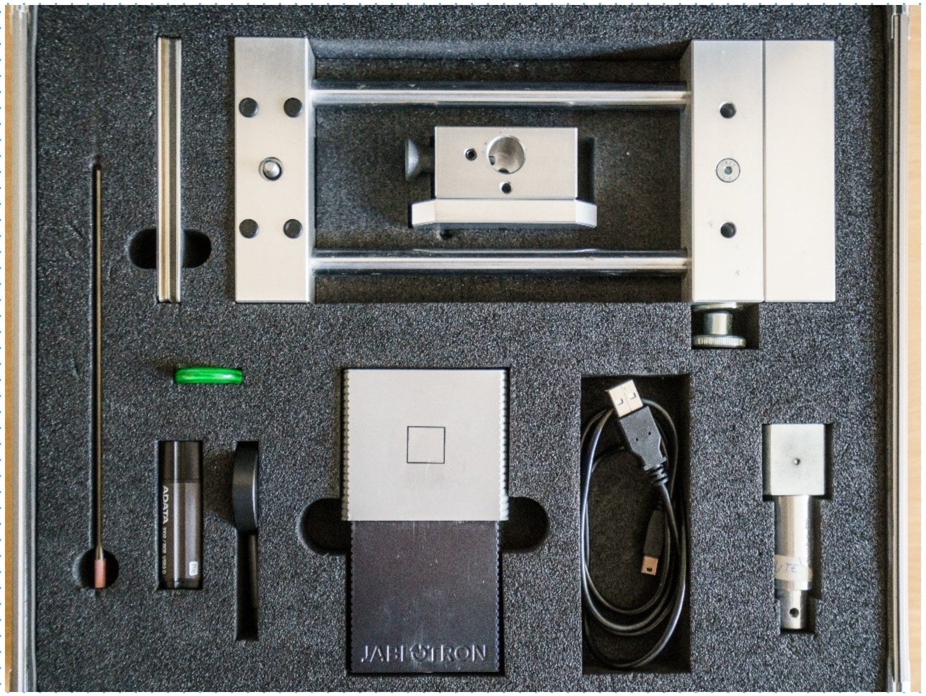
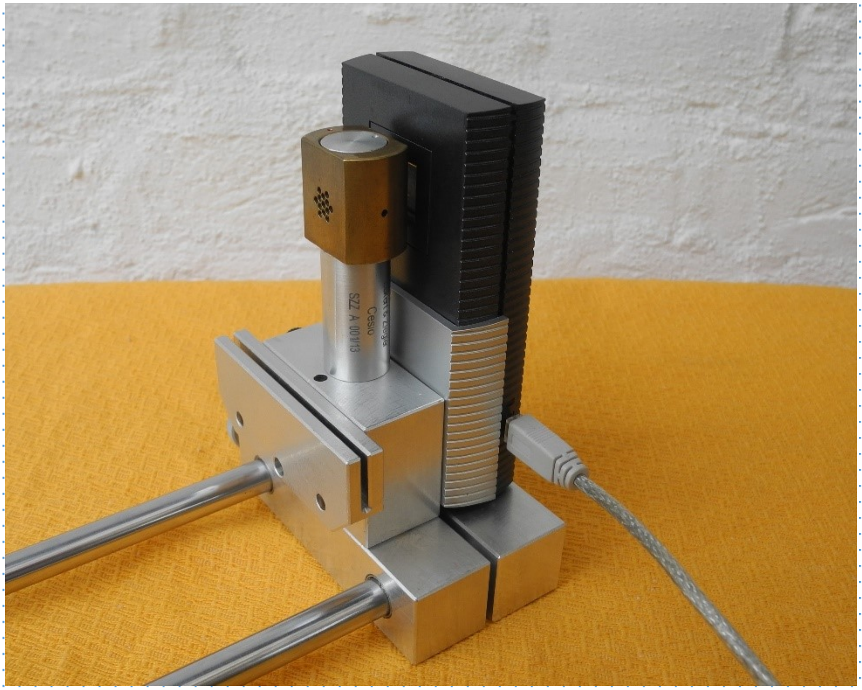
Detection of Neutrons Using Pixel Detector





Vladimir Vicha, Michael Holik, IEAP CTU Prague

Virtual IEEE NPSS Workshop on Applications of Radiation Instrumentation, Dakar 2020

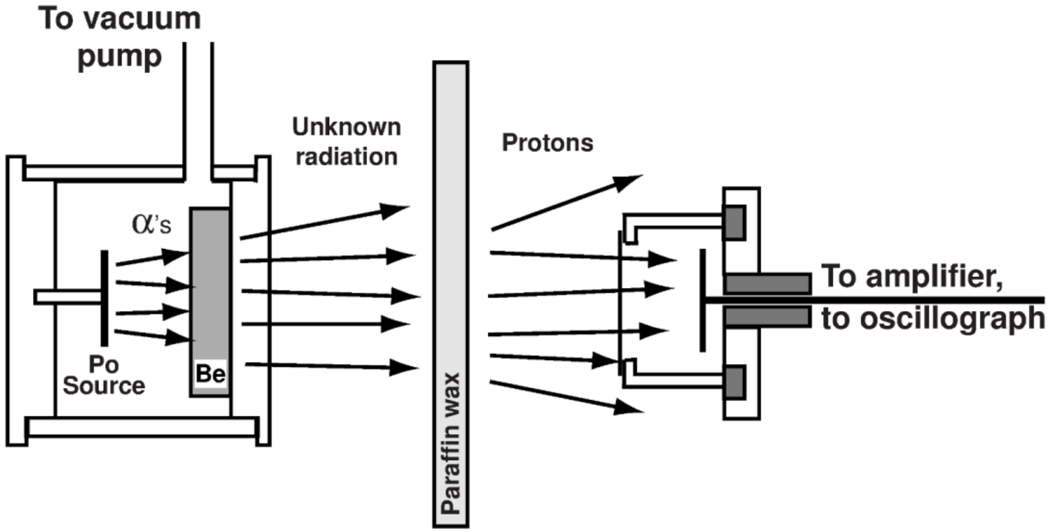
How to get free neutrons?

1931 Walther Bothe a Herbert Becker

Neutrons have not been known yet.

Beryllium exposed to alfa radiation (Po) → "beryllium radiation" (photons?)   He + Be → ??

1932 James Chadwick – ability of "beryllium radiation" to recoil protons from paraffin – neutron discovery



$$^{4}_{2}He + ^{9}_{4}Be \rightarrow ^{12}_{6}C + ^{1}_{0}n,$$

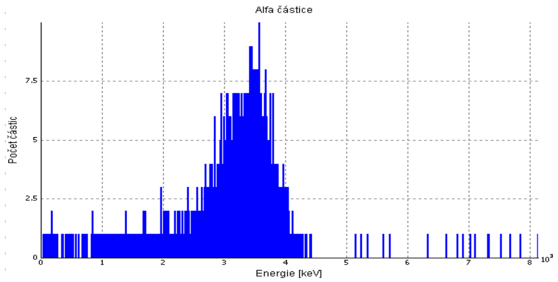
Bdushaw, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=6398200

How to get free neutrons?

AmBe – neutron source

$$^{241}_{95}Am \rightarrow {}^{237}_{93}Np + {}^{4}_{2}He$$

E (He) = 5,5 MeV, E_{γ}= 60 keV (max)

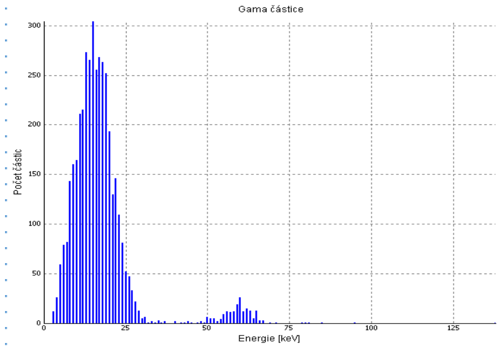


$$^{4}_{2}He + {}^{9}_{4}Be \rightarrow {}^{12}_{6}C + {}^{1}_{0}n$$

E_{max} (n)= 11,1 MeV

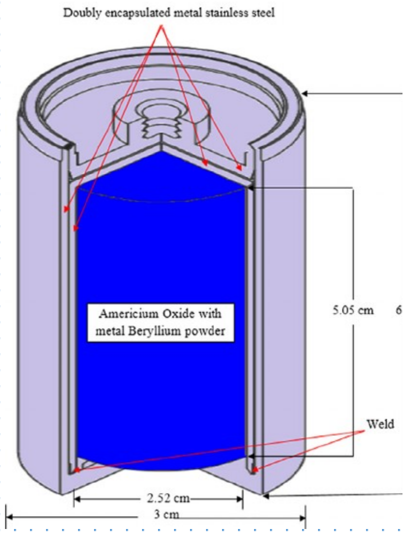
$$^{4}_{2}He + {}^{9}_{4}Be \rightarrow {}^{12}_{6}C + {}^{1}_{0}n + \gamma$$

