Neutrons:
production, detection and application

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Outline

- Where we can find neutrons?
- How to get neutrons?
- Sources of neutrons
- Why we need neutrons?
- Interactions of neutrons with matter
- Transport of neutrons in matter
- Neutron cross sections
- Kinematics of neutron reactions
- Nuclear reactions used for neutron detection and spectroscopy
- Gamma radiation accompanying neutrons

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Where we can find neutrons?

– neutrons are bounded in atomic nuclei due to strong interactions

$^{A}_{Z}X^{N}$

A – mass (nucleon) number

Z – atomic (proton) number

N – neutron number

$B_n(^{A}X) \sim 5 \div 11$ MeV   neutron binding energy

– neutron physics – interactions with atomic nuclei
– wave properties of neutrons

How to get neutrons?

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Nuclear reactions

- (α,n), natural α, $^{9}Be(\alpha,n)^{12}C$, Chadwick in 1932, accelerators
- (d,n), thermonuclear reactions, accelerators
- (p,n), threshold reactions, accelerators
- (γ,n), photonuclear reactions, γ-sources, accelerators of electrons (bremsstrahlung)
- (γ,f), photofission, bremsstrahlung
- (p,xn) spallation of heavy nuclei, accelerators

How to get neutrons (cont.)

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Spontaneous fission of transuranium isotopes

Neutron induced fission (n,f) of uranium and transuranium isotopes

Fast neutrons

Slow neutrons

Continuous sources

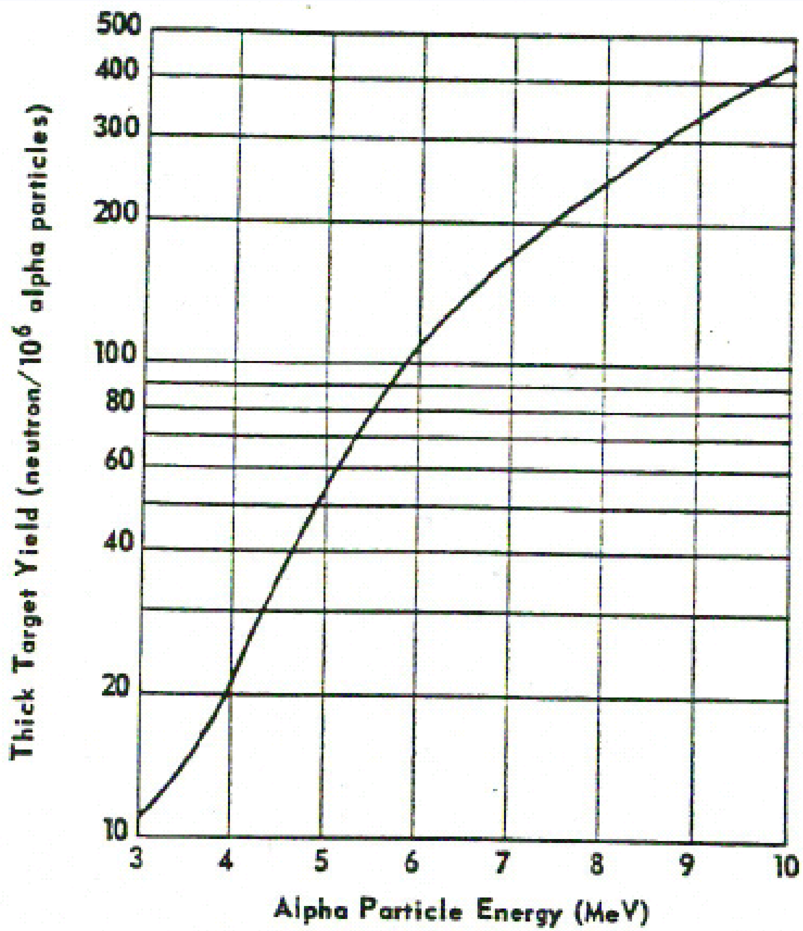
Pulsed sources , TOF techniques

Cold and ultracold neutrons

Moderation of neutrons

- Neutrons are always born fast (energetic) because they have to be released from atomic nuclei where are strongly bounded.
- For their slowing down, elastic and inelastic scattering processes are used. Neutrons are slowed down in any environment. However, the hydrogen rich compounds (water, heavy water, polyethylene) are the most effective ones. But also Be and graphite can be effectively used as a neutron moderator.
- An absorption of neutrons within an intentional slowing down process is unwanted. In the case of shielding against neutrons, the absorption is required, preferably without production of gamma rays.
- We talk about thermal neutrons, when neutron motion is in equilibrium with thermal motion of atoms and molecules in an environment. Distribution of neutron velocities corresponds to Maxwell-Boltzmann distribution at given temperature of the environment (mean neutron velocity at room temperature is about 2200 m/s).

Yield of neutrons from ^{9}Be(alpha,n)



Thick target yield of neutrons for alpha particles on beryllium
(From Anderson and Hertz.[22])

Neutron spectra of different radionuclide (α,n) sources

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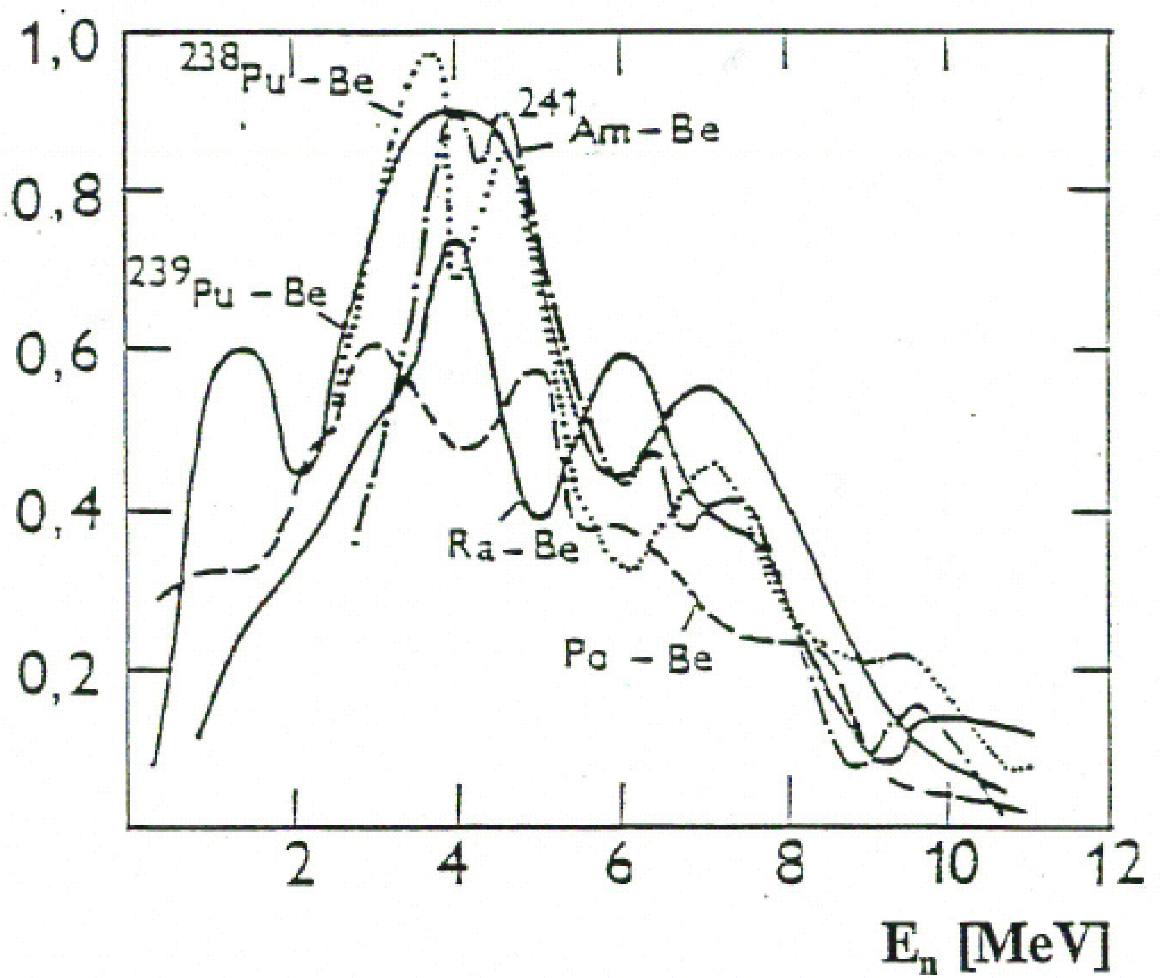

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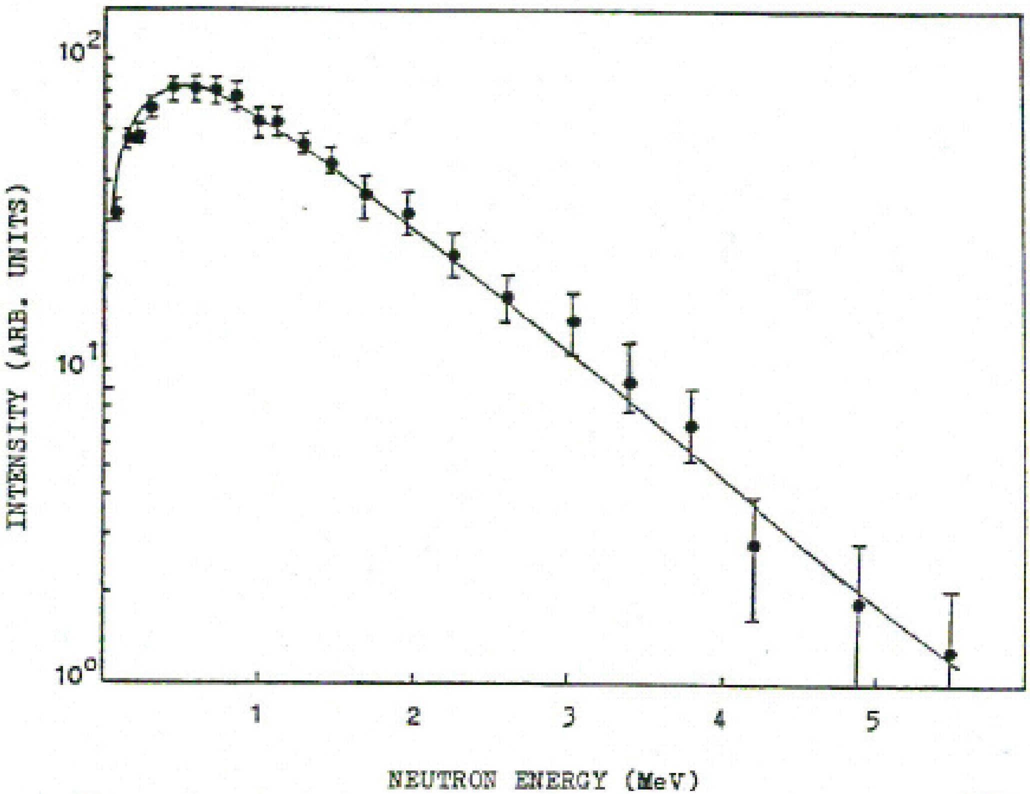
^{252}Cf neutron spectrum



Measured neutron energy spectrum from the spontaneous fission of ^{252}Cf.
(From Batenkov et al.[18])

Nuclear reactor as neutron source

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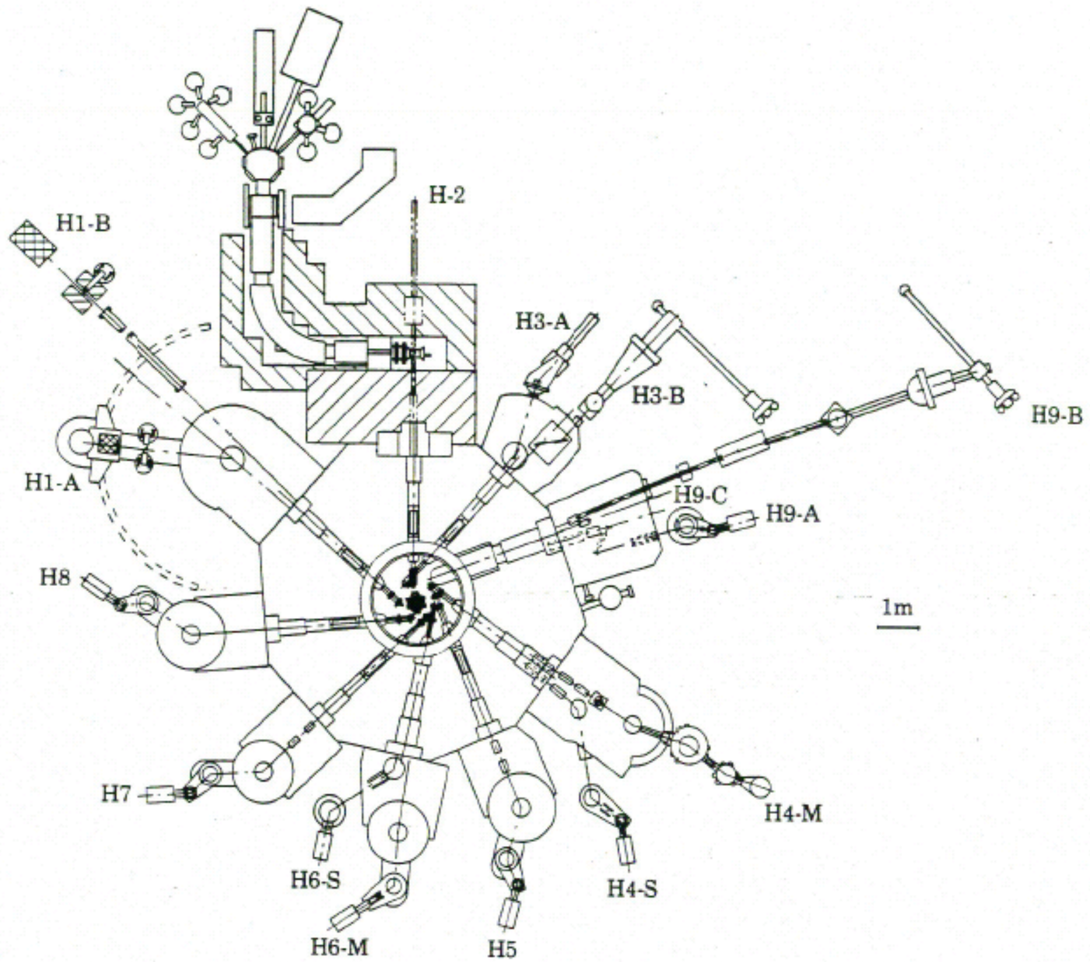

Schematic plan of spectrometers installed on the experimental level of the HFBR.

