Neutron Spectrometry

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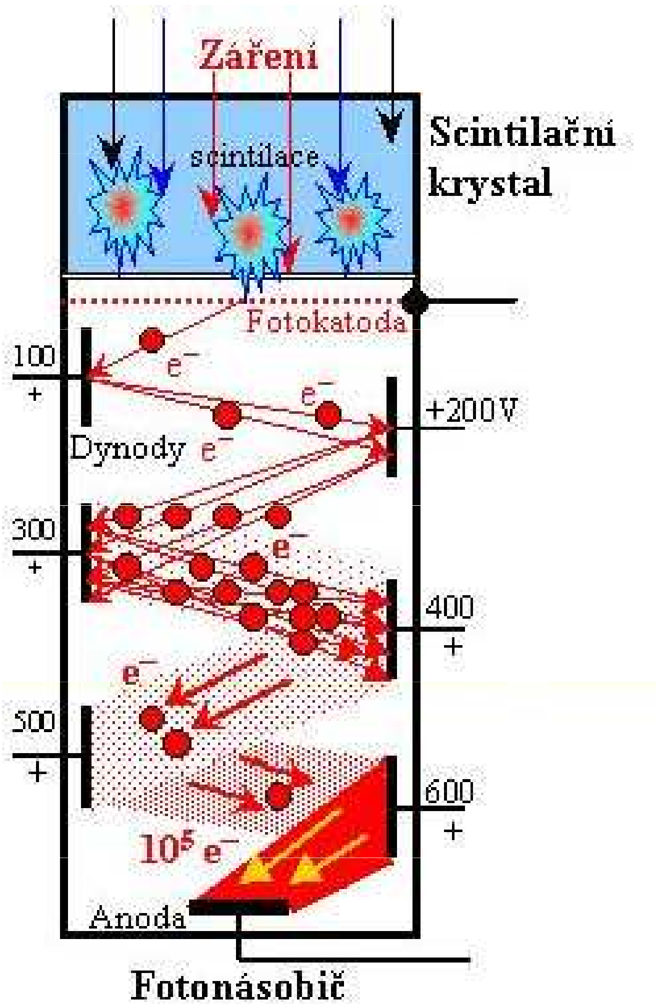
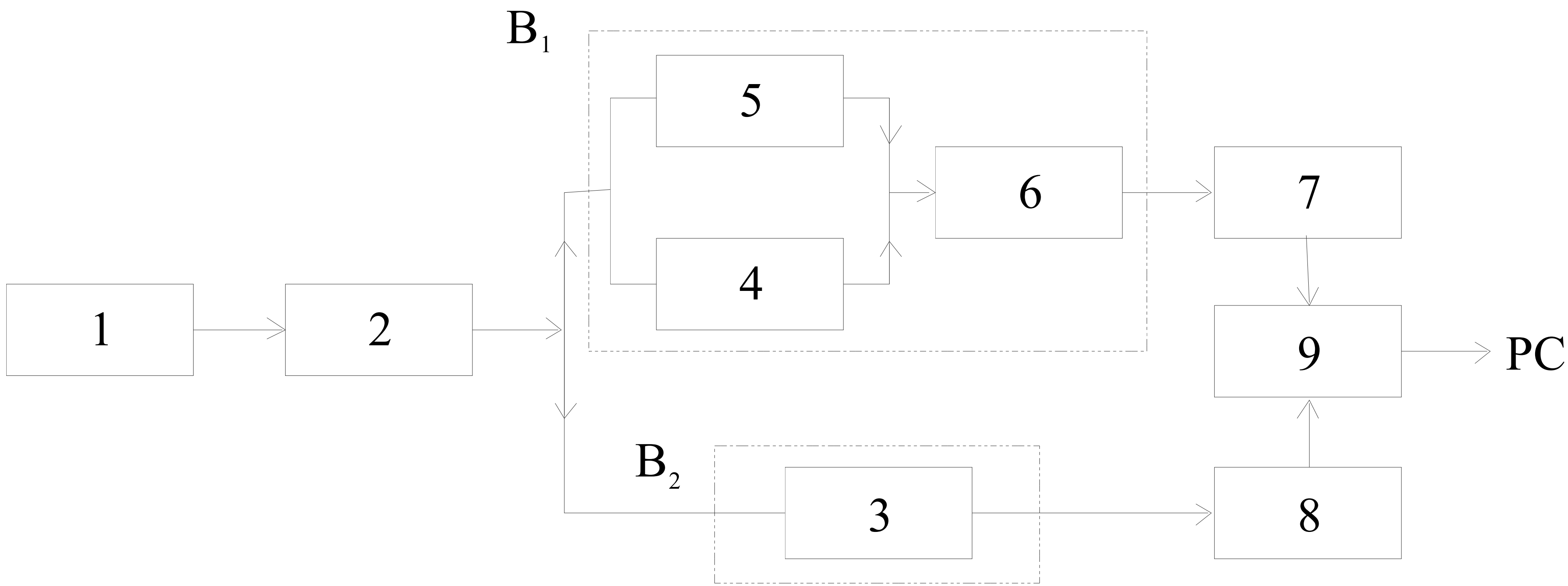
Motivation

