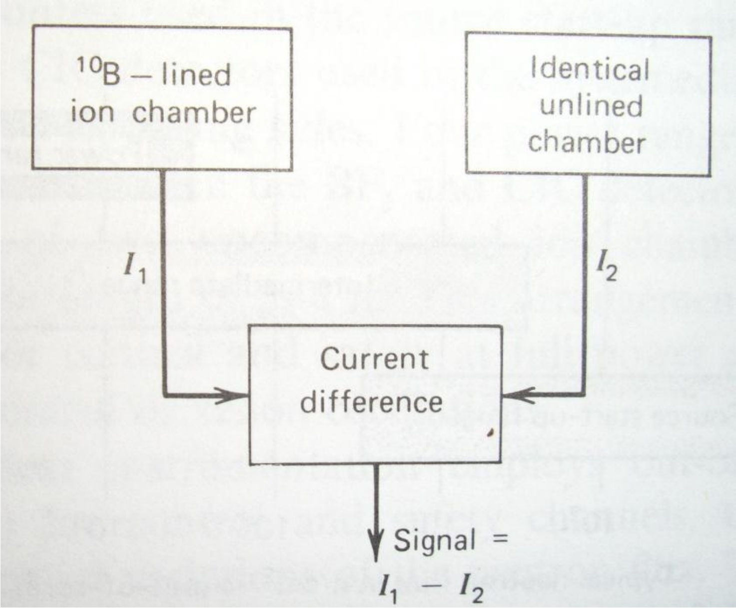
Ionization Chambers for Flux Measurement

Counting only for very low flux range possible (dead time)

-Ionization chambers are used in current mode

Reactors after shutdown have very high activity levels

Thus high levels of Gamma-background



Discrimination using compensation

(difference = neutron signal)

or

Look at rms-of current signal:

Fission event produces about 3 orders of magnitude more charge than gamma event!

Fast Neutron Spectroscopy

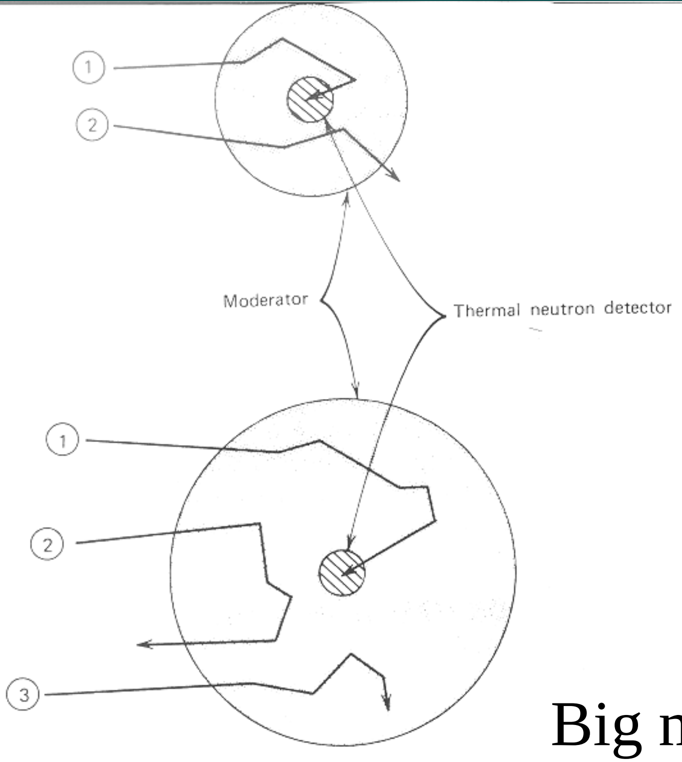
Spectroscopy of slow or even ultra cold neutrons not topic of this talk