Spallation neutron source

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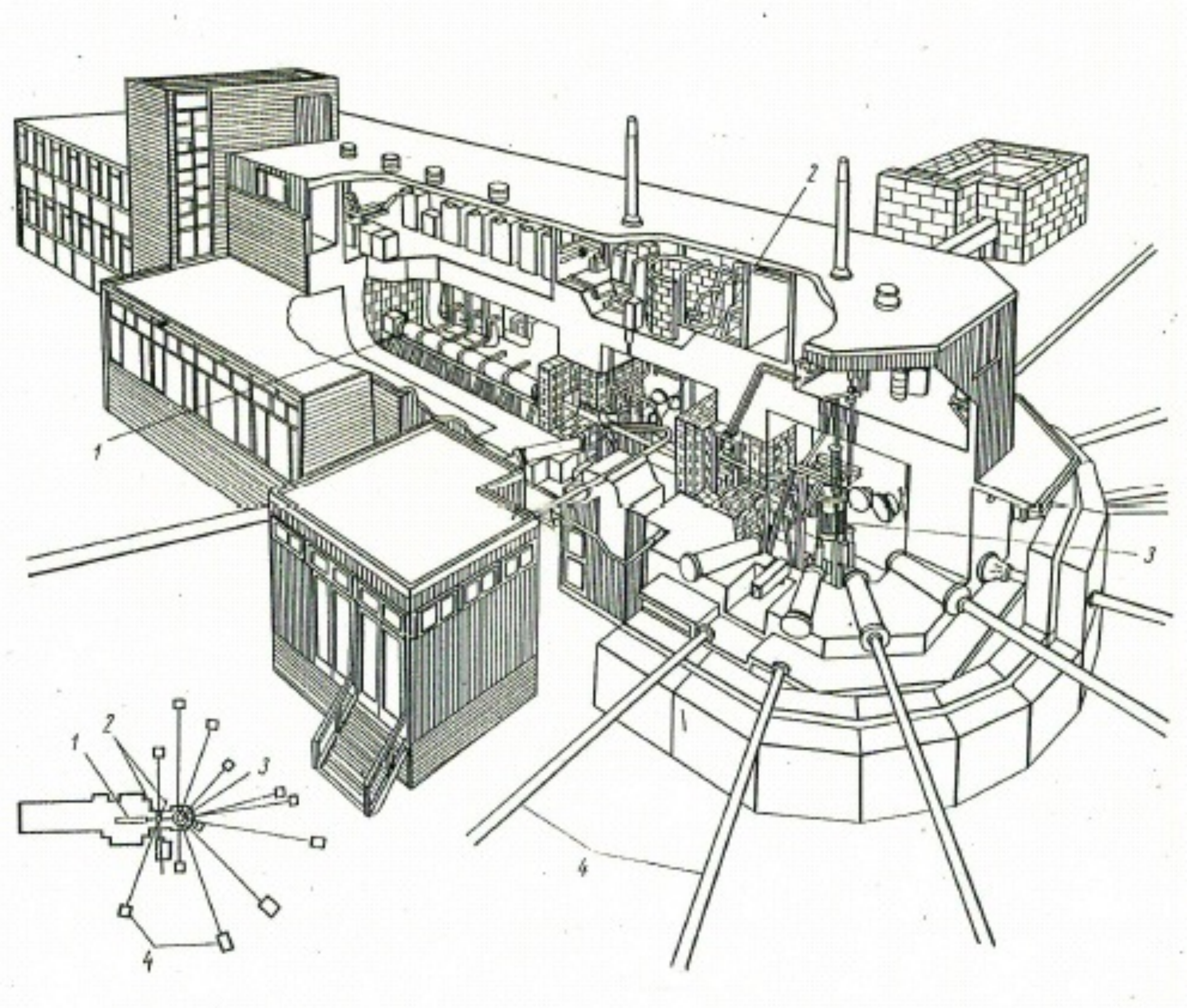

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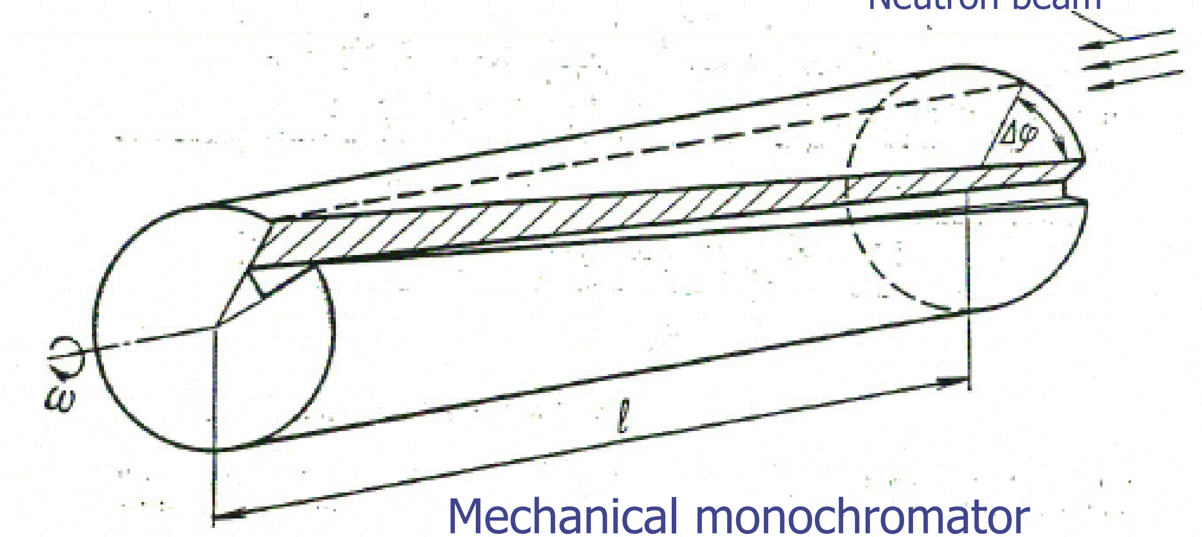
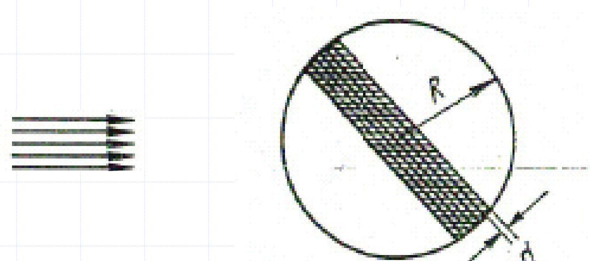
Monochromatic neutrons

Neutron beam



Mechanical monochromator

Neutron beam



Slow neutron chopper with Cd+Al slits

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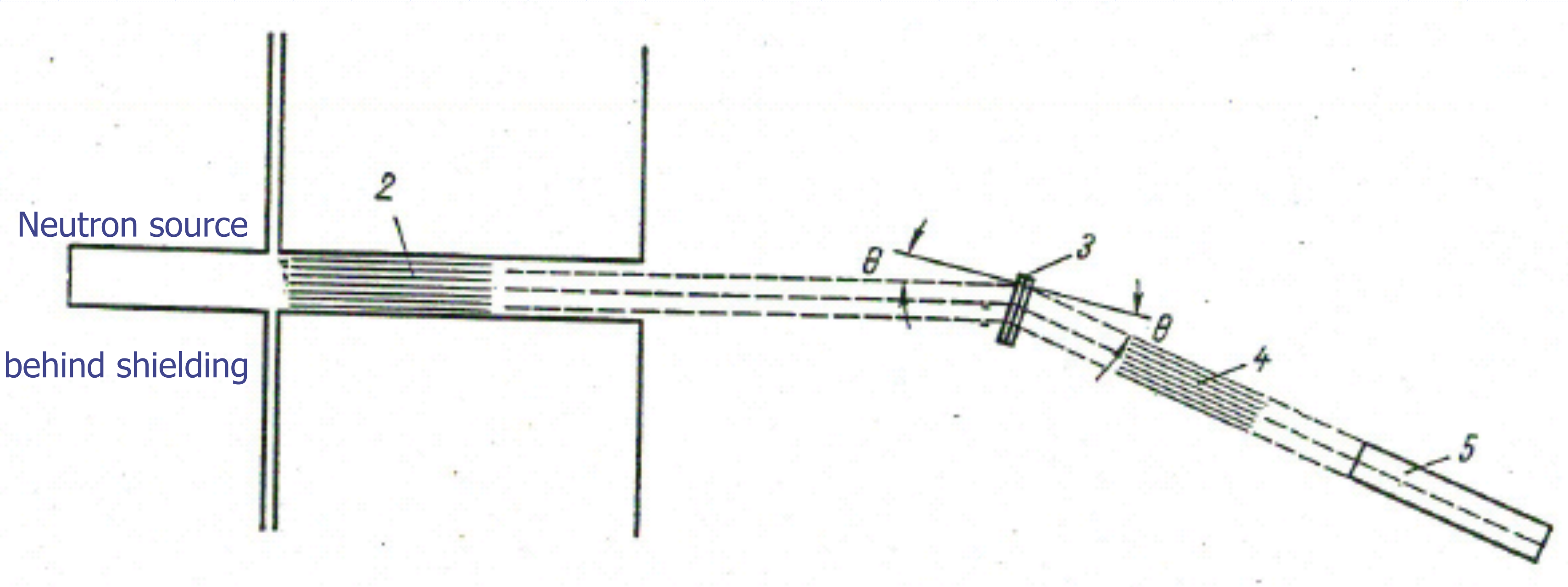

Crystal spectrometer-monochromator

2-collimator, 3-monocrystal, 4-collimator, 5-detector

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Why we need neutrons?

- to study atomic nuclei
- to study matter on the molecular and atomic level using de Broglie wave length properties of neutrons (neutral particles!)
- nuclear energy generation (fission)
- further applications (neutron therapy, neutron imaging, …)

Interactions of neutrons with matter

strong interaction, $\rho \lesssim 10^{-14}$ m $\Rightarrow$
negligible electromagnetic interactions

$\Rightarrow$ high penetrability of neutrons

Week interactions

What about gravitational interaction?
Ultracold neutrons, elementary particle physics at neV energy scale

Processes:

- elastic scattering $n + {}^{A}_{Z}X \longrightarrow {}^{A}_{Z}X + n$

- inelastic scattering $n + {}^{A}_{Z}X \longrightarrow {}^{A}_{Z}X^{*} + n'$

$\quad \hookrightarrow {}^{A}_{Z}X + \gamma$

- nuclear reactions

$${}^{1}_{0}n^{1} + {}^{A}_{Z}X^{N} \longrightarrow {}^{A'}_{Z'}Y^{N'} + {}^{a'}_{z'}y^{n'}$$

exoenergetic

endoenergetic

$$Q = (m_n + m_X - m_Y - m_y)c^2$$

excitation of Y

conservation laws of: A, Z, N, kinetic energy, momentum, coulomb barrier

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- radiative capture $n + {}^{A}_{Z}X \longrightarrow {}^{A+1}_{Z}X + \gamma$

slow neutrons

- fission on heavy nuclei

slow neutrons $n + {}^{A}_{Z}X \longrightarrow {}^{A_1}_{Z_1}Y_1 + {}^{A_2}_{Z_2}Y_2 + x\,n + \dots$

- spallation of heavy nuclei

fast neutrons ($T_n > 100\ MeV$), hadrons

shower

Transport of neutrons in matter

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- fast neutrons $\sigma_t \sim A^{2/3}$, $T_n > 100\,keV$

  slowing down processes (elastic, inelastic scattering), γ-rays

  neutron absorption, (n,p), (n,α) reactions,... is less important, γ-rays

- slow neutrons σ_t – fluctuates

  thermalization (equilibrium with thermal motion of atoms)

- slow neutrons σ_t – fluctuates

thermalization (equilibrium with thermal motion of atoms)

diffusion of neutrons

neutron absorption becomes most important n2

radiative capture – high energetic γ-ray production, $\sigma_{n\gamma} \sim \frac{1}{v_n}$

epithermal $T_n > 1 eV$

thermal $\overline{T_n} = 0.025 eV$

cold $T_n < 1 meV$

ultracold $T_n < 1 \mu eV$

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Neutron cross sections

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$$\sigma_t = \sigma_s + \sigma_a$$

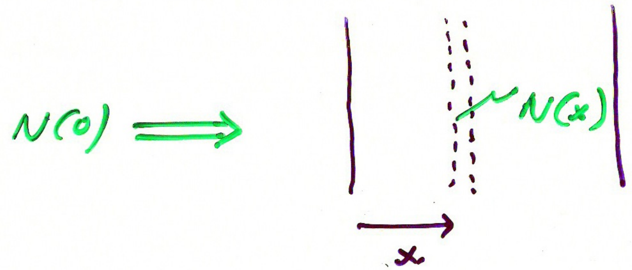
$$n\sigma = \Sigma$$ – macroscopic cross section

$$\lambda = \frac{1}{\Sigma}$$ – mean free path $\qquad \tau = \frac{\lambda}{v}$

$$\lambda_s = \frac{1}{\Sigma_s}, \quad \lambda_a = \frac{1}{\Sigma_a}, \quad \frac{1}{\lambda_t} = \frac{1}{\lambda_s} + \frac{1}{\lambda_a}$$

$$N(x) = N(0)\, e^{-\Sigma x} = N(0)\, e^{-\frac{x}{\lambda}}$$

Exponential attenuation



Shielding against neutrons

- dangerous to the man
- dangerous to the electronic devices

Basic principles:

- first moderate (H_2O, D_2O, C, Be, CO_2, CH_2, parafine)
- then capture (B, Li, Cd, Gd, ...)

γ-shielding ?