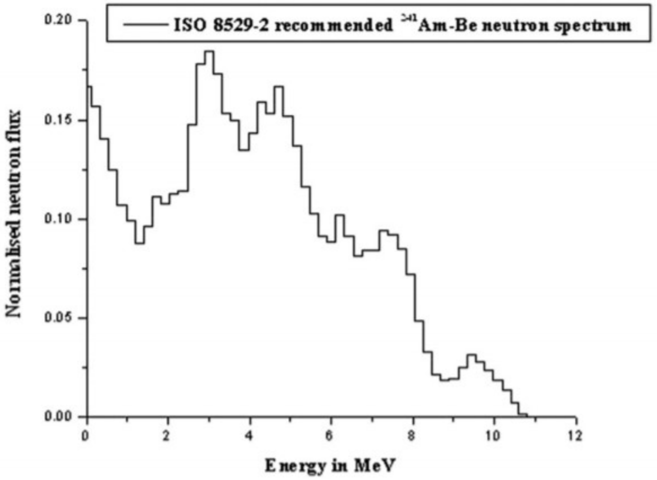
E_{max} (n) = 6,4 MeV, E_{γ}= 4,4 MeV



10 000 alpha particles is needed for generation of 1 neutron

Exemplar AmBe source with activity A = 1 Ci = $3{,}7.10^{10}$ Bq produces about ~10^{6} neutrons per second





https://www.researchgate.net/publication/285711386_Calculating_the_ambient_dose_equivalent_of_fast_neutrons_using_elemental_composition_of_human_body

Pujala, Usha, Selvakumaran, T.S., Mohapatra, D.K., Raja, E. Alagu, Subbaiah, K.V., Baskaran, R. "Analysis of Neutron Streaming Through the Trenches at LINAC Based Neutron Generator Facility, IGCAR." Indian Association for Radiation Protection, 34(2011):262-266.

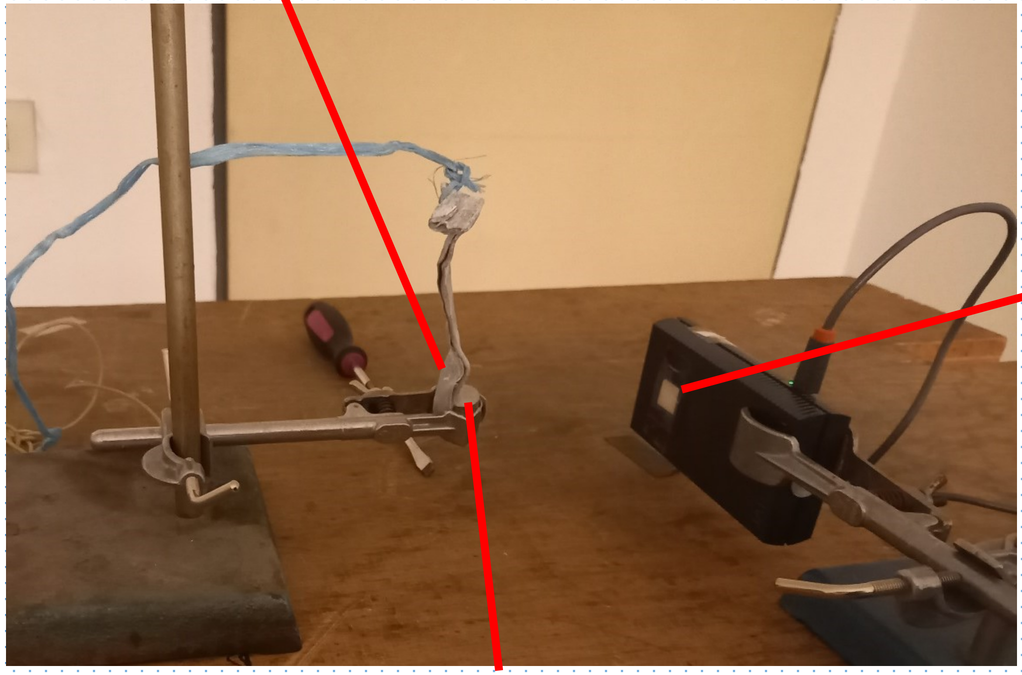
Is it possible to detect neutrons directly with silicon detectors?

Energy of reaction of neutron with Silicon is negative
The minimal threshold energy E_{thr} is needed to let the reaction to happen

	Q (MeV)	E_{thr} (MeV)	E_{max} (MeV) products
${}^{1}_{0}n + {}^{28}_{14}Si \rightarrow {}^{25}_{12}Mg + {}^{4}_{2}He$	-2,65	2,75	8,21
${}^{1}_{0}n + {}^{28}_{14}Si \rightarrow {}^{28}_{13}Al + {}^{1}_{1}p$	-3,86	4,00	7,22

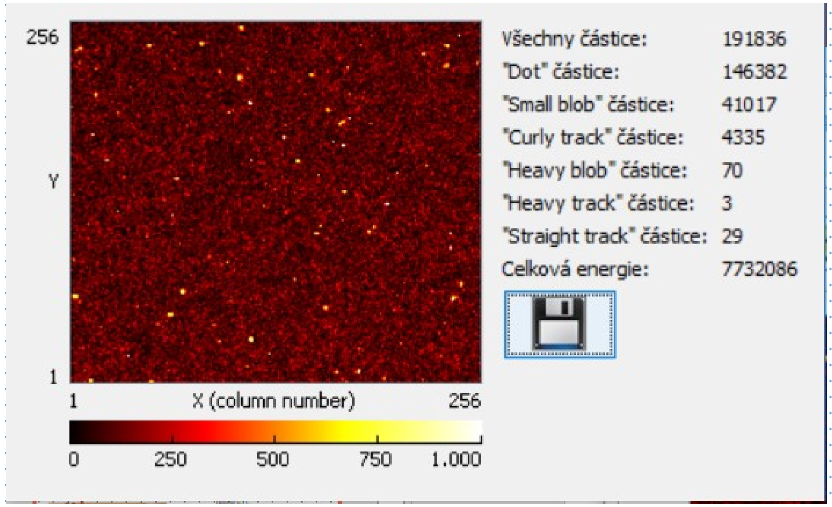
AmBe source provides fast neutrons with energies up to 11 MeV
The minimal threshold energy is lower than max energy of emitted fast neutrons
Therefore reaction of neutrons with Silicon is realistic.
The Si sensor can detect produced alphas and protons.

Detection of Fast Neutrons



Bare MX-10 sensor
AmBe source inside Pb cover is placed in distance 12 cm
Frame exposition time 0.1 s
Frame count 2400
Total measurement time 4 minutes

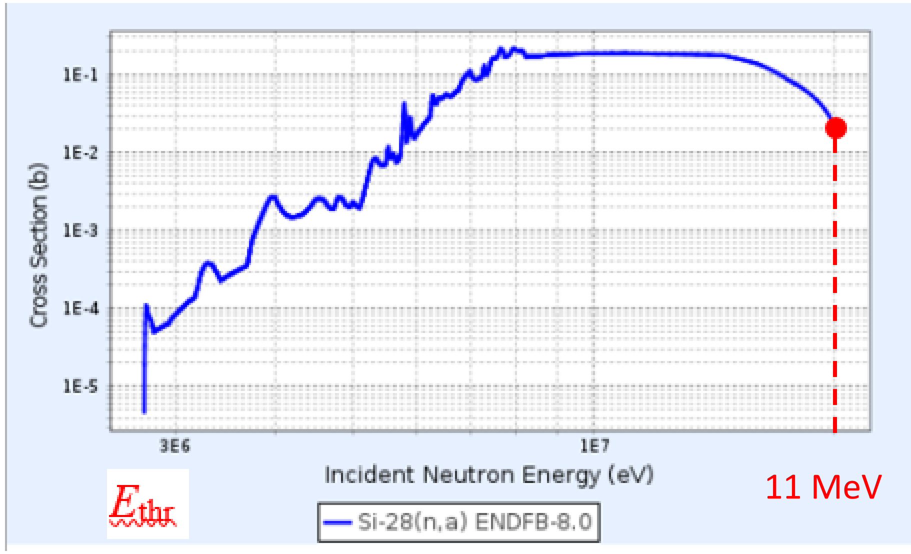
Videoclip 9

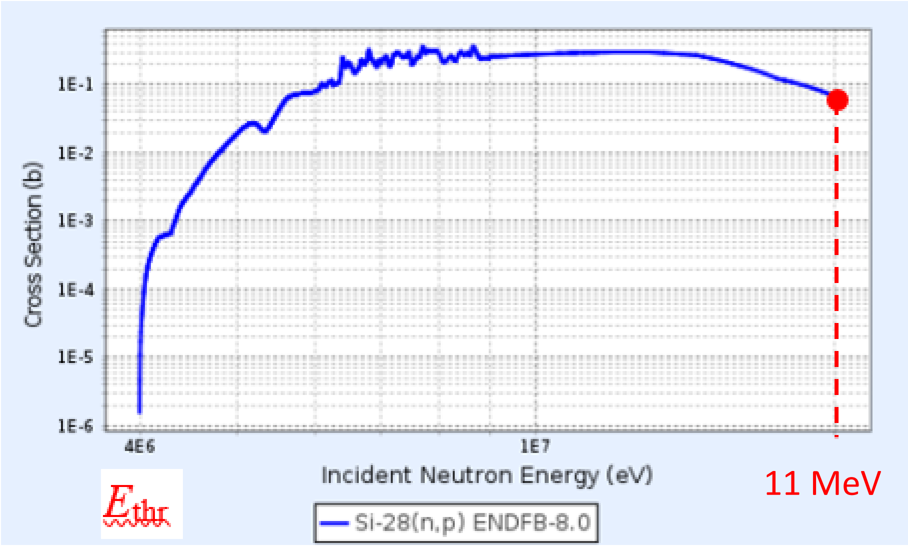


Extended particle recognition analysis is used.
Tracks created by heavy charged ions are classified as “Heavy Blobs”.