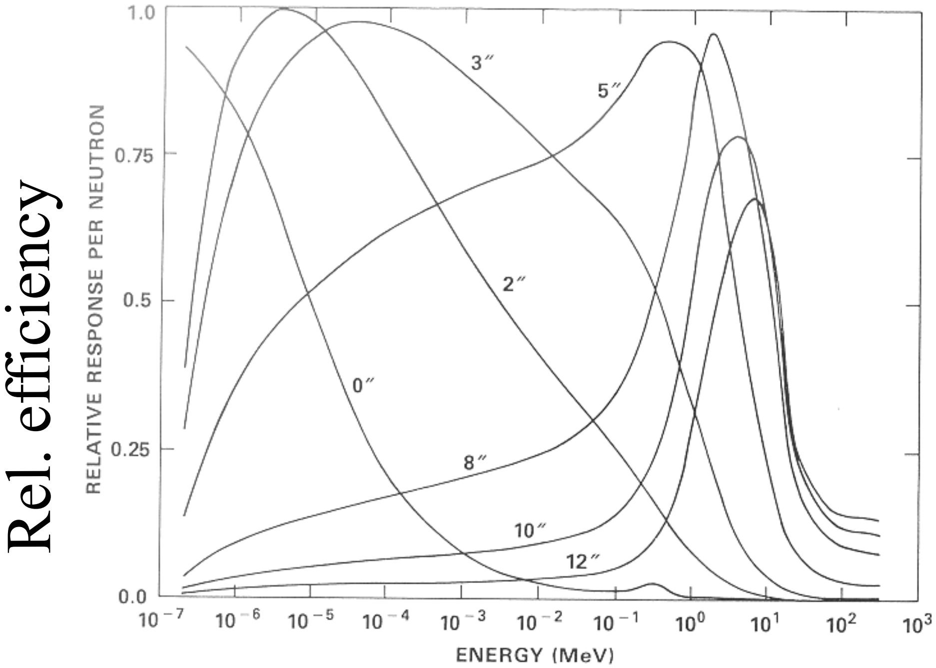
3 main methods to determine neutron energy spectra:

i) Measure thermal neutrons, using several detectors with different efficiency for different neutron energies:

“Bonner spheres”

Central 3He-Prop Counter



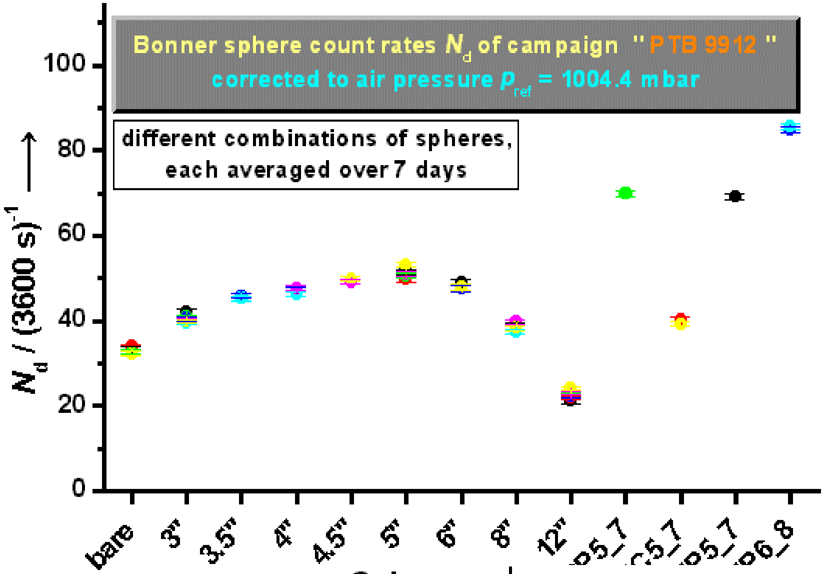


Big moderators sensitive to high energies

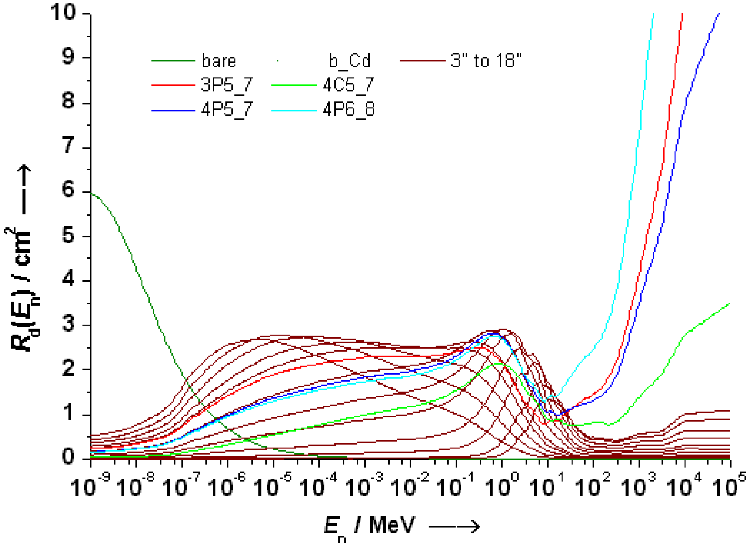
Deconvolution: Find original spectrum from the measurement