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Test of shielding against spallation neutrons

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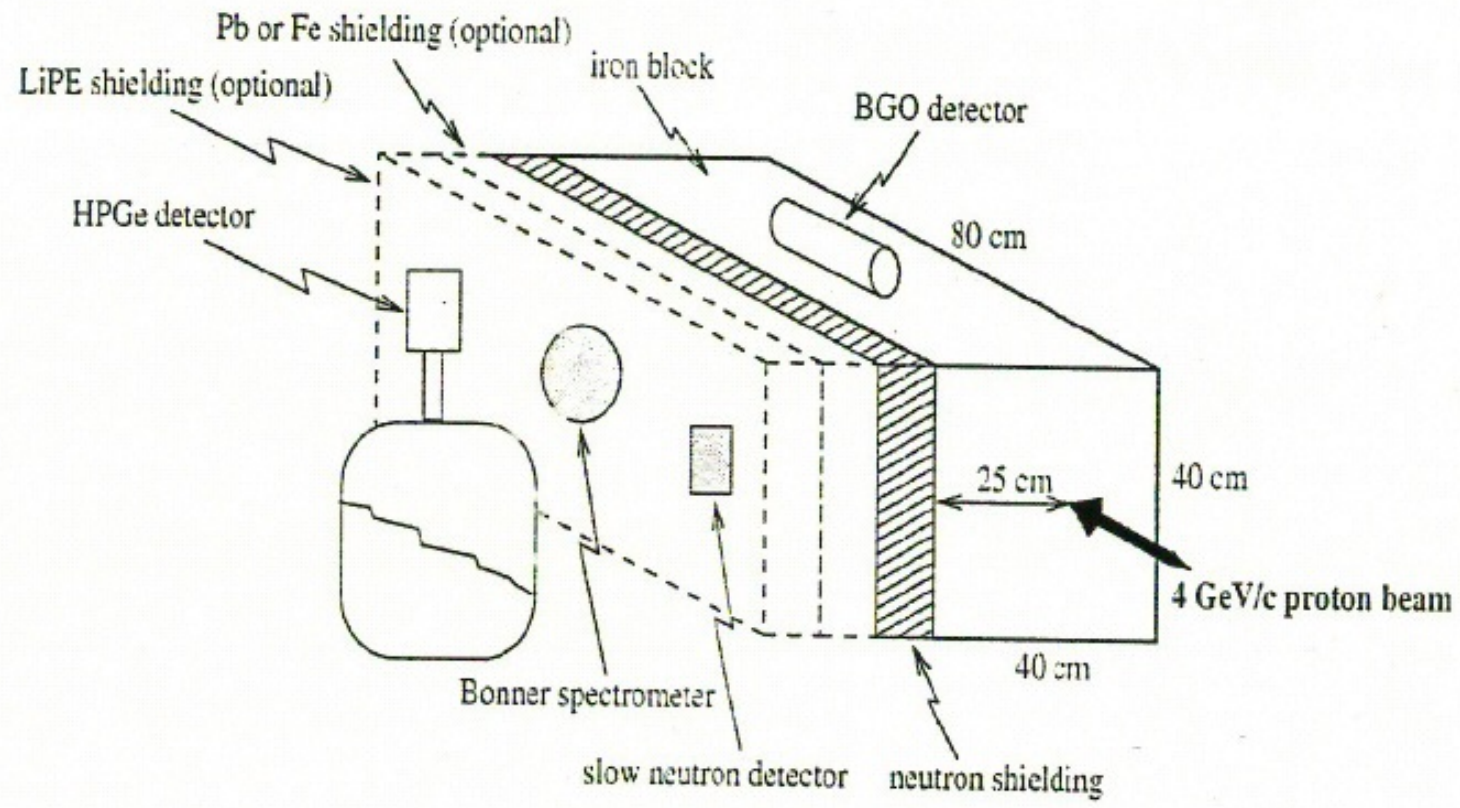

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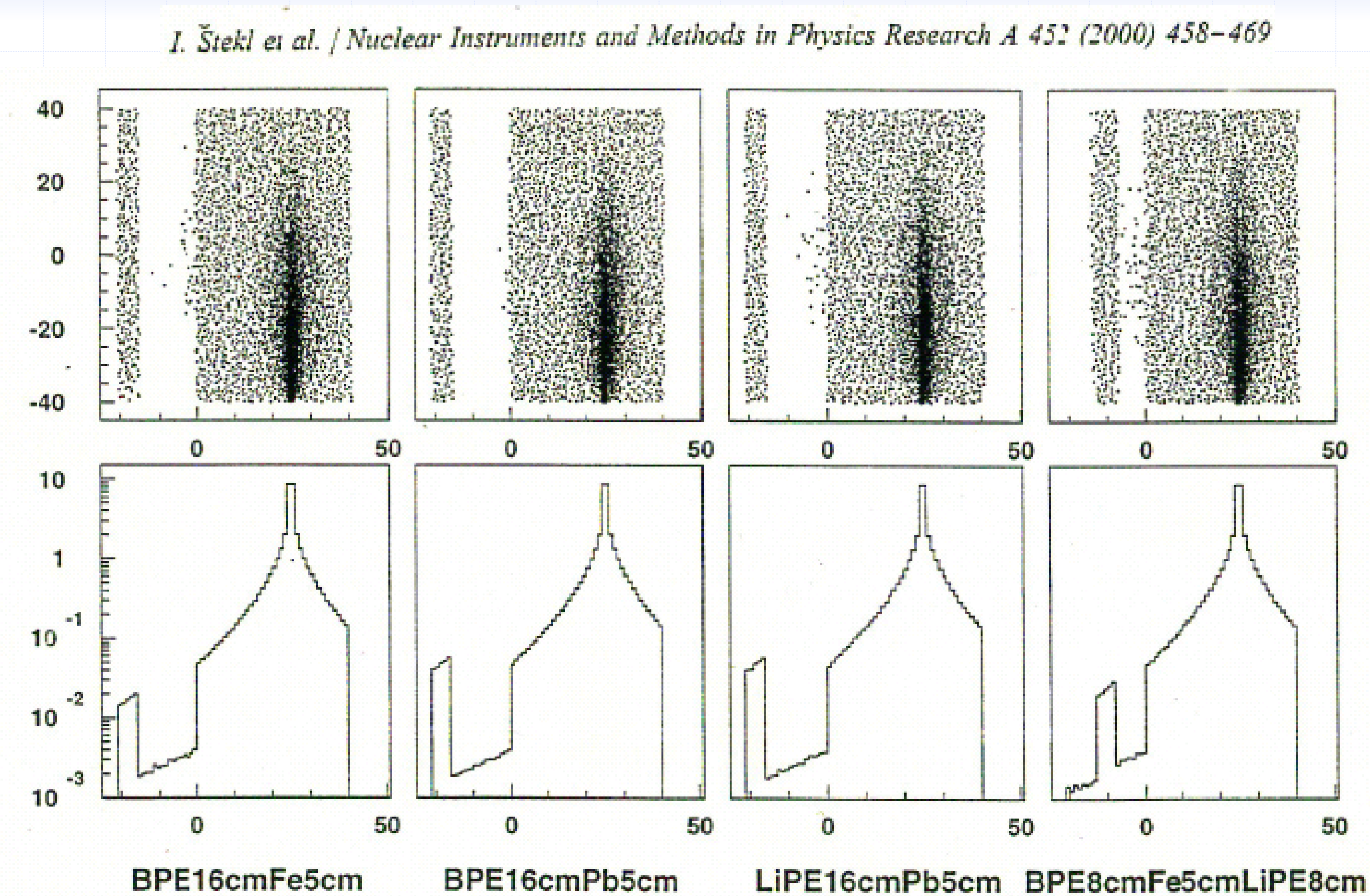
Neutron fluxes within the setup



Nuclear reactions often used for neutron detection and spectroscopy

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$^{1}H(n,n)^{1}H$ elastic scattering

$^{3}He(n,p)^{3}H$ $Q = 764$ keV

$^{6}Li(n,\alpha)^{3}H$ $Q = 4.78$ keV

$^{10}B(n,\alpha)^{7}Li$ $Q = 2.78$ MeV, 6%

$^{10}B(n,\alpha)^{7}Li^{*}$ $Q^{*} = 2.30$ MeV, 94%

$\hookrightarrow$ $^{7}Li + \gamma$ (478 keV)

$^{157}Gd(n,\gamma)^{158}Gd$ $\sigma_{n\gamma} = 255000$ barns

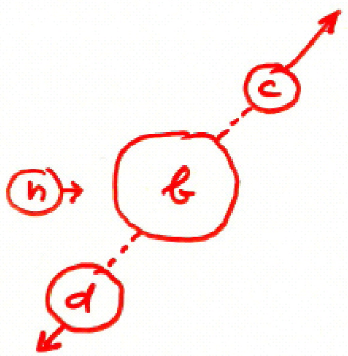
Kinematics of neutron reactions

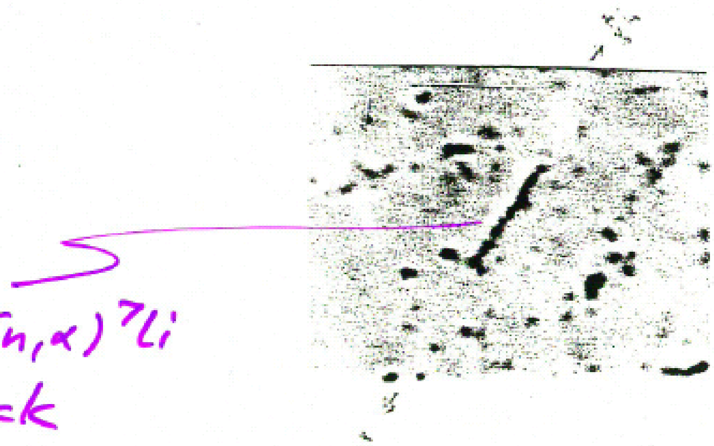
ECL: $(m_a + m_b)c^2 + T_a + T_b = (m_c + m_d)c^2 + T_c + T_d$

MCL: $\vec{p}_a + \vec{p}_b = \vec{p}_c + \vec{p}_d$

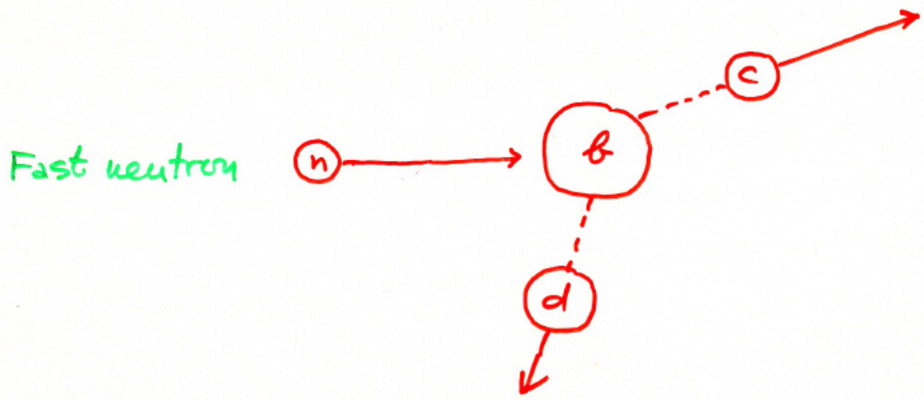
Cross section => efficiency

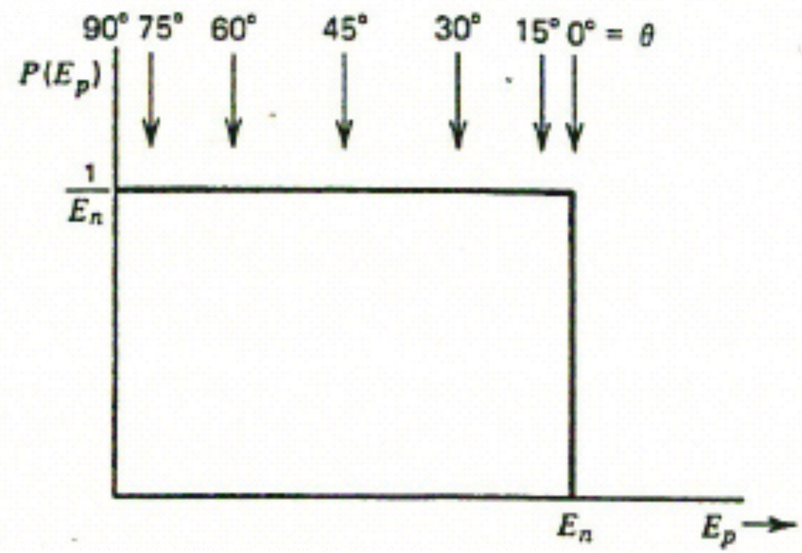
Slow neutron





$^{10}B(n,\alpha)^7Li$ track





Energy distribution of recoil protons E_n produced by monoenergetic neutrons.

Recoiled proton semiconductor spectrometer

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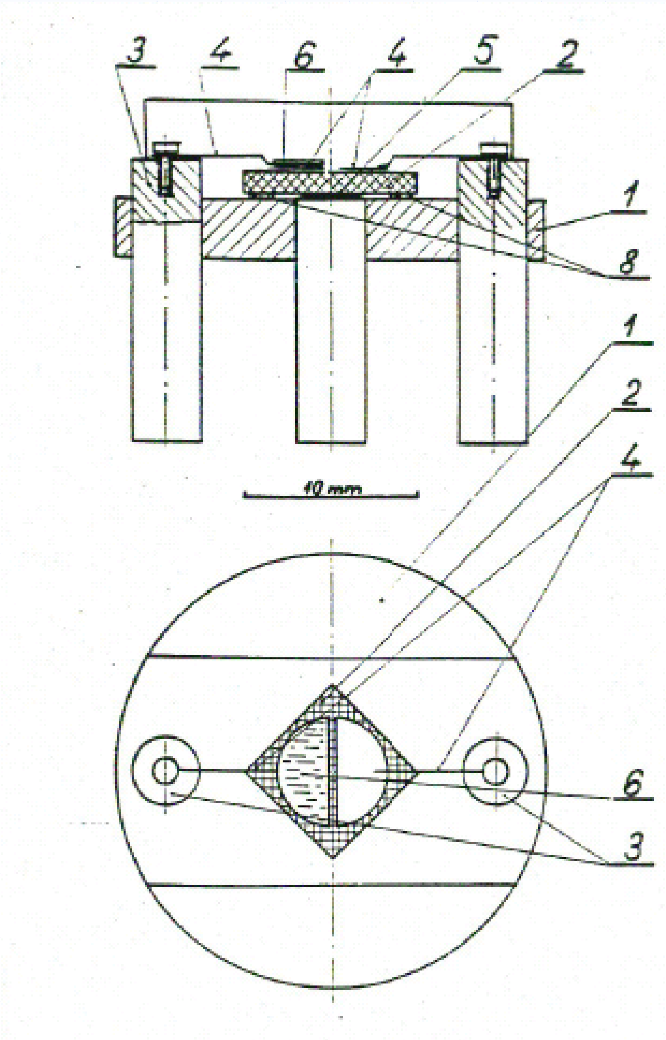