Microscopic cross section σ

Microscopic cross-section σ, interaction probability, significantly depends on energy of neutron and kind of the targeting nucleus.
Value is stated in barns (marked b)
1 b = 10^{-28} m^2





$${}_{0}^{1}n + {}_{14}^{28}Si \rightarrow {}_{12}^{25}Mg + {}_{2}^{4}He$$

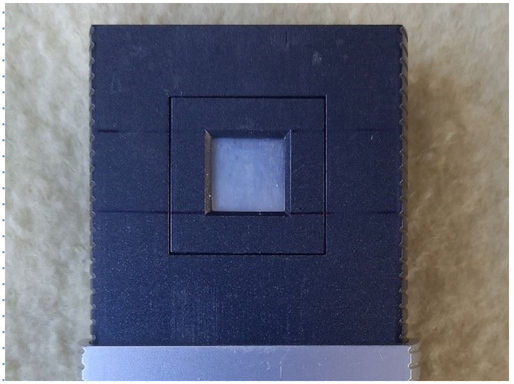
at 11 MeV je $\sigma \approx 0{,}02$ b

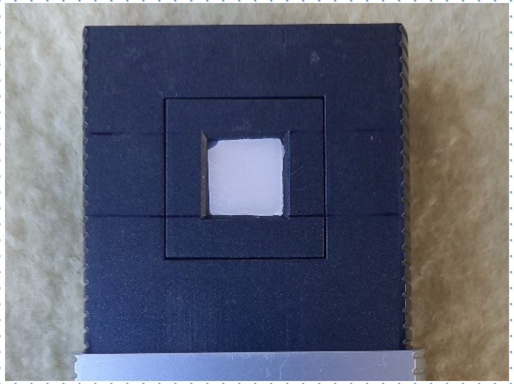
$${}_{0}^{1}n + {}_{14}^{28}Si \rightarrow {}_{13}^{28}Al + {}_{1}^{1}p$$

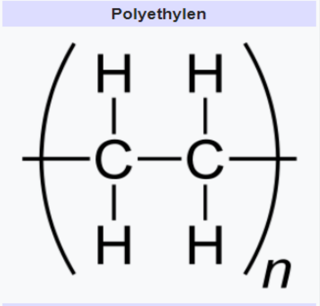
at 11 MeV je $\sigma \approx 0{,}06$ b

Considering entire spectrum of AmBe generated neutrons the maximal cross section value reaches 0.3b

Paraffin as a Neutron Convertor

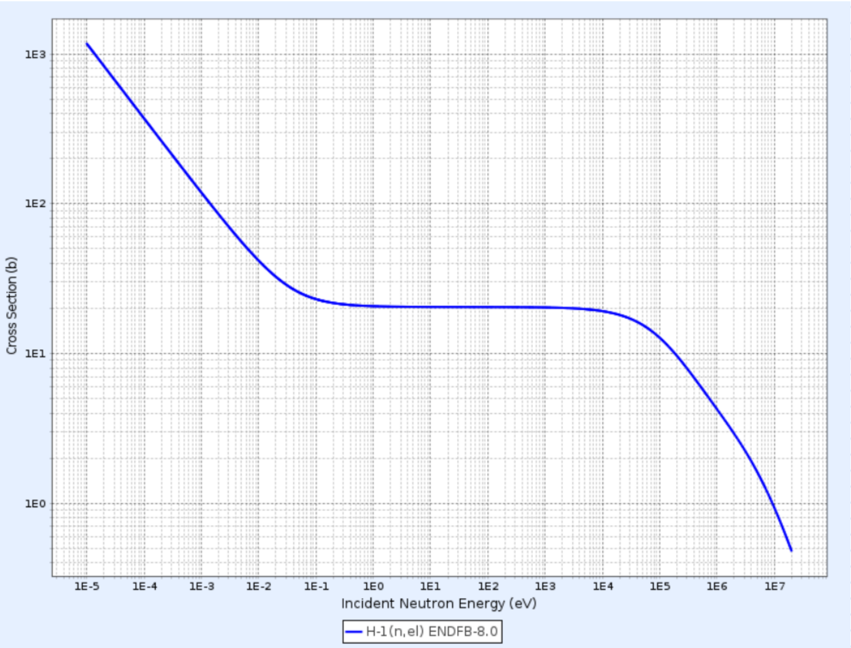




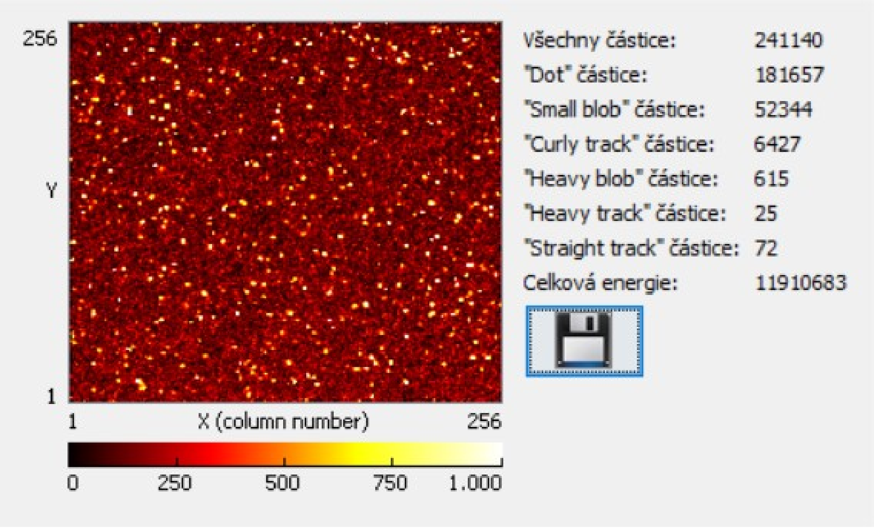


Left – bare silicon sensor MX-10 without any converter   Right – MX-10 assembled with paraffin converter

Effective cross-section for elastic scattering neutron for ^{1}H at energies in MeV order is $\sigma = 20$ b.



Videoclip 10



Thermalized neutrons interact with significantly higher probability

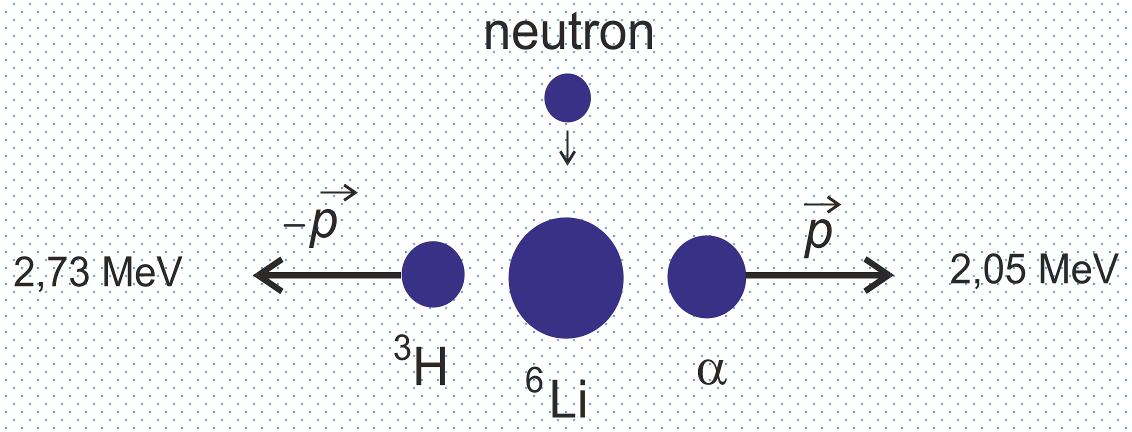
When neutrons get slowed down and original fast neutrons become thermal neutrons then effective cross section of reaction with light nuclei like lithium and boron increases significantly

	1 MeV	0.025 eV
Targeting Nucleus	σ [b]	σ [b]
^{6}Li	1.28	938
^{10}B	2.68	3845

Neutron hydrogen nucleus scattering can be modelled with “Newton's cradle”, i.e. collision of two balls with the same mass.
Impacting ball (neutron) gets stopped if target ball is centrally hit. The targeting ball (hydrogen nucleus) starts to move with speed of the impacting ball.
If the target is not hit centrally then the impacting ball keeps on moving with partially reduced speed and energy. After several consequent collisions, energy of free neutron is reduced down to the level of surrounding atoms determined by temperature.
Materials that effectively slow down fast neutrons are called **moderators**. These materials are often rich in hydrogen concentration, e.g. paraffin, polyethylene, water…