Measurement: Convolution of spectrum S(E) with response R(E_n,E)

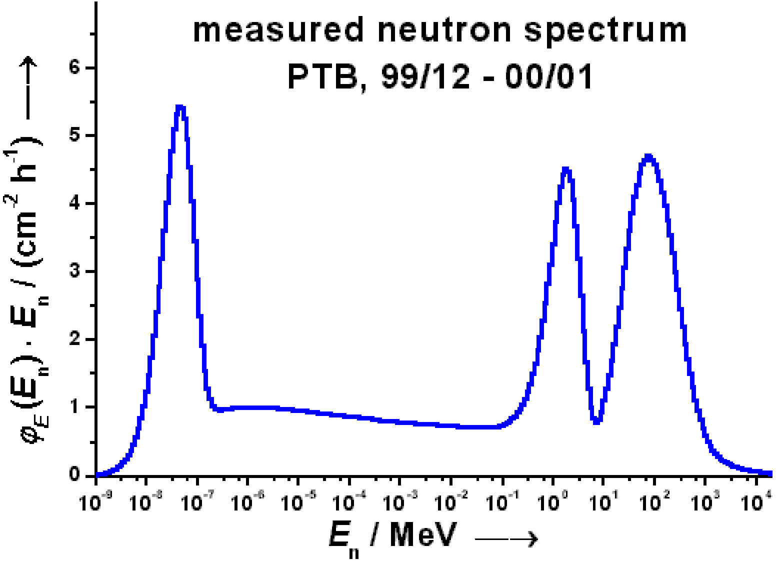
Natural background in Braunschweig
Mean flux dens. 46 n/cm²h (1y measuring time)



Counts in the spheres



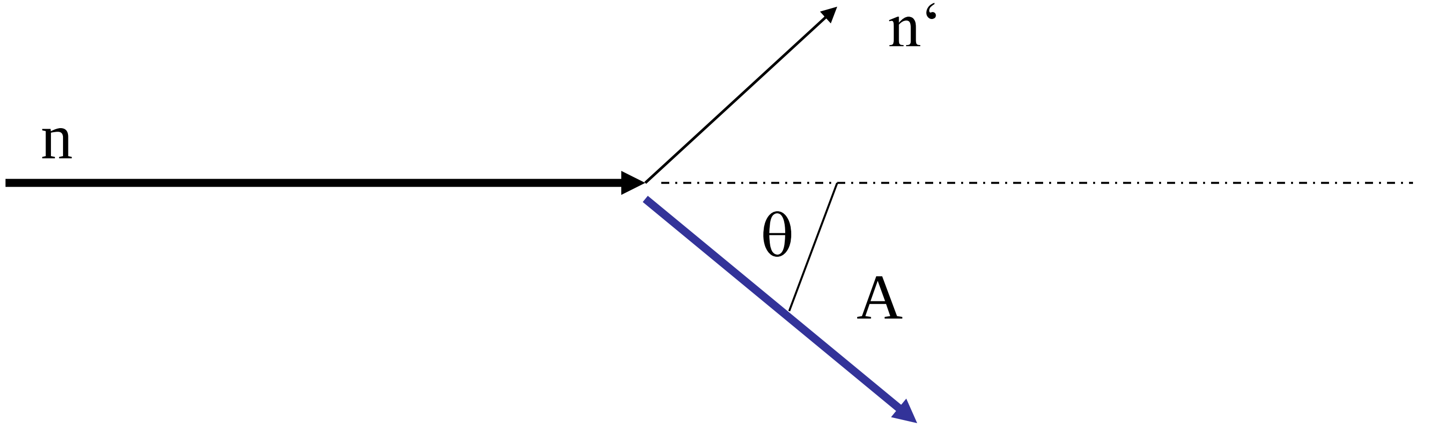
Response of spheres



Program MAXED

M. Matzke: *Unfolding of Pulse Height Spectra: The HEPRO Program System*, PTB Report PTB-N-19, ISBN 3-89429-543-0 (1994).