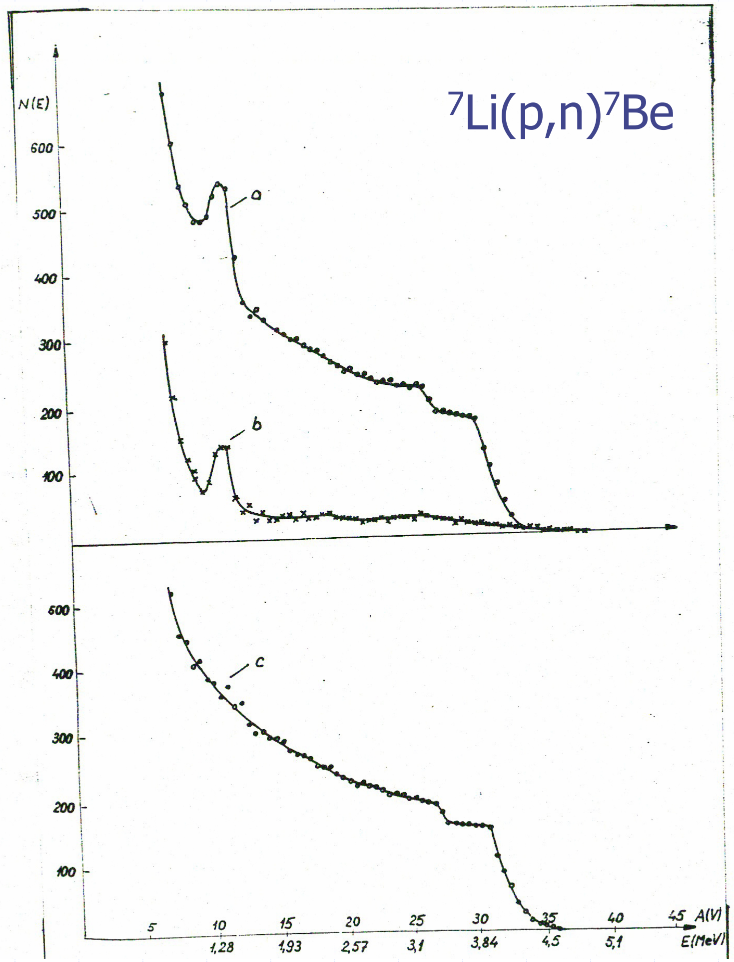

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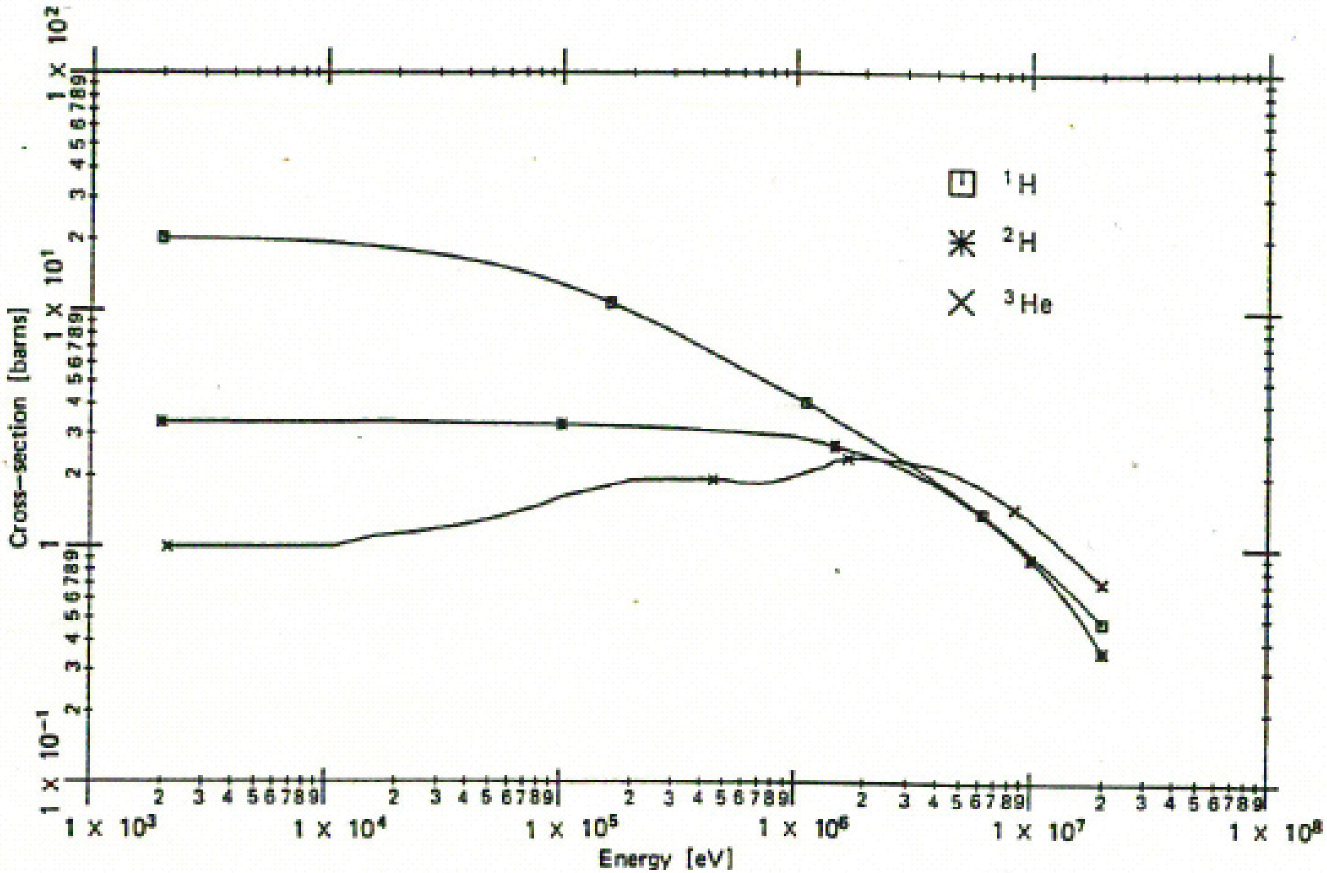


Elastic scattering cross sections for ^{1}H, ^{2}H, and ^{3}He.

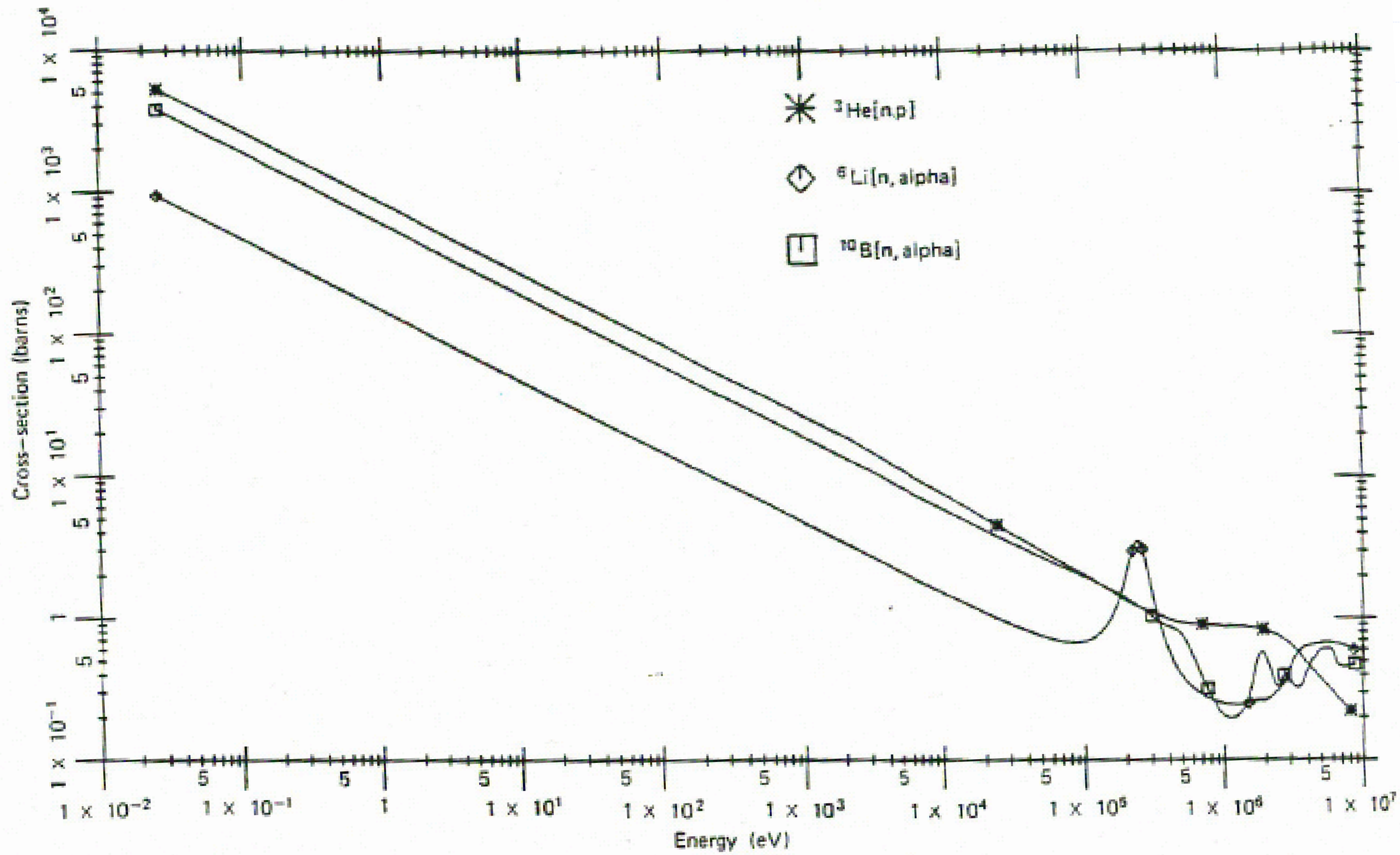
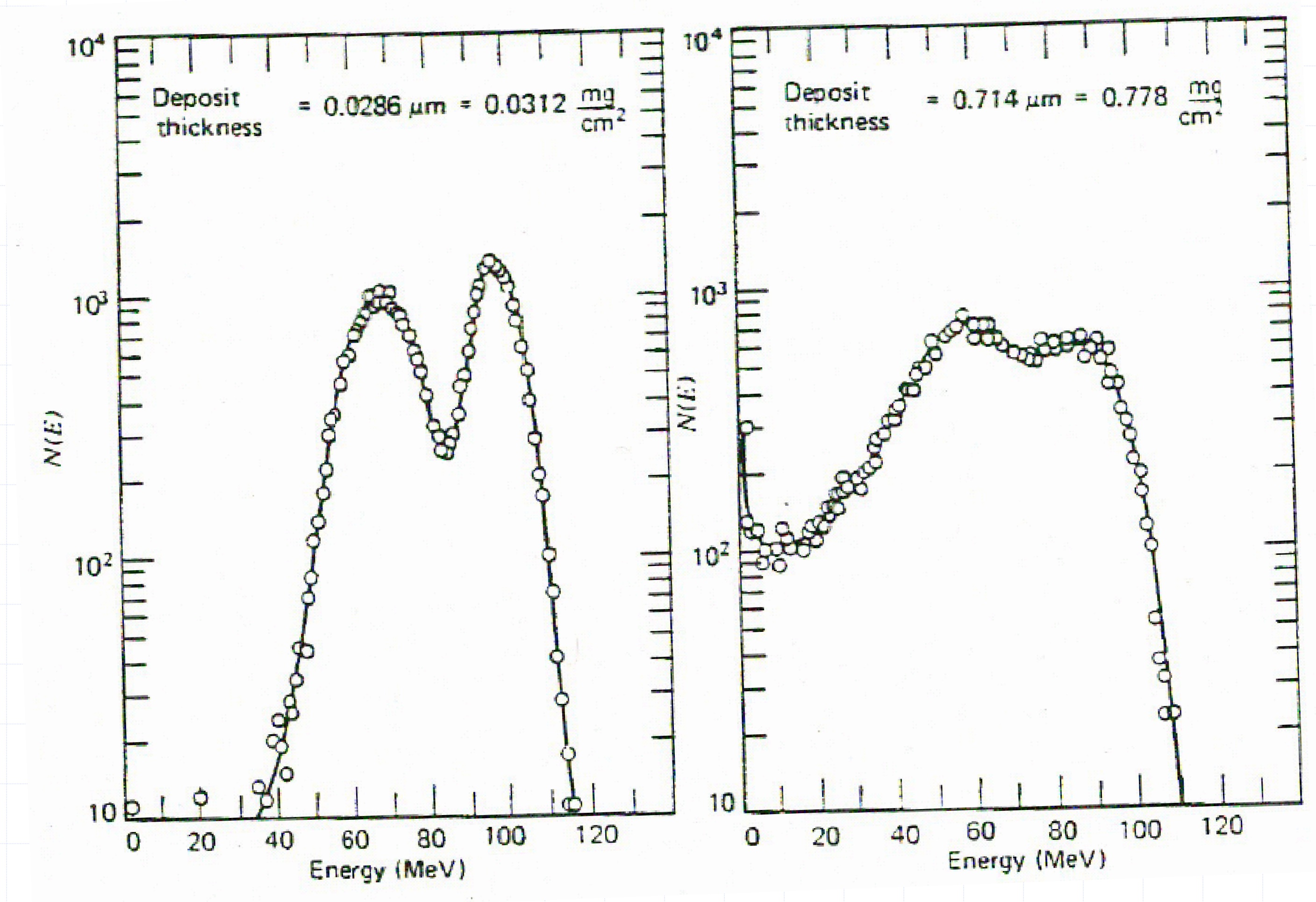


Figure 14.1 Cross section versus neutron energy for some reactions of interest in neutron detection.