Reaction of neutrons with lithium ^{6}Li nuclei

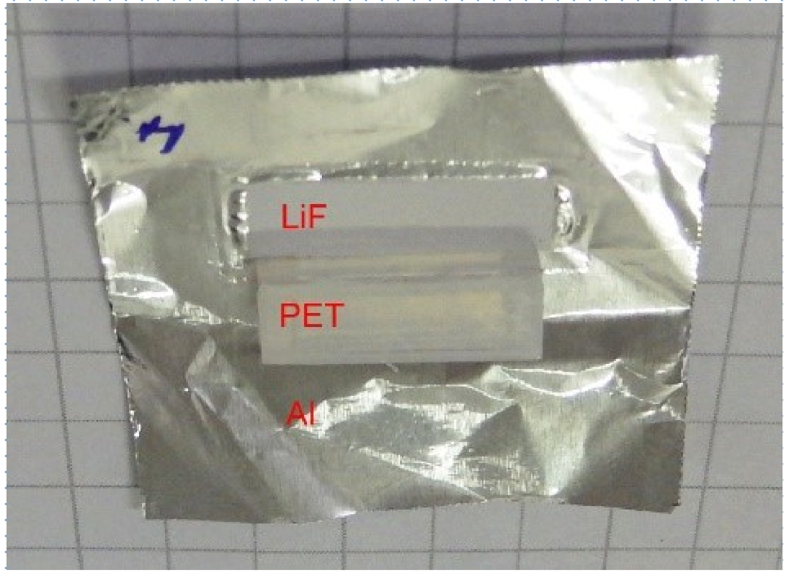
$$^{6}_{3}\mathrm{Li} + ^{1}_{0}\mathrm{n} \rightarrow ^{4}_{2}\alpha + ^{3}_{1}\mathrm{H}$$

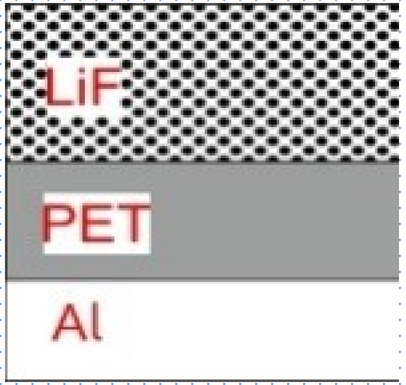


Energy of reaction is positive Q = +4.78 MeV (there is no minimal threshold energy)
Tritium product nucleus shares 2.73 MeV and alpha particle product shares 2.05 MeV from released energy
Reaction products have the same momentum but directed oppositely
Products, charged ions, can be registered by the pixel detector

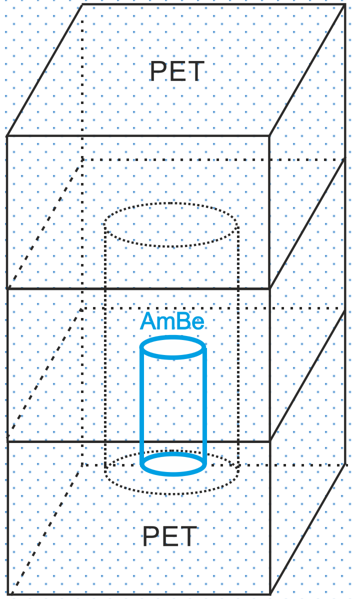
LiF Converter

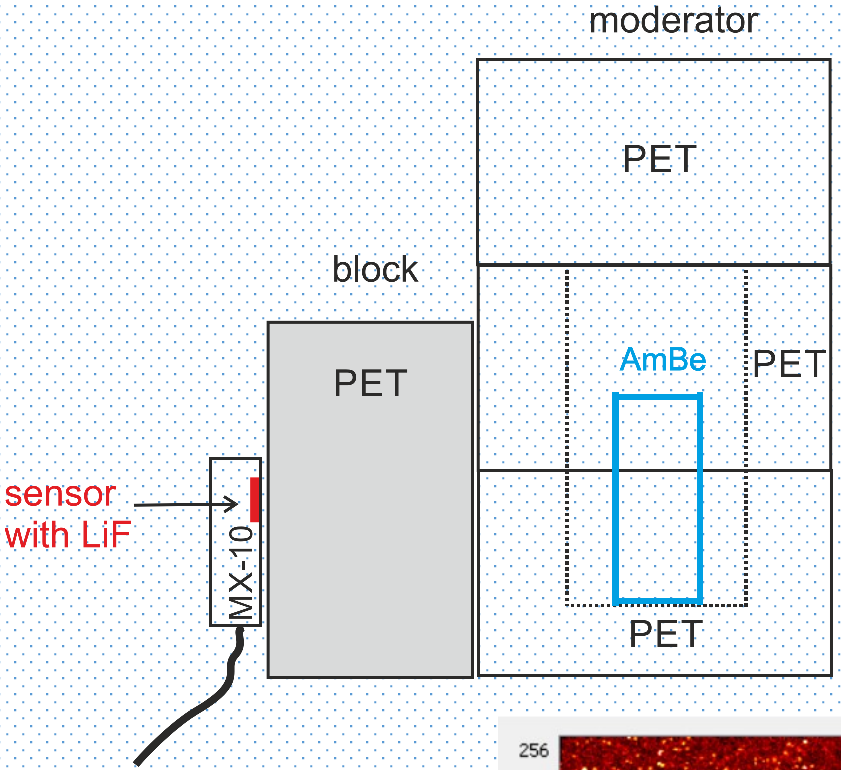
Lithium Fluoride, containing enriched isotope ^{6}Li
LiF is spread on the aluminium foil (supporting material)
Area density - 3,6 mg/cm^2 ………. Layer thickness - 18 μm



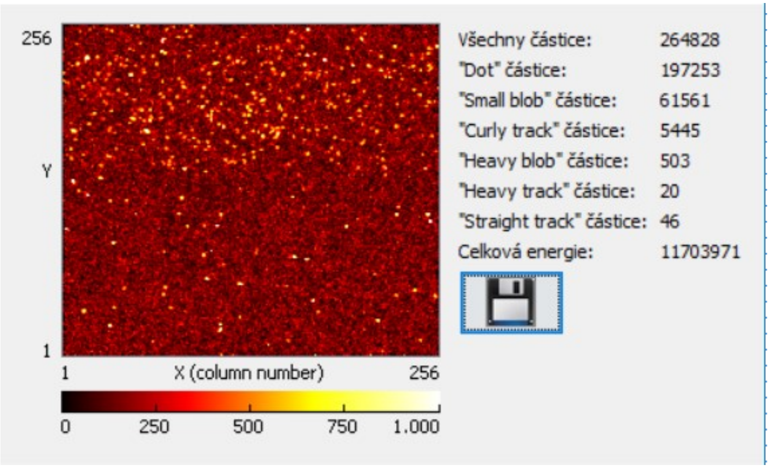


Detection of thermal neutrons using LiF converter





Videoclip 11



AmBe source has been put in the cavity inside the polyethylene block serving as a moderating material to get thermal neutrons

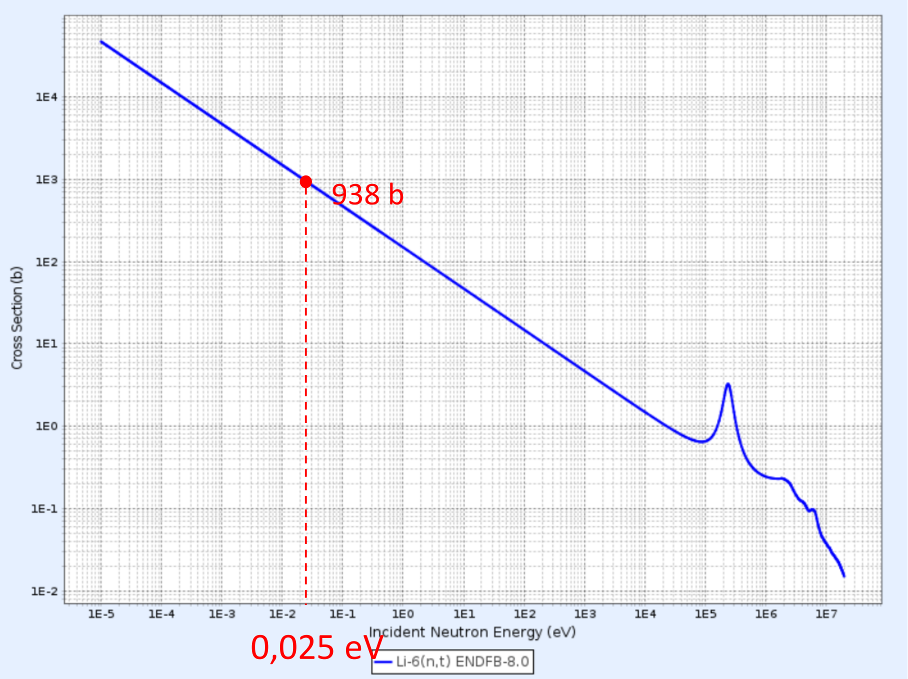
Another moderating polyethylene block has been added side-by.

The upper third of the MX-10 sensor area has been covered with LiF converter.