ii) Use the kinematics of elastic scattering

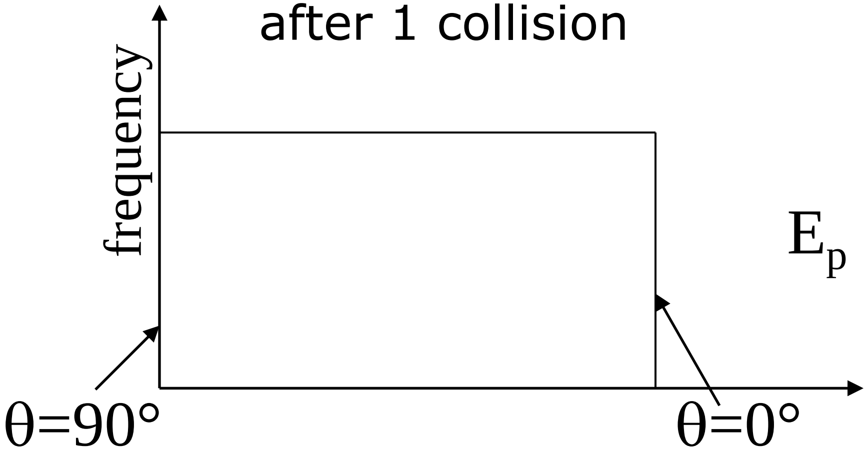


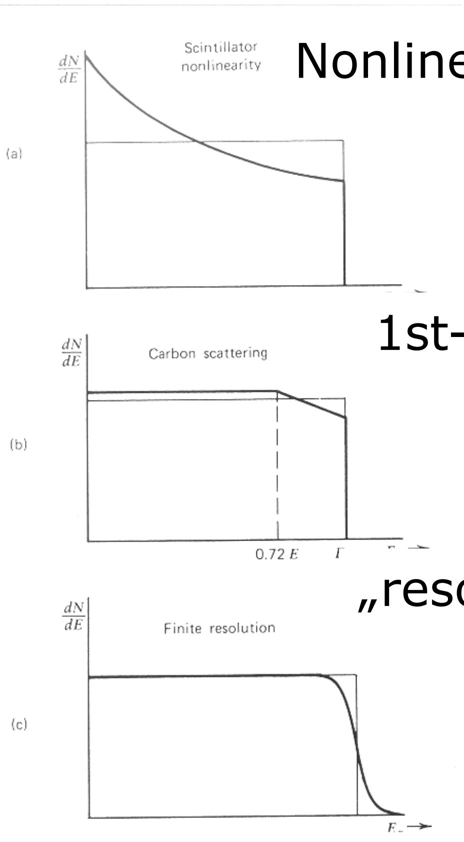
Energy of the recoil nucleus A

$$E_A = \frac{4A}{(1+A)^2}(\cos^2\theta)E_n$$

For proton:
energy between 0 and E_n ,
since A=1

Recoil of the protons after 1 collision

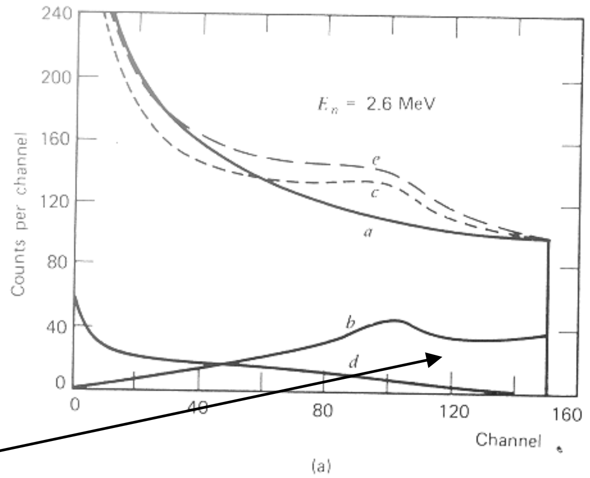




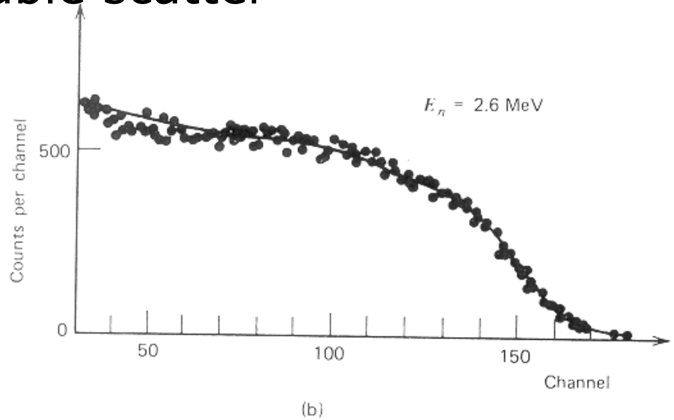
Nonlinearity

1st-scatter on C