Energies of fission fragments



Gamma spectrum from radiative capture of neutrons by ^{113}Cd

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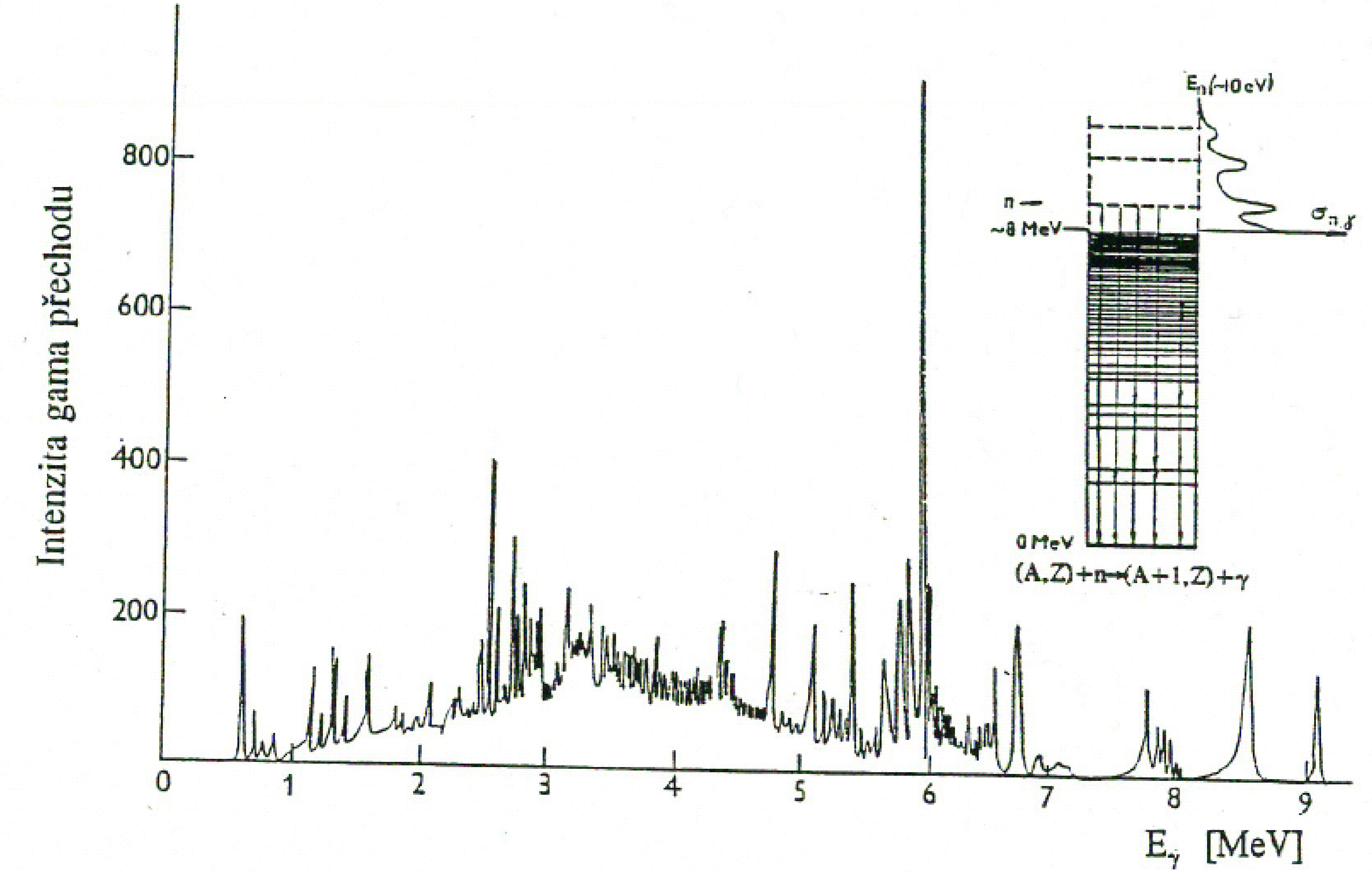
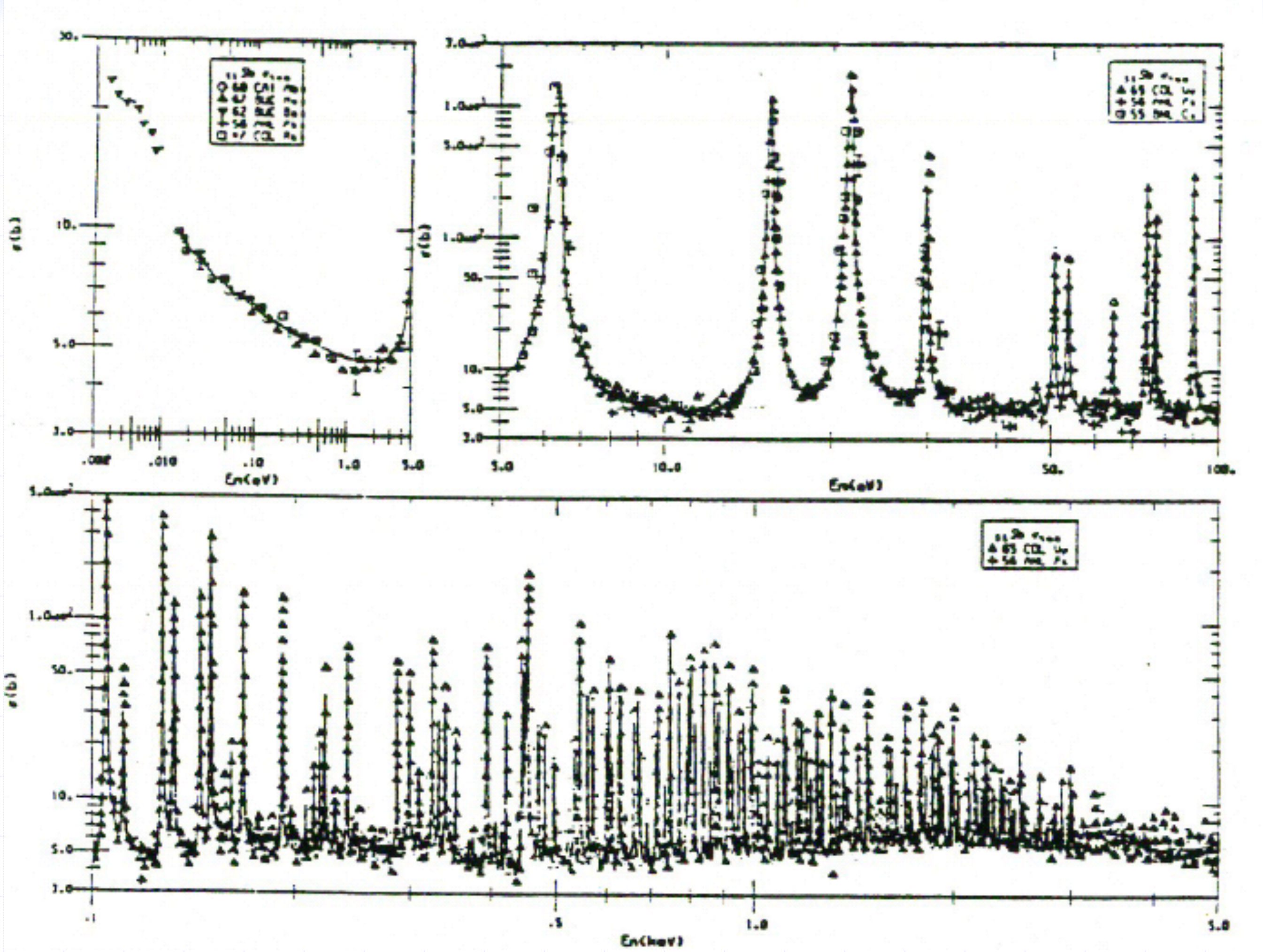


Total neutron cross section for Antimony below 5 keV



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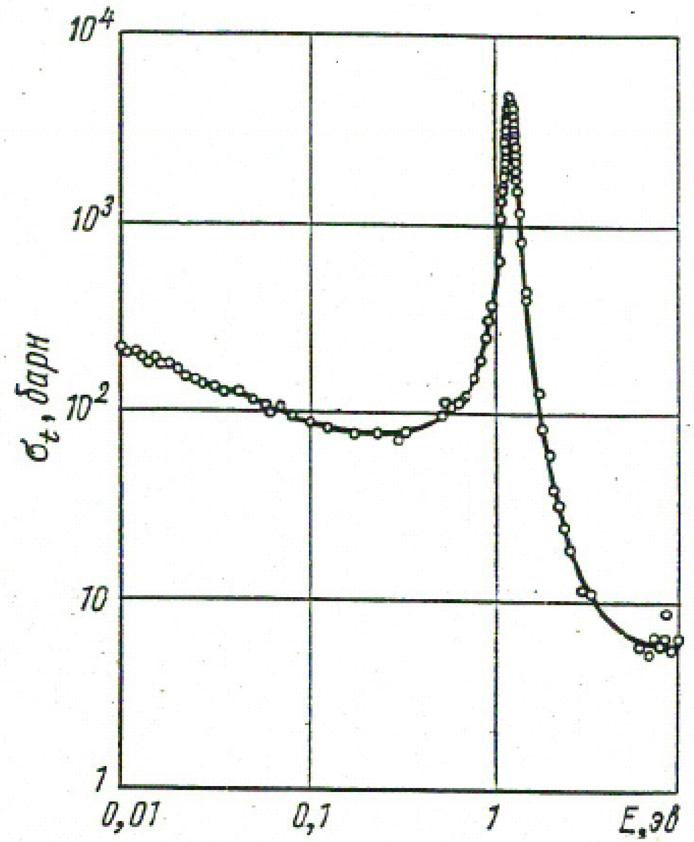
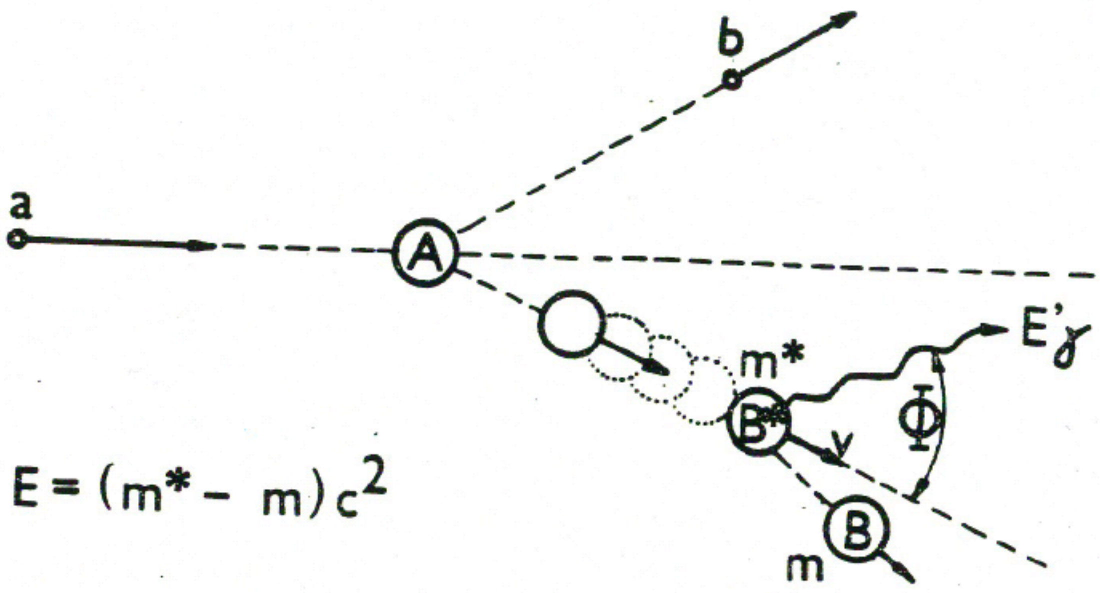
Breit-Wigner resonance (Rhodium)

$$\sigma_{n,\gamma}(E) = \pi \lambda\!\!\!^{-2} \frac{\Gamma_n \Gamma_\gamma}{(E - E_R)^2 + (\Gamma/2)^2}$$



Doppler effect in neutron induced reactions



$$a + A \rightarrow B^* + b$$
$$B^* \rightarrow B + \gamma$$

$$E'_\gamma = E\left(1 + \frac{v}{c}\cos\phi\right)$$

Doppler shift

Doppler broadening

Gamma spectrum of 241AmBe neutron source shielded by polyethylene moderator

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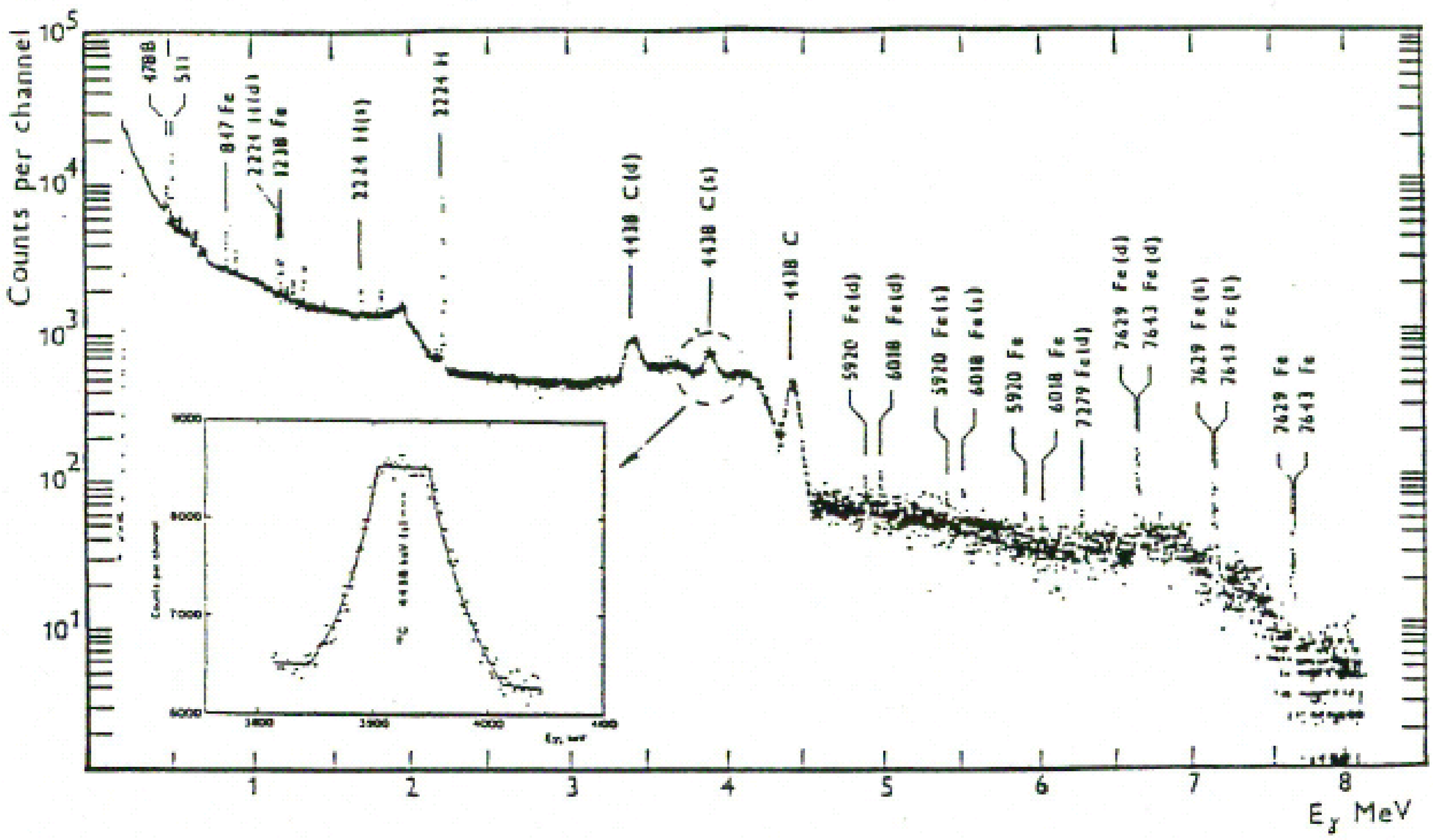