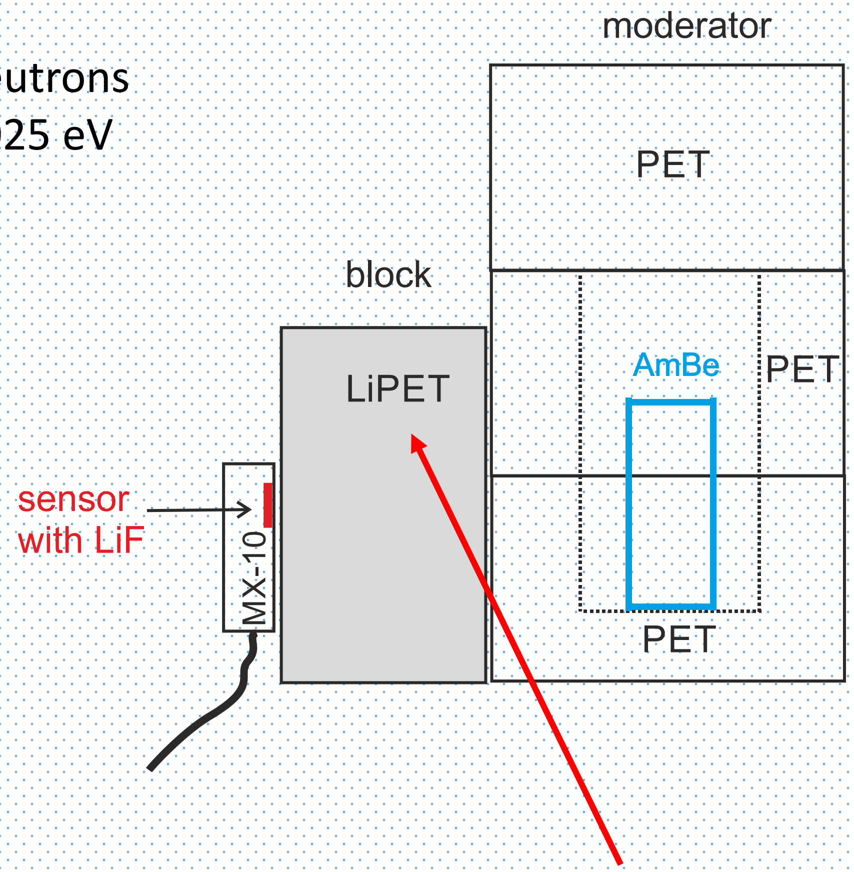
Shielding of thermal neutrons using lithium ^{6}Li

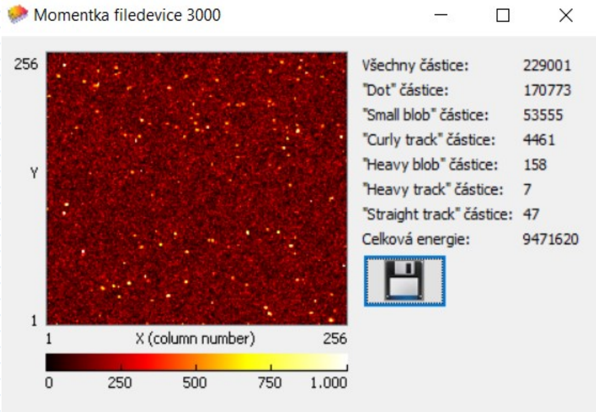
$$^{6}_{3}\mathrm{Li} + ^{1}_{0}\mathrm{n} \rightarrow ^{4}_{2}\alpha + ^{3}_{1}\mathrm{H}$$

Effective cross-section significantly rises with decreasing neutron energy (note logarithmic scale)



e.g. Thermal neutrons
with energy 0,025 eV
σ = 938 b





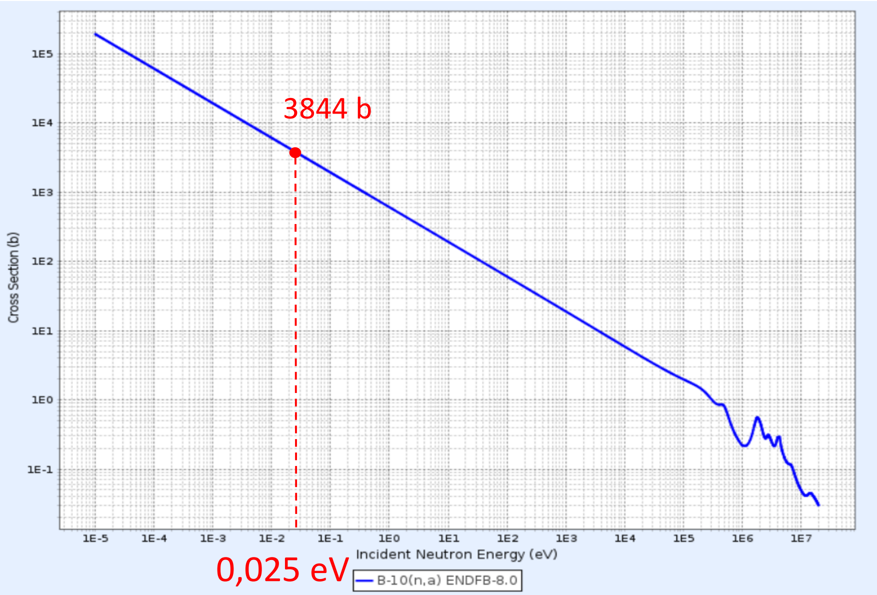
Videoclip 12

The pure polyethylene block is replaced by the lithium dopped block (containing 10 % of lithium ^{6}Li)

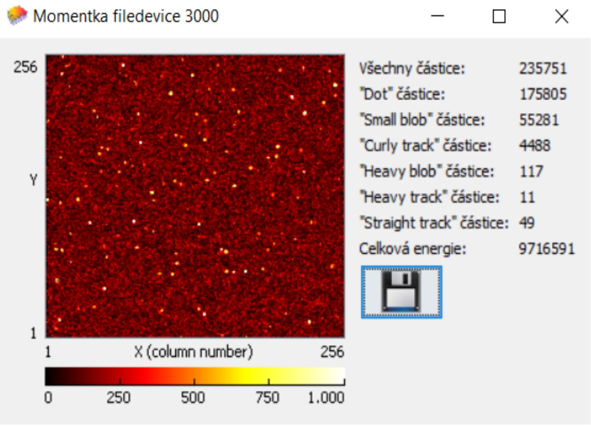
Shielding thermal neutrons using boron ^{10}B

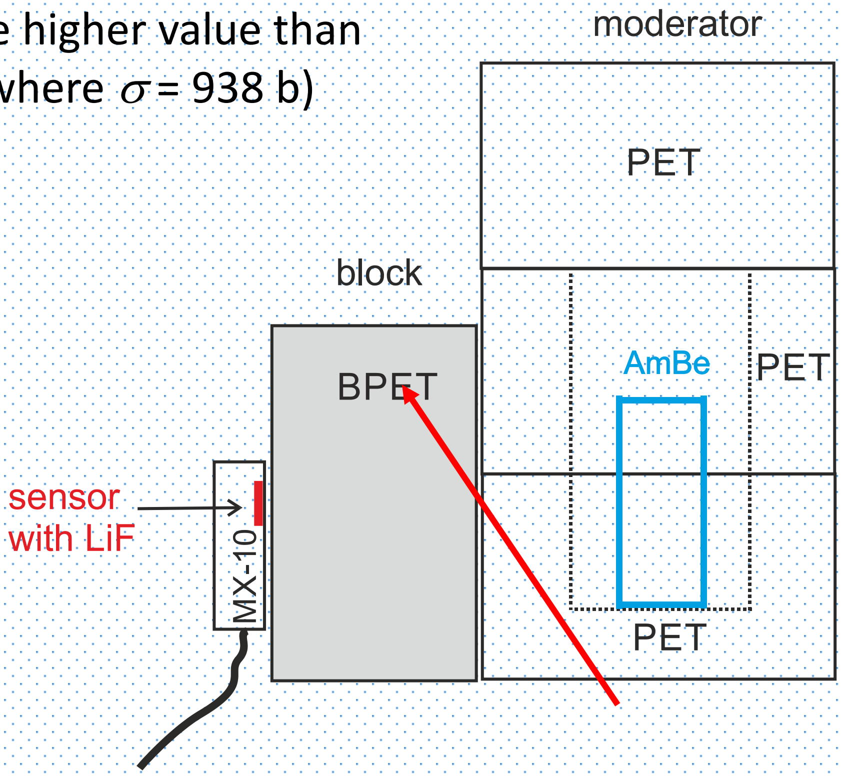
$$^{10}_{5}\mathrm{B} + ^{1}_{0}\mathrm{n} \rightarrow ^{7}_{3}\mathrm{Li} + ^{4}_{2}\alpha \qquad 6\ \%$$

$$^{10}_{5}\mathrm{B} + ^{1}_{0}\mathrm{n} \rightarrow ^{7}_{3}\mathrm{Li} + ^{4}_{2}\alpha + \gamma \qquad 94\ \%, \quad E_{\gamma} = 480\ \mathrm{keV} \quad \text{(radiative capture)}$$



cross section for reaction of ^{10}B with thermal neutrons at energy 0,025 eV is **σ = 3844 b**.
(It poses four time higher value than reaction with ^{6}Li where σ = 938 b)