„resolution“

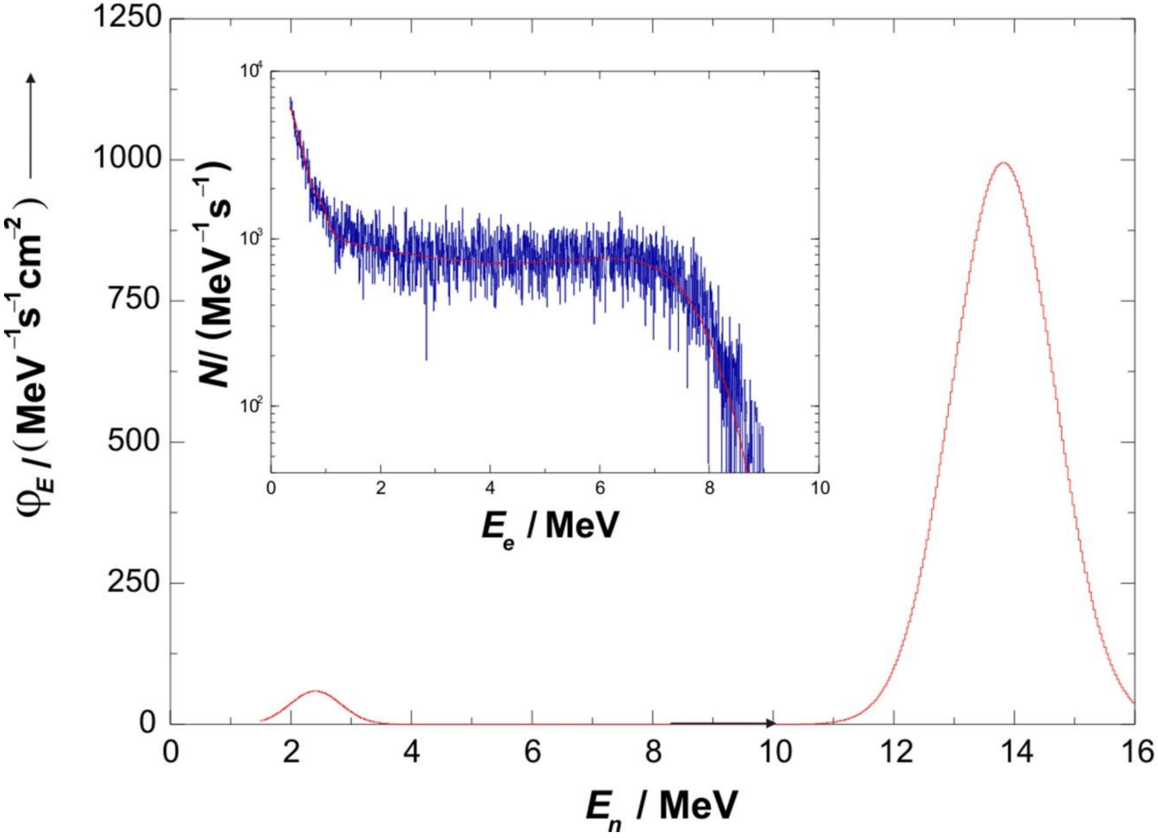


Double scatter



Distortions to the ideal response

Real measurement for 2.6 MeV neutrons



Blue-inset: measured response of liquid scintillator

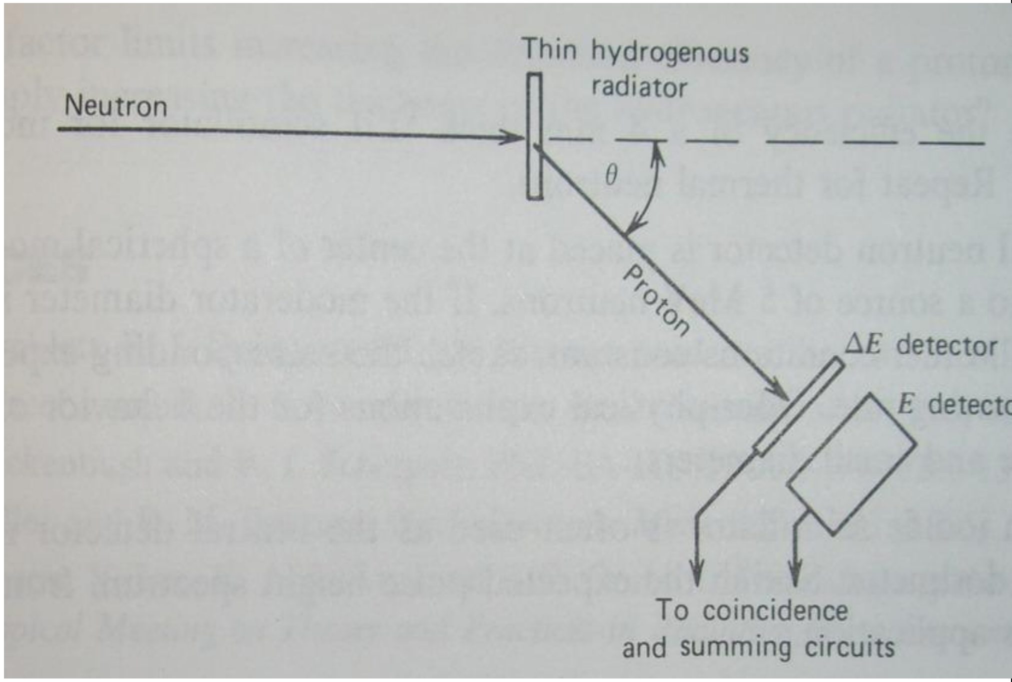
Example of PTB: dd- and dt-reaction in JET (Culham)

If Scintillator, H_2 or ^{4}He prop. counter is used - these “boxes” are obtained (isotropic angular cross sections)

Again deconvolution is required (In Germany – ask PTB)

Measured counts at pulse height h:
Convolution of spectrum $S(E_n)$ with response $R(E_n,h)$

Tedious but straightforward for directed neutron beam:



Proton recoil detector

Here: the energy of each neutron is measured individually using the kinematics

Requires a “start” signal either from pulsed accelerator or from scintillating target.

iii) TOF (time of flight measurement)