Neutron detection and spectroscopy

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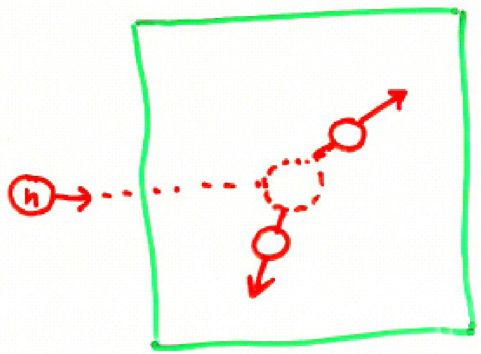
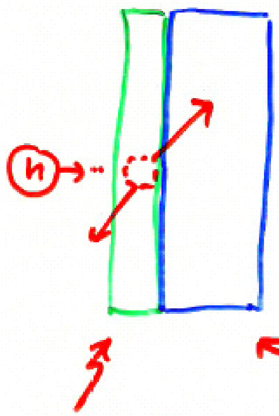
- conversion of neutron into charged particles or γ-rays

- detection of reaction products

- spectroscopy of reaction products

Activation foils - threshold reactions





conversion takes place in the sensitive volume of a detector

(scintillator, ionizing chamber)

converter layer (thickness)

sensitive volume of a detector

surface/volume ratio – wall effects

Responses to neutrons

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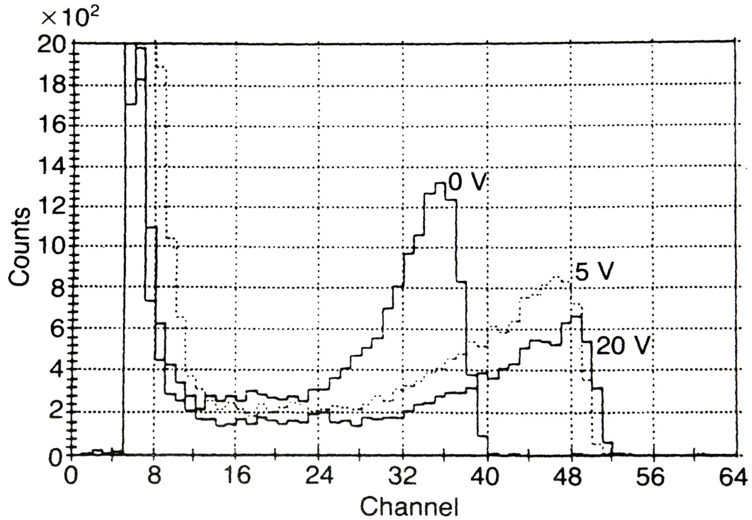
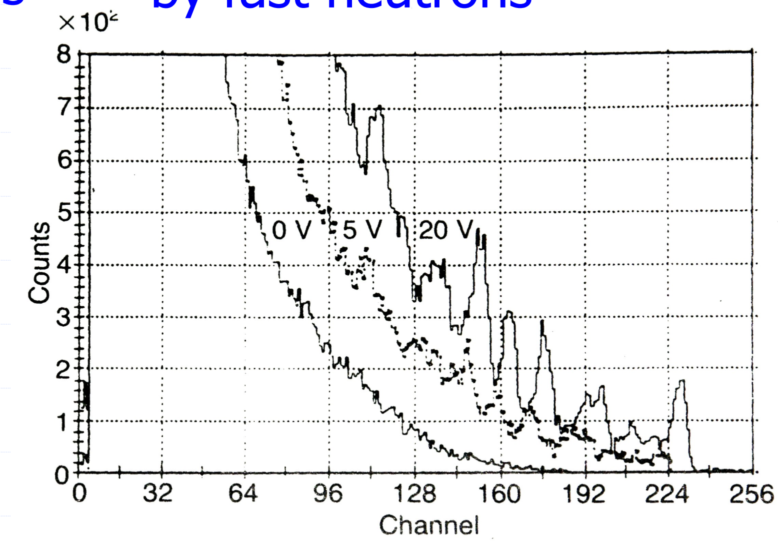
Silicon diode + ^{6}LiF converter
Illuminated by thermal neutrons



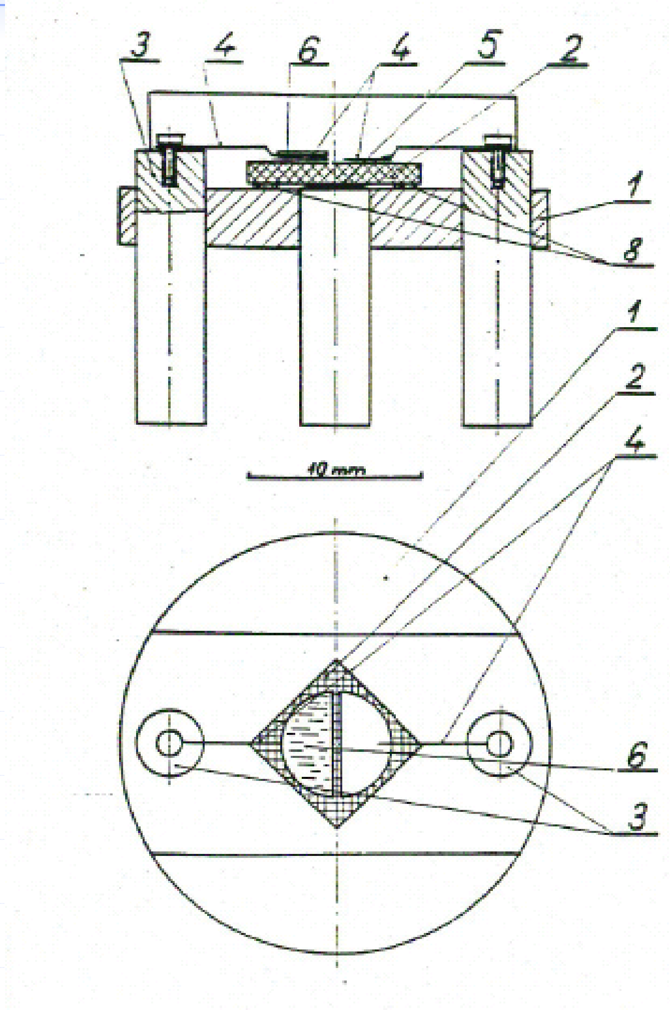
Pulse height distributions of neutron detector on thermal neutrons at different bias (0, 5, 20 V). Detector operates well in the self-biased regime.

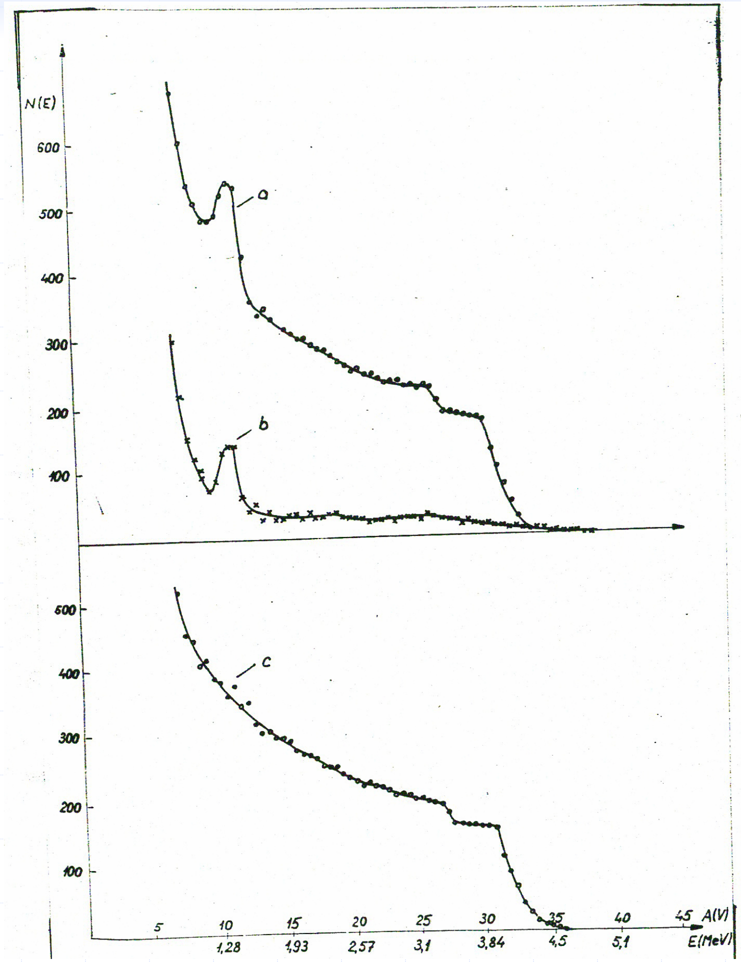
Silicon diode illuminated
by fast neutrons



Pulse height distributions of neutron detector when illuminated by fast neutrons (14.8 MeV) at different bias (0, 5, 20 V). Peaks from interaction of fast neutrons with ^{28}Si are clearly seen

Recoiled proton spectrometer based on Silicon Surface Barrier Detector
with 2 pixels (one covered by polyethylene converter)
Reproduced from SP's diploma thesis, Prague 1964





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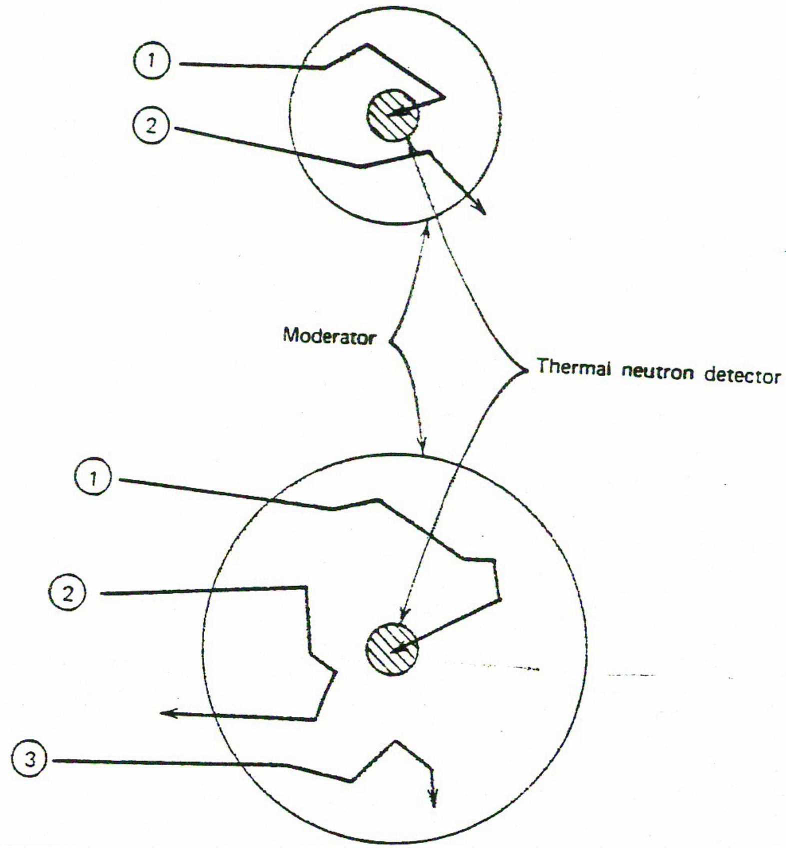
Bonner spectroscopy (indirect spectroscopy)



Capture gated fast neutron spectrometer of plastic scintillator loaded by 10B

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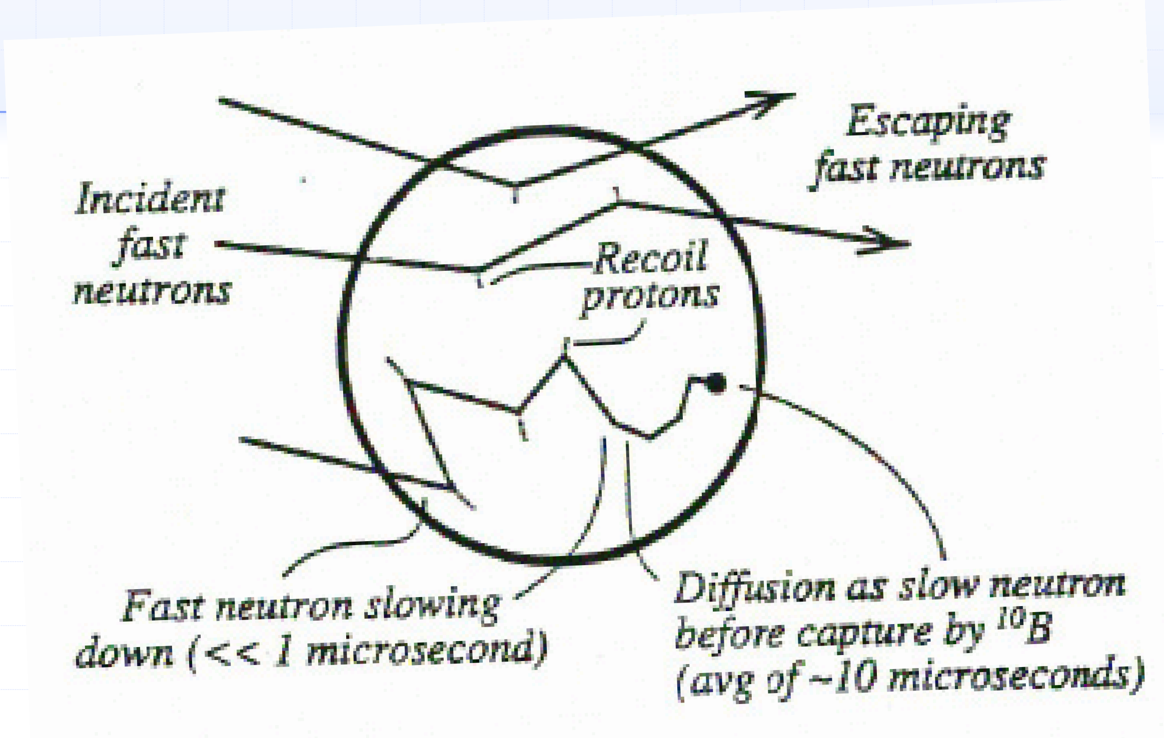