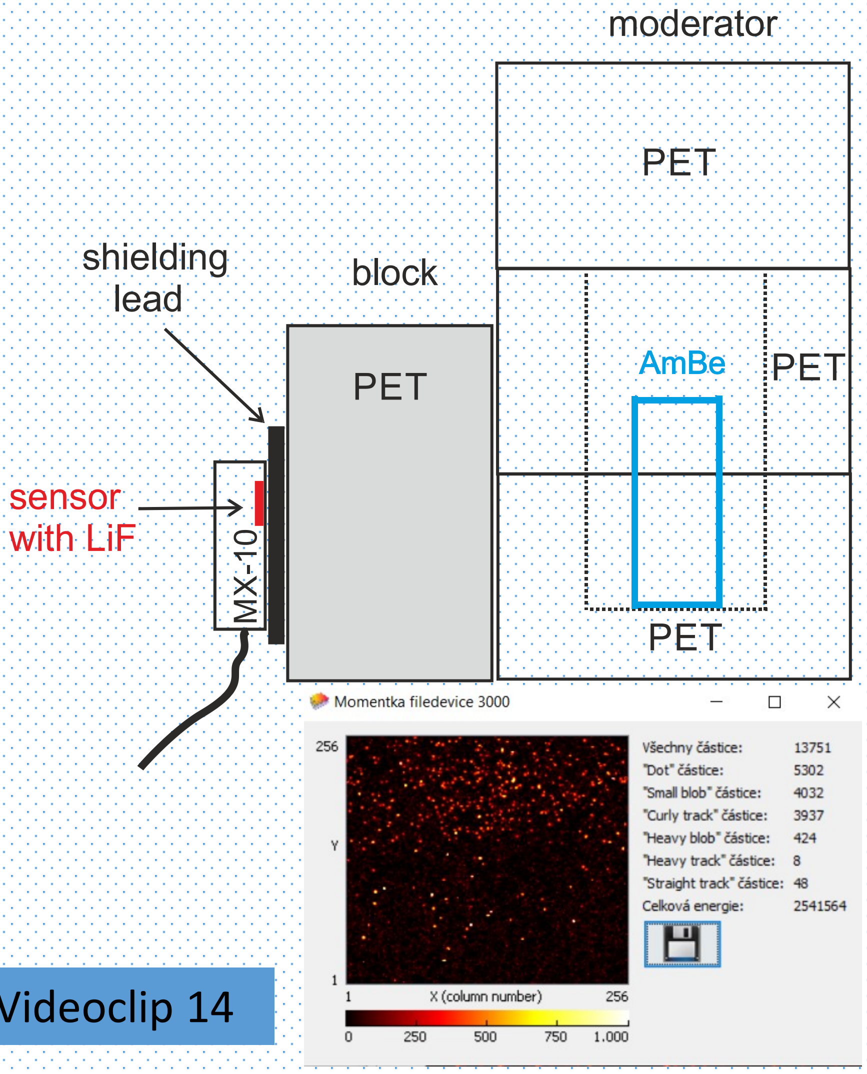


Videoclip 13

Lithium doped polyethylene block is replaced by the boron doped polyethylene block (containing 5 % of boron ^{10}B)

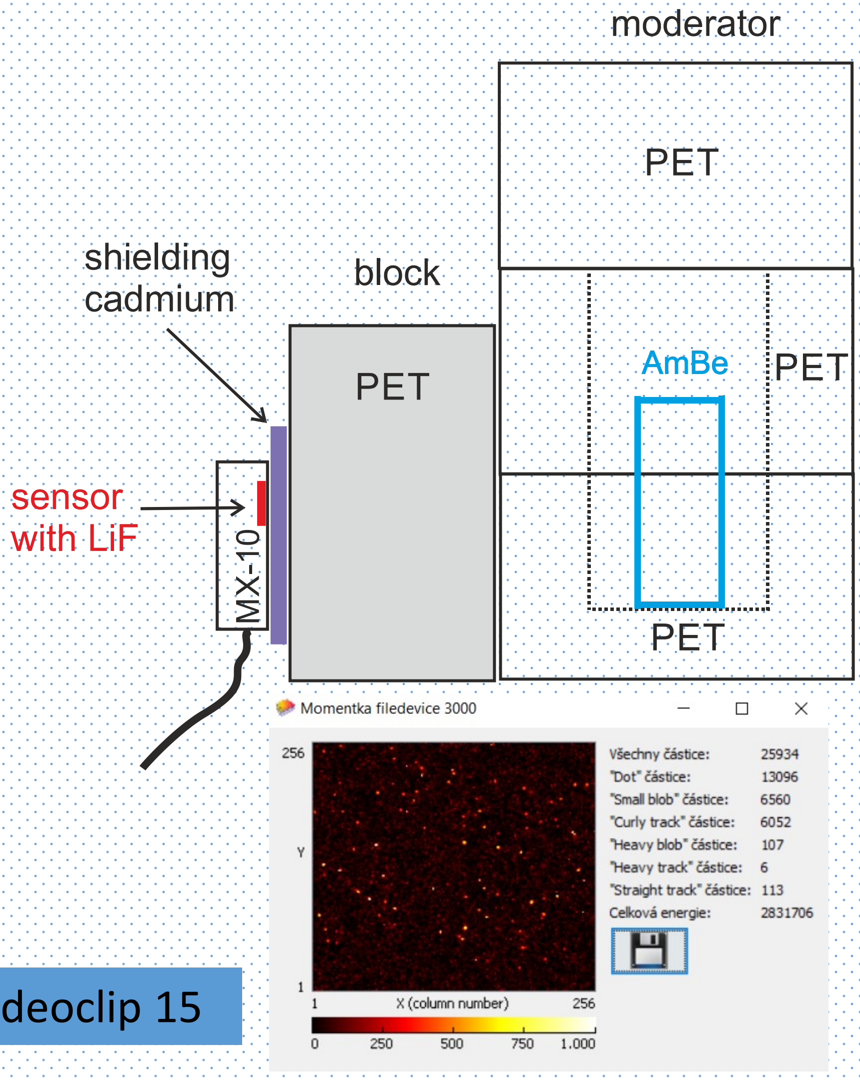
Shielding of thermal neutrons using lead and cadmium

Lead is often referenced as radiation shielding material.
Would it also serve well to shield neutrons???
1mm thick Pb plate has been placed between
polyetylene brick and sensor covered with LiF converter



Videoclip 14

In the next step, 0.7mm thick Cd plate has been
placed between the polyethylene brick
and the sensor covered with LiF converter.