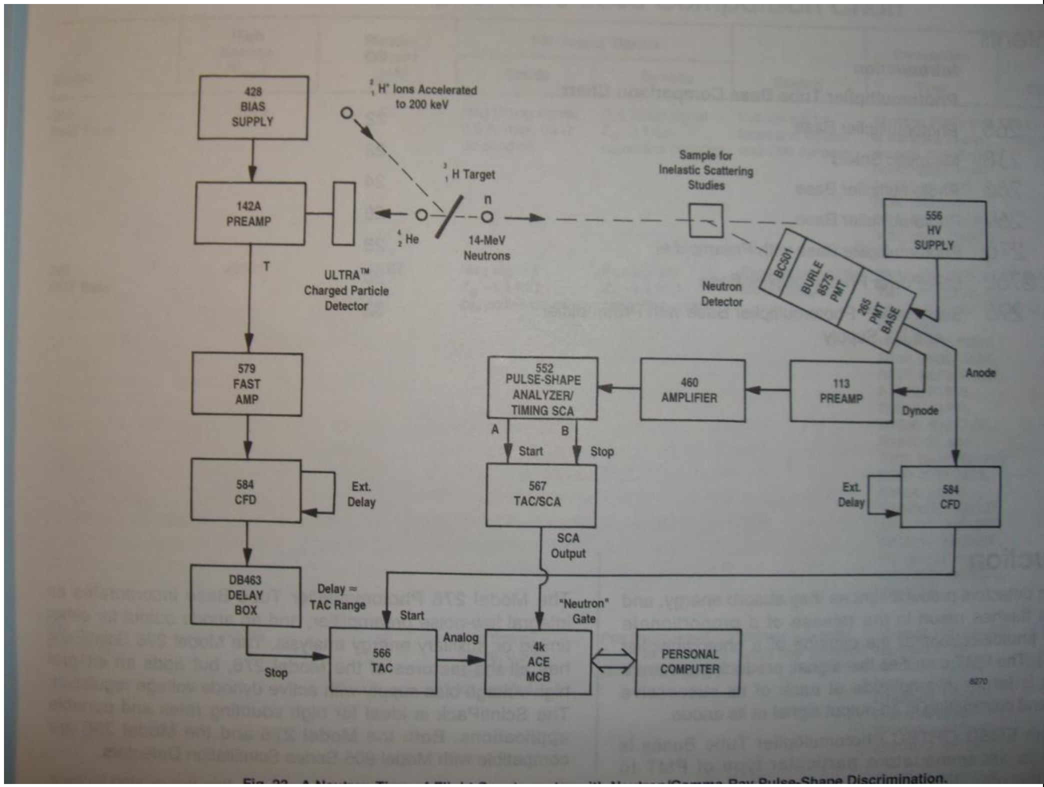
$$v = \sqrt{\frac{2E}{m}} = \sqrt{\frac{2E/\mathrm{MeV}}{939}}\,c$$

Using the nonrelativistic formula one finds for a 1 MeV neutron:

It takes roughly 75 ns for 1 m flight

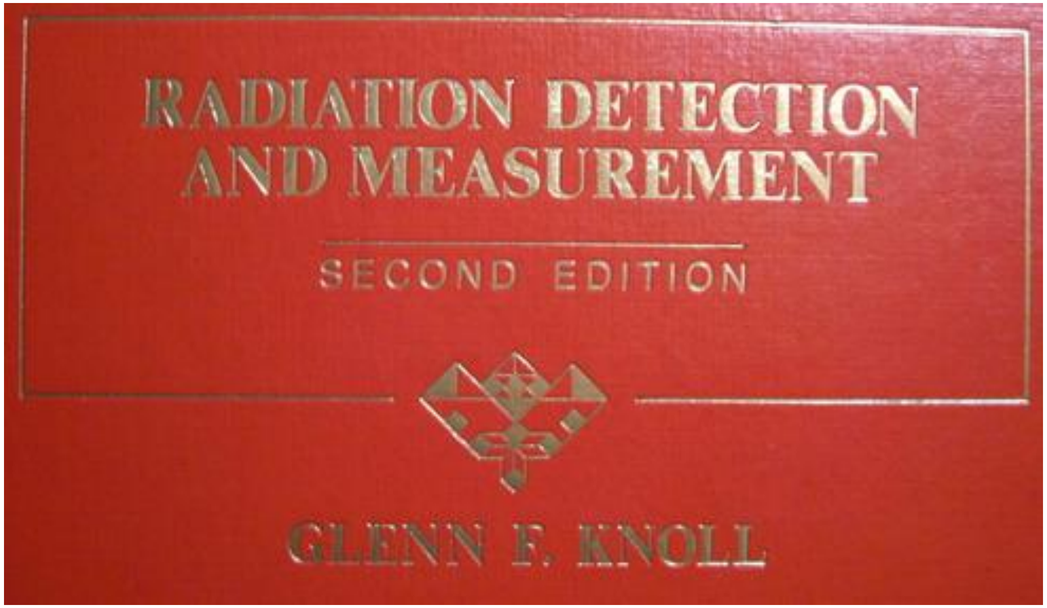
One needs a (fast) start signal. (Pulsed accelerator or associated particle in a (d,t)-generator)

Electronics for TOF spectrometer including the Gamma-discrimination



Literature

My favorite book



RADIATION DETECTION
AND MEASUREMENT

SECOND EDITION

GLENN F. KNOLL

- Atoms, Radiation, and Rad. Protection, James E. Turner
- Nuclear Physics, John Lilley
- Ortec catalogue of 1995
- Canberra Eurisys catalogue (CD-rom)

Thank you for your attention

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