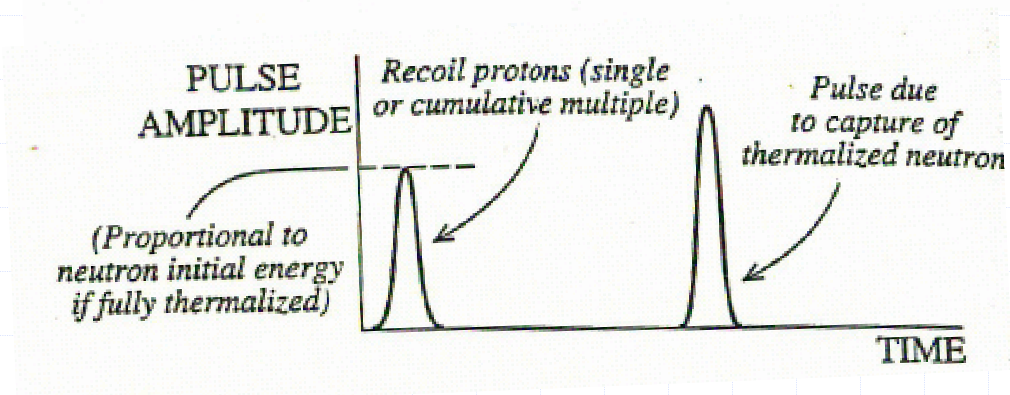

Applications of neutrons

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- Structure studies of materials based on wave properties (diffraction and scattering on crystallic materials of anorganic and organic origin, …) Investigation of elemental composition of materials:
  - Activation analysis
  - PNGA analysis (Geological survey / bore-hole logging, bulk ore processing)
  - Neutron Depth Profiling (NDP)
- Modification of semiconductor materials (transmutation of Si)
- Neutron imaging

Neutron imaging: neutron radiography and tomography

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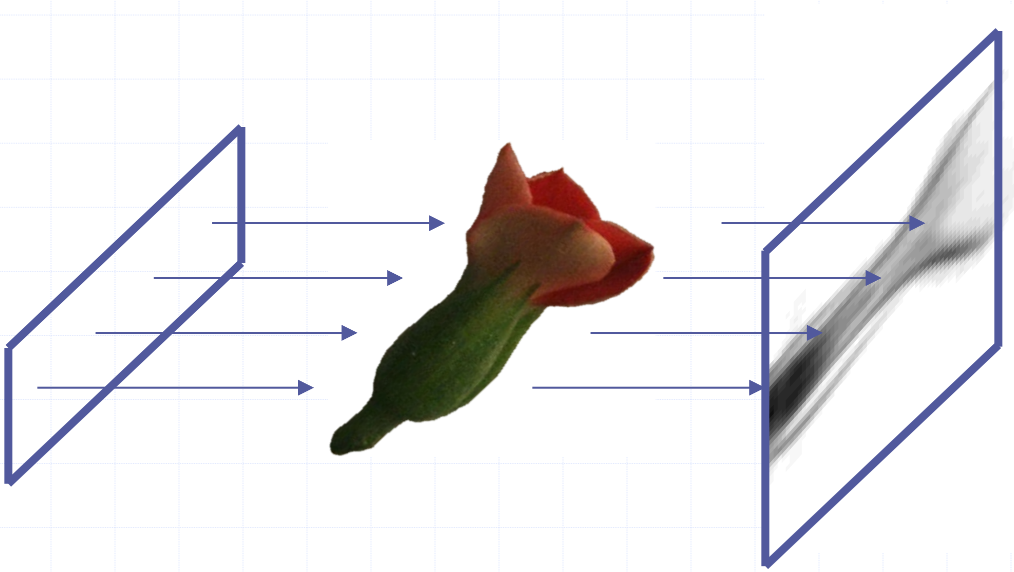
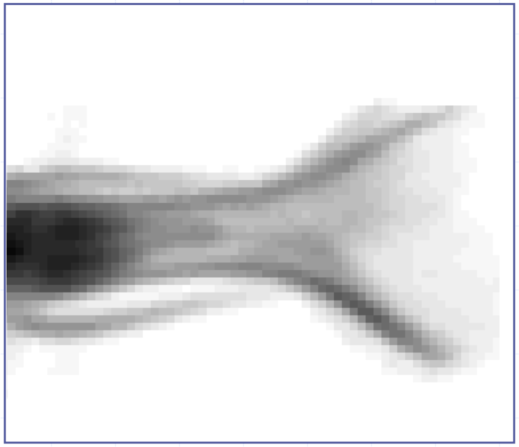


Parallel beam of thermal neutrons

Subject attenuating the beam

Shadow on a detector plane



Neutronogram

Why neutron radiography?

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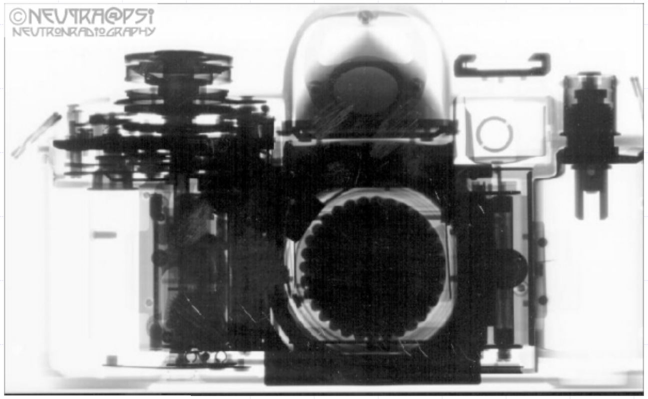
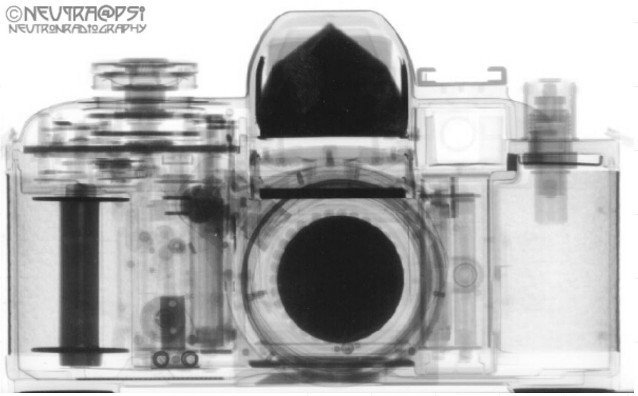
- While X-rays are attenuated more effectively by heavier materials like metals, neutrons allow to image some light materials such as hydrogenous substances with high contrast.
- Neutron radiography can serve as complementary technique to X-ray radiography



X-rays



Neutrons

In the X-ray image, the metal parts of the photo camera are seen clearly, while the neutron radiogram shows details of the plastic parts. Courtesy of PSI Neutra colleagues

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X-rays

Attenuation coefficients with X-ray [cm?^{1}]

1a	2a	3b	4b	5b	6b	7b	8			1b	2b	3a	4a	5a	6a	7a	0
H 0.02																	He 0.02
Li 0.06	Be 0.22											B 0.28	C 0.27	N 0.11	O 0.16	F 0.14	Ne 0.17
Na 0.13	Mg 0.24											Al 0.38	Si 0.33	P 0.25	S 0.30	Cl 0.23	Ar 0.20
K 0.14	Ca 0.26	Sc 0.48	Ti 0.73	V 1.04	Cr 1.29	Mn 1.32	Fe 1.57	Co 1.78	Ni 1.96	Cu 1.97	Zn 1.64	Ga 1.42	Ge 1.33	As 1.50	Se 1.23	Br 0.90	Kr 0.73
Rb 0.47	Sr 0.86	Y 1.61	Zr 2.47	Nb 3.43	Mo 4.29	Tc 5.06	Ru 5.71	Rh 6.08	Pd 6.13	Ag 5.67	Cd 4.84	In 4.31	Sn 3.98	Sb 4.28	Te 4.06	I 3.45	Xe 2.53
Cs 1.42	Ba 2.73	La 5.04	Hf 19.70	Ta 25.47	W 30.49	Re 34.47	Os 37.92	Ir 39.01	Pt 38.61	Au 35.94	Hg 25.88	Tl 23.23	Pb 22.81	Bi 20.28	Po 20.22	At	Rn 9.77
Fr	Ra 11.80	Ac 24.47	Rf	Ha													

Lanthanides	Ce 5.79	Pr 6.23	Nd 6.46	Pm 7.33	Sm 7.68	Eu 5.66	Gd 8.69	Tb 9.46	Dy 10.17	Ho 10.91	Er 11.70	Tm 12.49	Yb 9.32	Lu 14.07
*Actinides	Th 28.95	Pa 39.65	U 49.08	Np	Pu	Am	Cm	Bk	Vf	Es	Fm	Md	No	Lr x-ray

Legend

Attenuation coefficient [cm?^{1}] = sp.gr. * μ/δ

sp.gr.: Handbook of Chemistry and Physics, 56th Edition 1975-1976.

μ/δ: J. H. Hubbell[+] and S. M. Seltzer Ionizing Radiation Division, Physics Laboratory National Institute of Standards and Technology Gaithersburg, MD 20899, http://physics.nist.gov/PhysRefData/XrayMassCoef/tab3.html.

Thermal neutrons

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Attenuation coefficients with neutrons [cm?^{1}]

1a	2a	3b	4b	5b	6b	7b	8			1b	2b	3a	4a	5a	6a	7a	0
H 3.44																	He 0.02
Li 3.30	Be 0.79											B 101.60	C 0.56	N 0.43	O 0.17	F 0.20	Ne 0.10
Na 0.09	Mg 0.15											Al 0.10	Si 0.11	P 0.12	S 0.06	Cl 1.33	Ar 0.03
K 0.06	Ca 0.08	Sc 2.00	Ti 0.60	V 0.72	Cr 0.54	Mn 1.21	Fe 1.19	Co 3.92	Ni 2.05	Cu 1.07	Zn 0.35	Ga 0.49	Ge 0.47	As 0.67	Se 0.73	Br 0.24	Kr 0.61
Rb 0.08	Sr 0.14	Y 0.27	Zr 0.29	Nb 0.40	Mo 0.52	Tc 1.76	Ru 0.58	Rh 10.88	Pd 0.78	Ag 4.04	Cd 115.11	In 7.58	Sn 0.21	Sb 0.30	Te 0.25	I 0.23	Xe 0.43
Cs 0.29	Ba 0.07	La 0.52	Hf 4.99	Ta 1.49	W 1.47	Re 6.85	Os 2.24	Ir 30.46	Pt 1.46	Au 6.23	Hg 16.21	Tl 0.47	Pb 0.38	Bi 0.27	Po	At	Rn
Fr	Ra 0.34	Ac	Rf	Ha													

*Lanthanides	Ce 0.14	Pr 0.41	Nd 1.87	Pm 5.72	Sm 171.47	Eu 94.58	Gd 1479.04	Tb 0.93	Dy 32.42	Ho 2.25	Er 5.48	Tm 3.53	Yb 1.40	Lu 2.75
**Actinides	Th 0.59	Pa 8.46	U 0.82	Np 9.80	Pu 50.20	Am 2.86	Cm	Bk	Cf	Es	Fm	Md	No	Lr neut.

Legend

$$\text{Attenuation coefficient [cm?}^{1}\text{]} = \frac{\sigma\text{-total} * \text{sp.gr.} * 0.6023}{\text{at.wt.}}$$

σ-total: JEF Report 14, TABLE OF SIMPLE INTEGRAL NEUTRON CROSS SECTION DATA FROM JEF-2.2, ENDF/B-VI, JENDL-3.2, BROND-2 AND CENDL-2, AEN NEA, 1994.
and Special Feature: Neutron scattering lengths and cross sections, Varley F. Sears, AECL Research, Chalk River Laboratories Chalk River, Ontario, Canada KOJ 1JO, Neutron News, Vol. 3, 1992, http://www.ncnr.nist.gov/resources/n-lengths/list.html.

sp.gr.: Handbook of Chemistry and Physics, 56th Edition 1975-1976.

at.wt.: Handbook of Chemistry and Physics, 56th Edition 1975-1976.

Medipix-2 device

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Silicon pixel detector can not detect neutrons directly.
⇒ Conversion of thermal neutrons to detectable radiation in a converter layer deposited on the detector surface.

Converter materials:

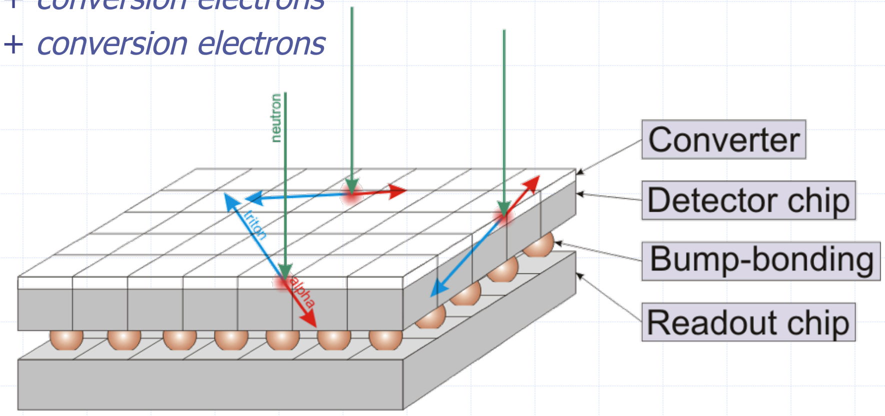
^{6}Li: $^{6}Li + n \rightarrow \alpha$ (2.05 MeV) + ^{3}H (2.72 MeV) σ = 940 barn

^{10}B: $^{10}B + n \rightarrow \alpha$ (1.47 MeV) + ^{7}Li (0.84 MeV) + γ (0.48MeV) (93.7%)
$^{10}B + n \rightarrow \alpha$ (1.78 MeV) + ^{7}Li (1.01 MeV) σ = 3840 barn (6.3%)

^{113}Cd: $^{113}Cd + n \rightarrow {}^{114}Cd + \gamma$ (0.56MeV) + *conversion electrons*

^{155}Gd: $^{155}Gd + n \rightarrow {}^{156}Gd + \gamma$ (0.09, 0.20, 0.30 MeV) + *conversion electrons*
^{157}Gd: $^{157}Gd + n \rightarrow {}^{158}Gd + \gamma$ (0.08, 0.18, 0.28 MeV) + *conversion electrons*

Detector:
300 μm thick silicon pixel detector (pixel size 55 μm) bump bonded to Medipix-2 readout chip.