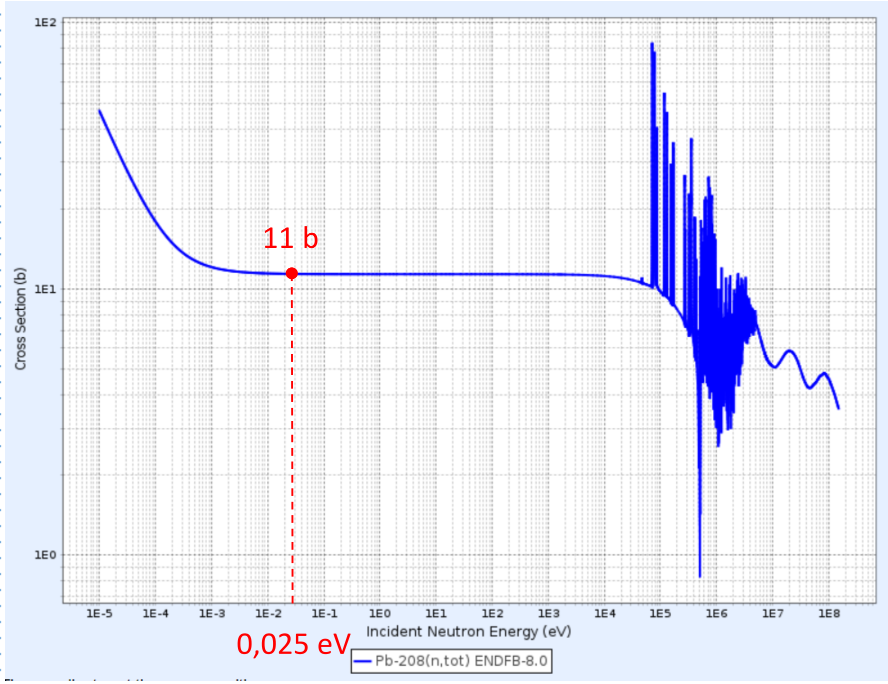


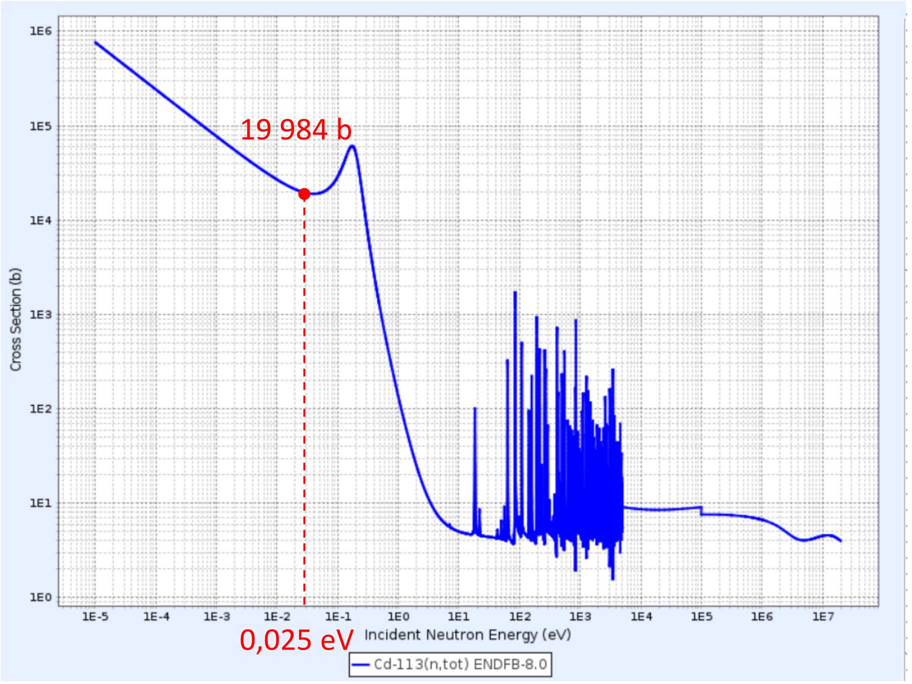
Videoclip 15

Effective cross section for neutron reaction with lead and cadmium

Isotopes ^{206}Pb, ^{207}Pb, ^{208}Pb exhibit cross section $\sigma = 11$ b for thermal neutrons with energy 0,025 eV.

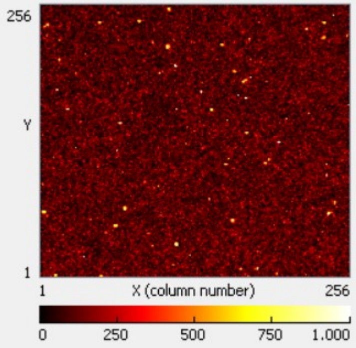
Isotope ^{113}Cd exhibits cross section $\sigma = 19\,984$ b for thermal neutrons with energy 0,025 eV.





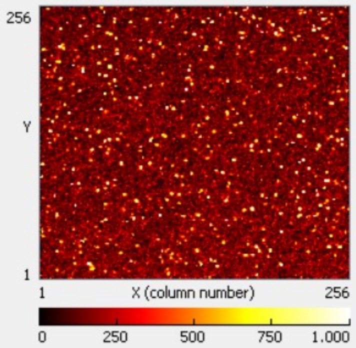
All results

No converter (bare Si sensor)



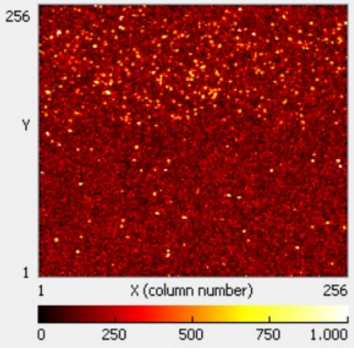
Všechny částice:	191836
"Dot" částice:	146382
"Small blob" částice:	41017
"Curly track" částice:	4335
"Heavy blob" částice:	70
"Heavy track" částice:	3
"Straight track" částice:	29
Celková energie:	7732086

Paraffin converter



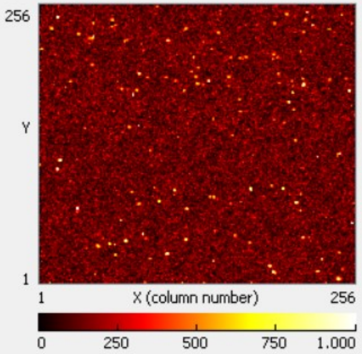
Všechny částice:	241140
"Dot" částice:	181657
"Small blob" částice:	52344
"Curly track" částice:	6427
"Heavy blob" částice:	615
"Heavy track" částice:	25
"Straight track" částice:	72
Celková energie:	11910683

Converter LiF through pure PET



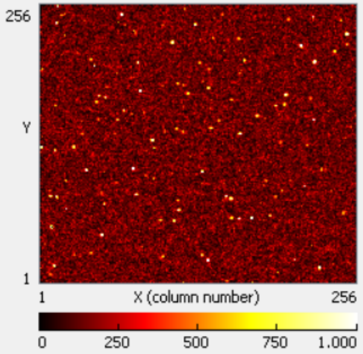
Všechny částice:	264828
"Dot" částice:	197253
"Small blob" částice:	61561
"Curly track" částice:	5445
"Heavy blob" částice:	503
"Heavy track" částice:	20
"Straight track" částice:	46
Celková energie:	11703971

Converter LiF through LiPET



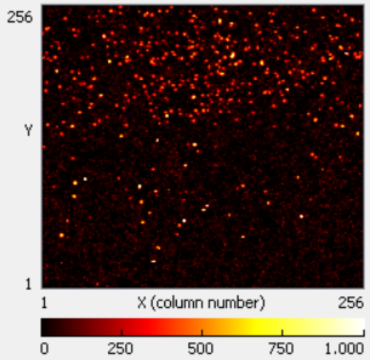
Všechny částice:	229001
"Dot" částice:	170773
"Small blob" částice:	53555
"Curly track" částice:	4461
"Heavy blob" částice:	158
"Heavy track" částice:	7
"Straight track" částice:	47
Celková energie:	9471620

Converter LiF through BPET



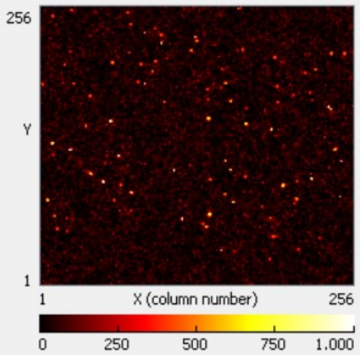
Všechny částice:	235751
"Dot" částice:	175805
"Small blob" částice:	55281
"Curly track" částice:	4488
"Heavy blob" částice:	117
"Heavy track" částice:	11
"Straight track" částice:	49
Celková energie:	9716591

Converter LiF through pure PET and Pb



Všechny částice:	13751
"Dot" částice:	5302
"Small blob" částice:	4032
"Curly track" částice:	3937
"Heavy blob" částice:	424
"Heavy track" částice:	8
"Straight track" částice:	48
Celková energie:	2541564

Converter LiF through pure PET and Cd

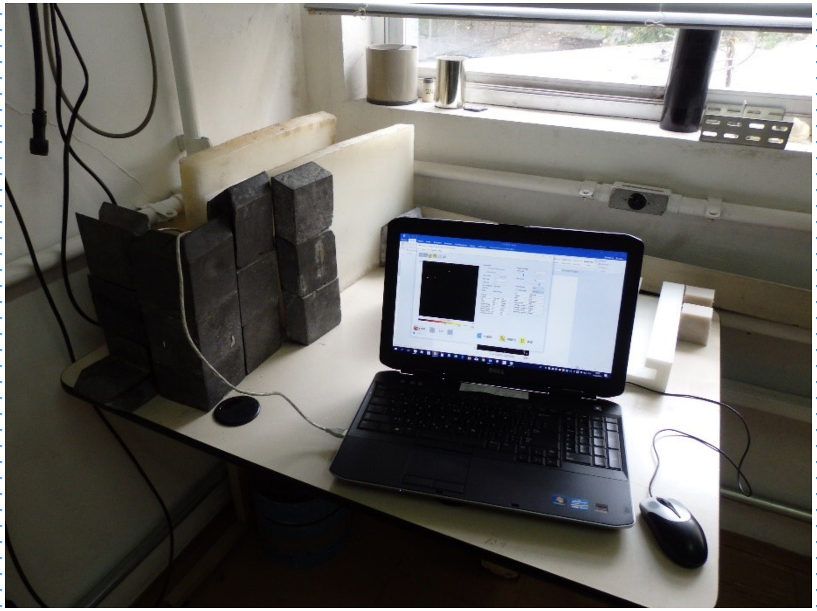


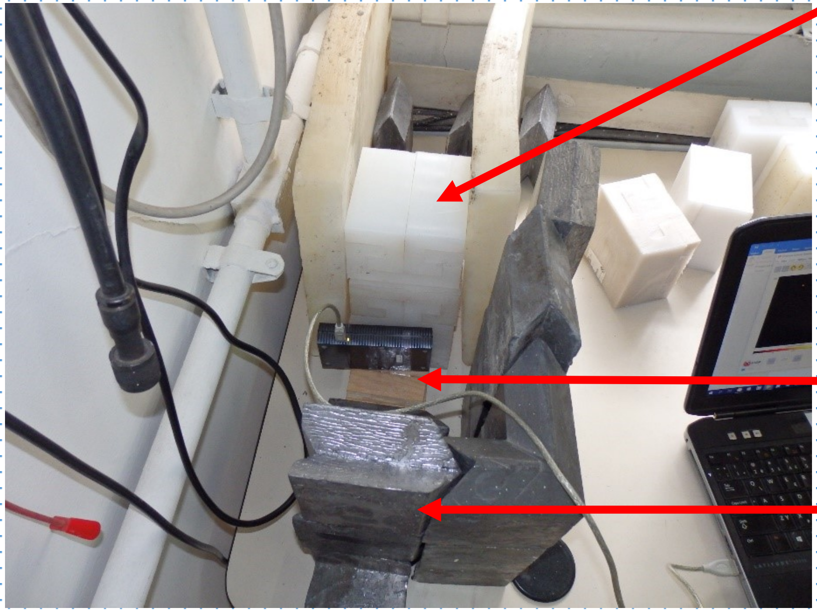
Všechny částice:	25934
"Dot" částice:	13096
"Small blob" částice:	6560
"Curly track" částice:	6052
"Heavy blob" částice:	107
"Heavy track" částice:	6
"Straight track" částice:	113
Celková energie:	2831706

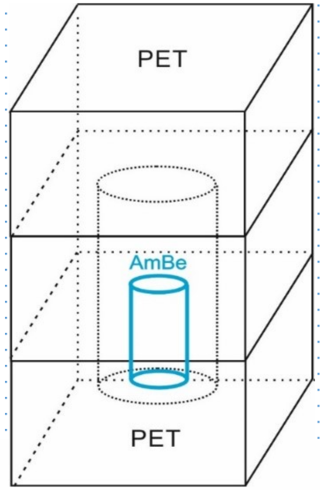
References

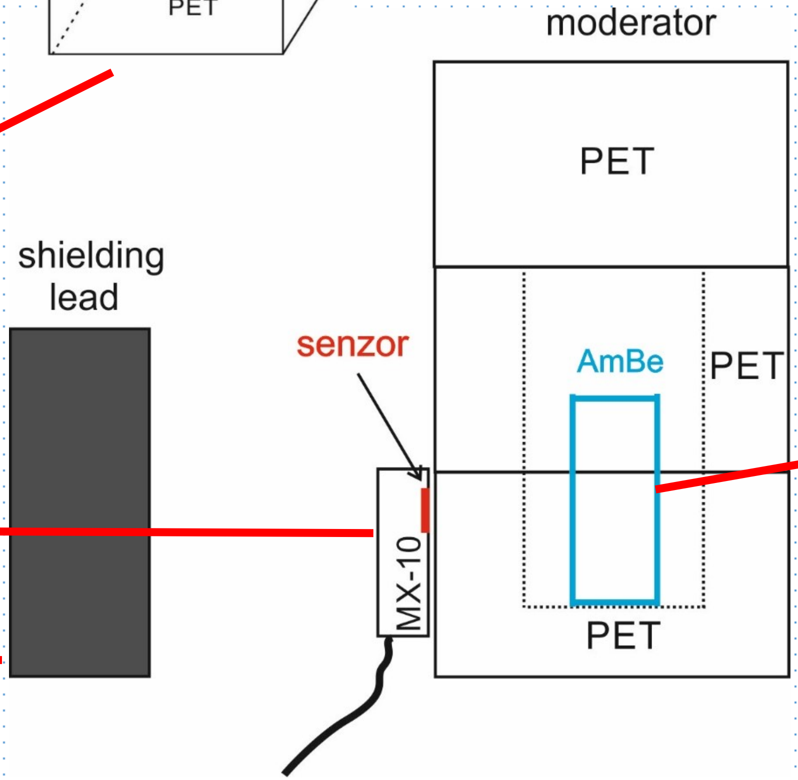
- Vícha V.: *Experiments Using Pixel Detector in Teaching Nuclear and Particle Physics*, Czech Technical University, Prague 2017, ISBN 978-80-01-06108-4, p. 41-43, 77-80.
- Pujala, Usha, Selvakumaran, T.S., Mohapatra, D.K., Raja, E. Alagu, Subbaiah, K.V., Baskaran, R. *Analysis of Neutron Streaming Through the Trenches at LINAC Based Neutron Generator Facility, IGCAR*. Indian Association for Radiation Protection, 34(2011):262-266.
- [3] Nuclear Data Center at KAERI, available online: http://atom.kaeri.re.kr/
- [4] Rinard P.: *Neutron Interaction with Matter*. [cit 9. 9. 2020]. Dostupné online: https://www.lanl.gov/org/ddste/aldgs/sst-training/_assets/docs/PANDA/Neutron%20Interactions%20with%20Matter%20Ch.%2012%20p.%20357-378.pdf
- [5] Hůlka J., Kánský Z., Janout Z., Pospíšil S.: *Detektor tepelných neutronů využívající křemíkový polovodičový detektor s povrchovou bariérou*. ACTA POLYTECHNICA – Práce, Praha 1980.

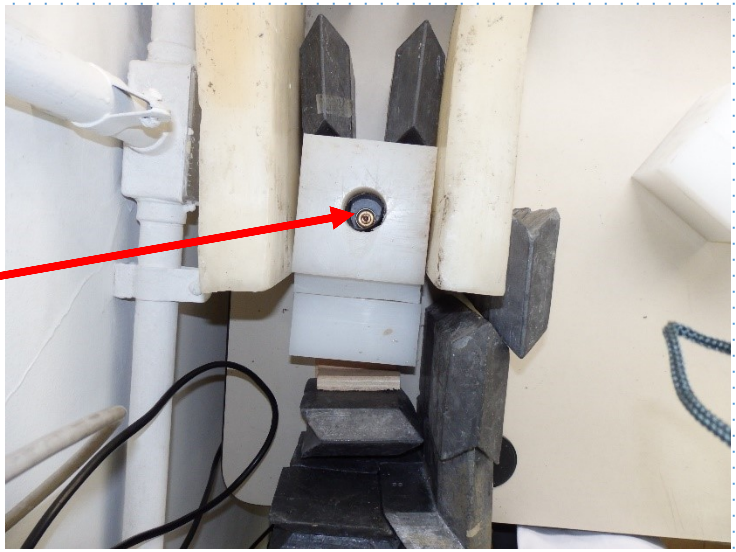
Measurement set-up assembled at IPEN laboratory in Sao Paulo
Better shielding arrangement – In vivo demonstration



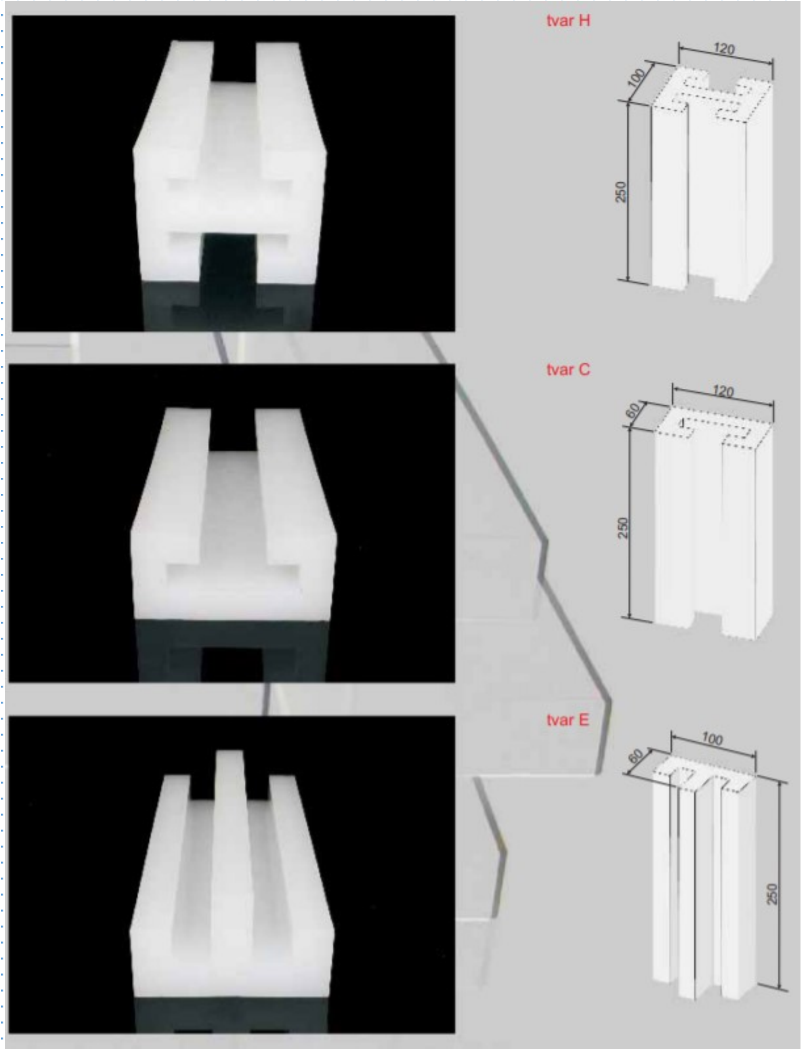








Profiles NEUTROSTOP



Exemplar fabricated profiles
(Czech Republic – Kolin)

H0, C0, E0 - pure polyethylen	PET
H3, C3, E3 – Bor additive - 3,5 %	BPET
H5, C5, E5 – Bor additive - 5 %	
H10, C10, E10 – Lithium additive - 10 %	LiPET