Spatial resolution estimation

Spatial resolution is affected by:

- Range of heavy charged particles in converter material – depends on density

  ^{6}LiF (ρ=1.6 g/cm^{3}): R_{Triton}=52μm, R_{α}=10μm

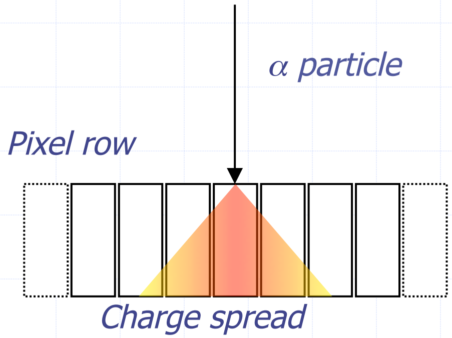
  ^{10}B (r=1.2 g/cm^{3}): R_{Li}=5μm, R_{a}=7μm

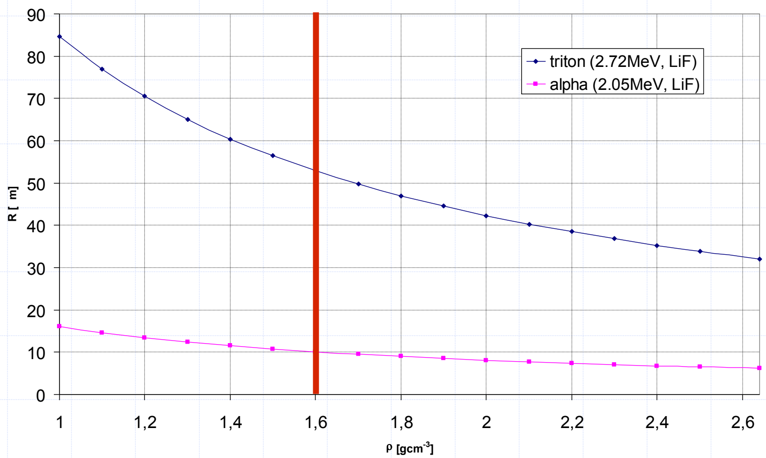
- Range in silicon

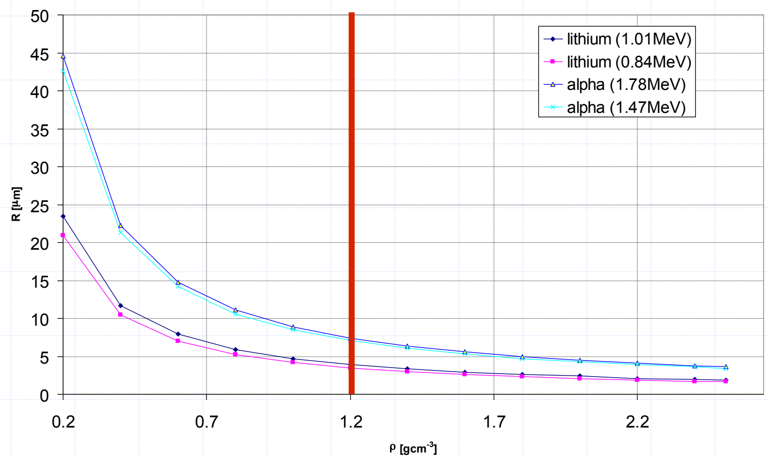
  ^{6}LiF: R_{Triton}=44.1μm, R_{α}=8.6μm.

  ^{10}B: R_{Li}=3μm / 2.7μm, R_{α}=5.4μm / 5.2μm

- Charge sharing effect ?







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Tests with Thermal Neutrons

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- NEUTRA station of spallation neutron source SINQ in Paul Scherrer Institute, Villigen, Switzerland
  - Intensity about $3 \cdot 10^6$ neutrons/cm^{2}s at proton accelerator current of 1mA and proton energy of 590 MeV
  - Beam Cross section: 40 cm in diameter

- Horizontal channel of the LVR-15 nuclear research reactor at Nuclear Physics Institute of the Czech Academy of Sciences at Rez near Prague.
  - Intensity is about 10^7 neutrons/cm^{2}s (at reactor power of 8MW)
  - Beam Cross section: 4 mm (height) x 60 mm (width)
  - The divergence of the neutron beam is < 0.5°

Flower behind Al plate

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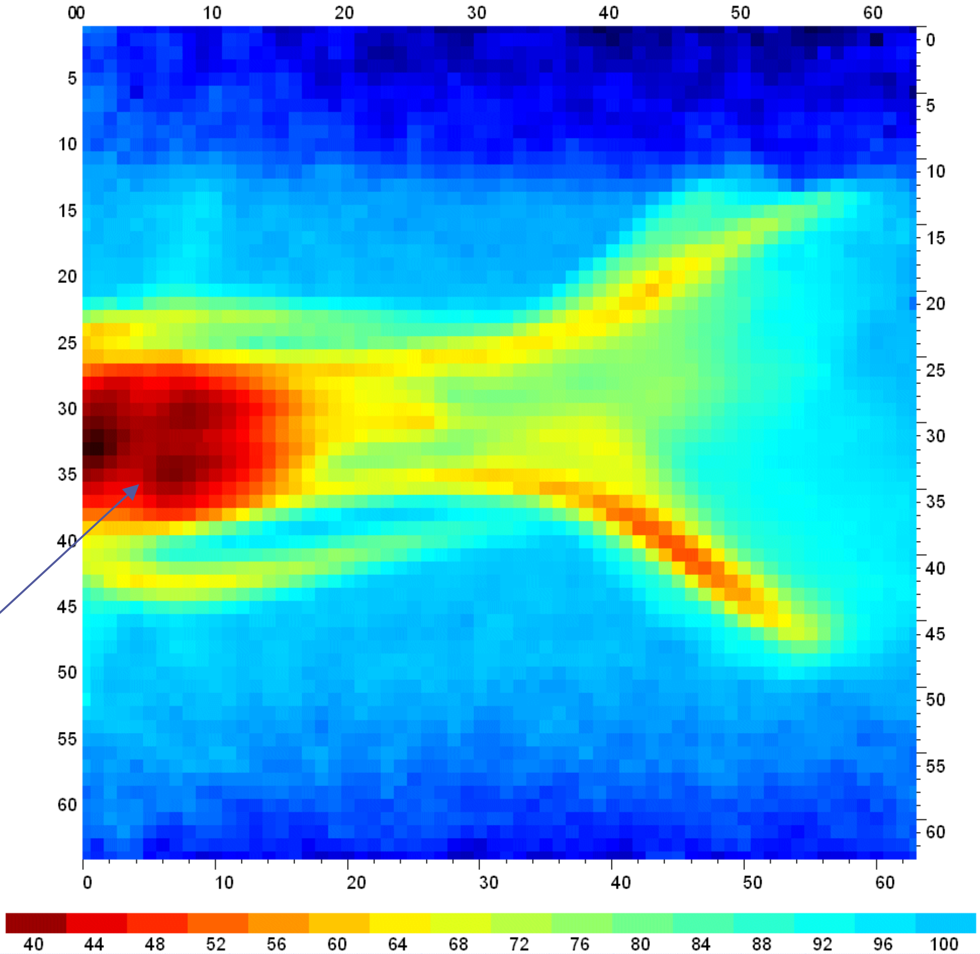
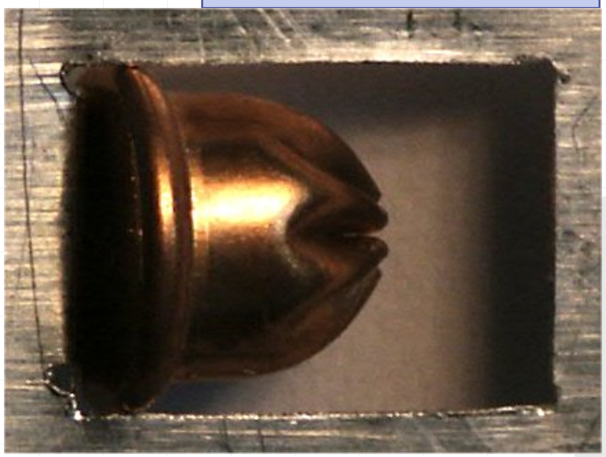
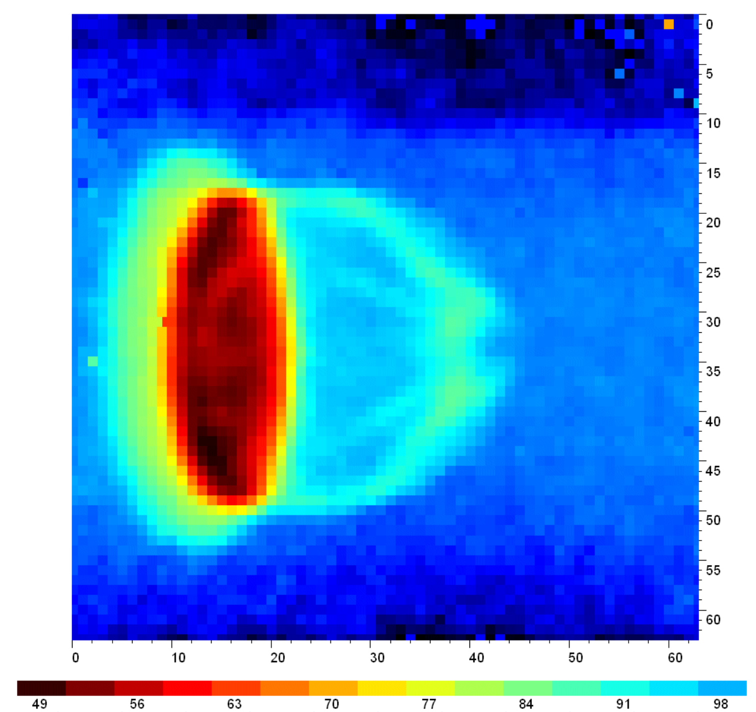


Look through metals!

Photography



Roentgenogram



Blank shell (cartridge)

Explosive filling

3D reconstructions

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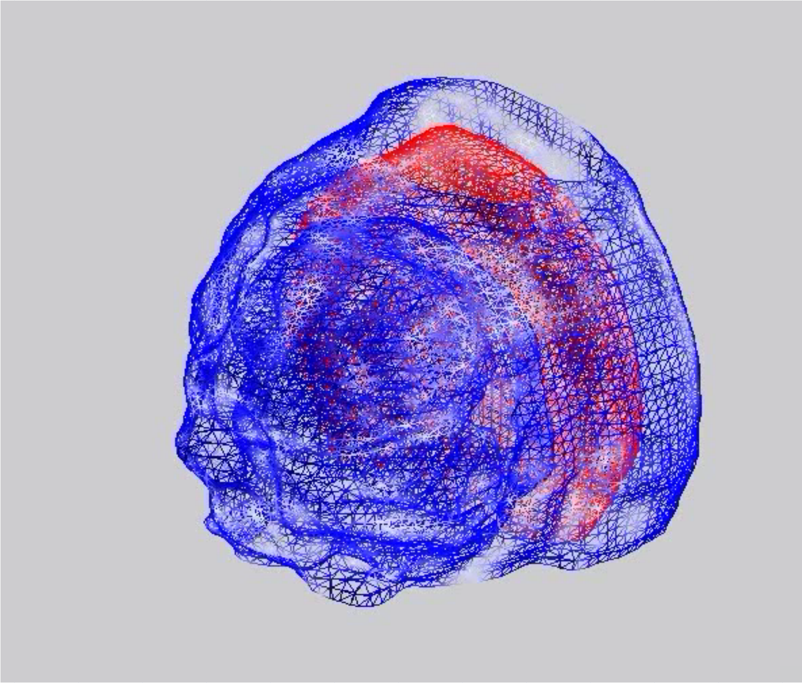
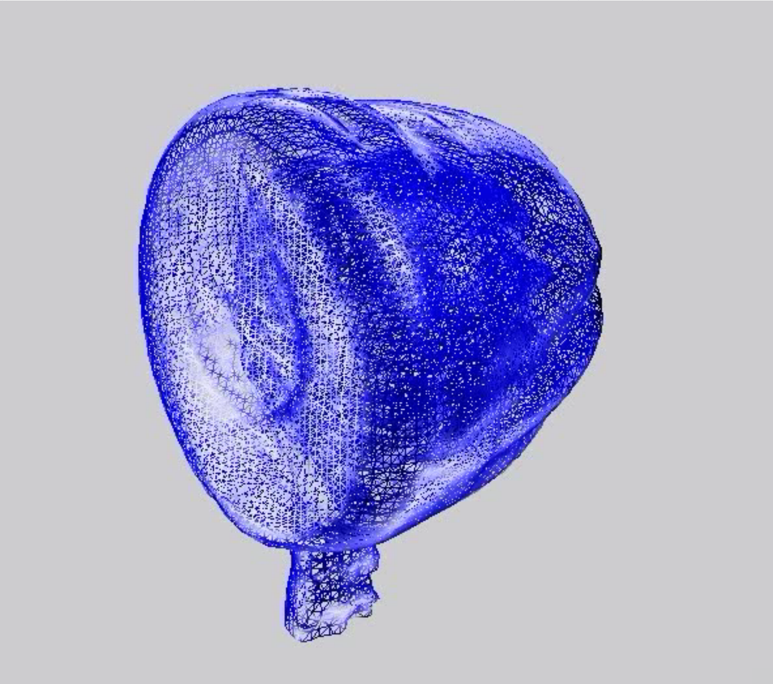
3D reconstruction - neutron



3D reconstruction – X-ray



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Thank you for your attention!