- Neutron spectral flux density – “neutron spectrum” – “what energies are present and what is their proportion”
- Applications:
  - verification of functionality of nuclear reactors
  - estimation of pressure vessel damage
  - radiation protection
  - radiotherapy
  - estimation of biological effects
  - nuclear weapons (mainly in the past)

Scintillation Detector

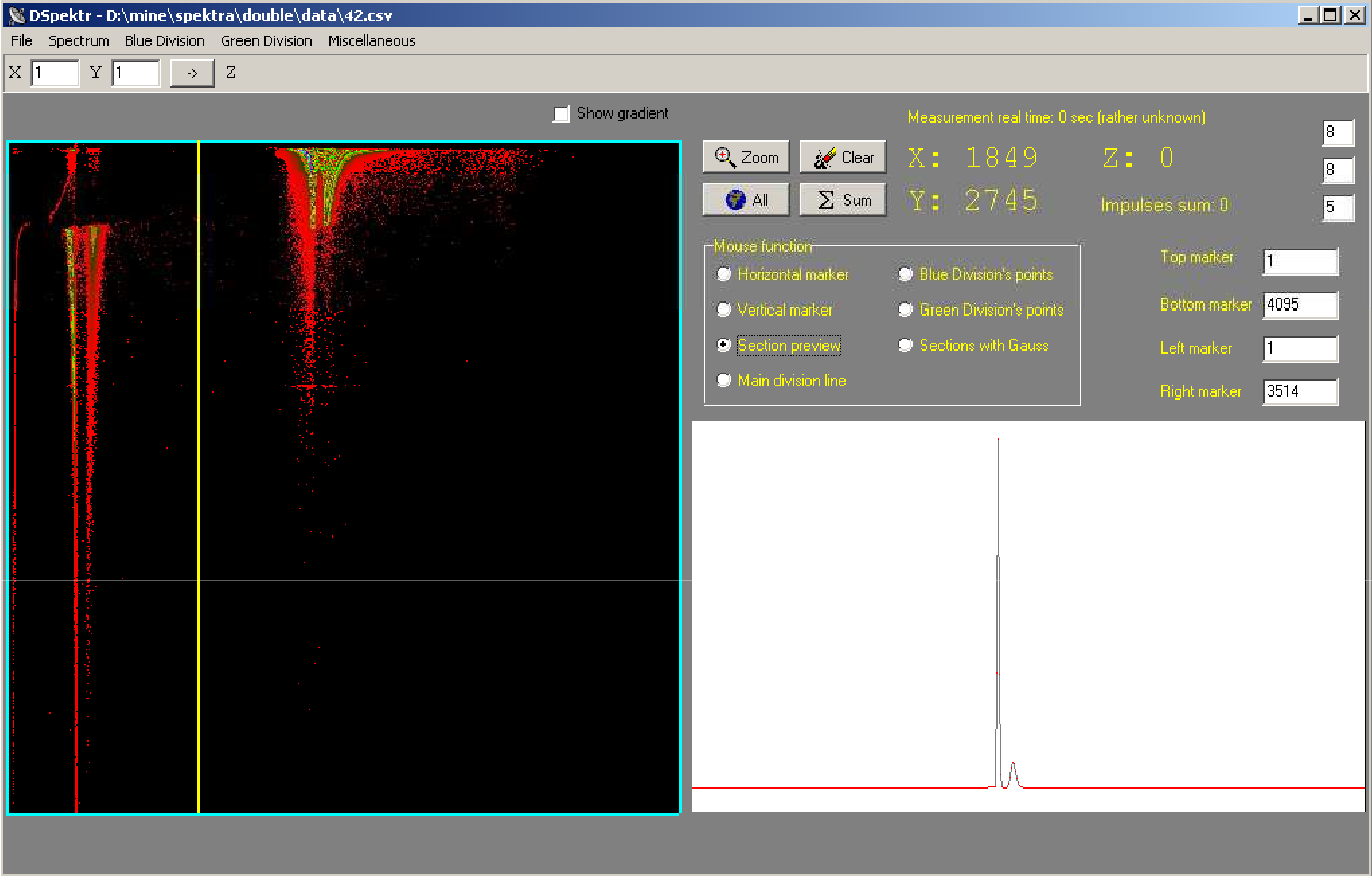


Block Scheme



1 - detector
2 - preamplifier
3 - linear amplifier
4 - pulse shape analyzer 1 (PSA1)
5 - pulse shape analyzer 2 (PSA2)
6 - logic unit
7 - AD 1 converter
8 - AD 2 converter
9 - data storage unit (DP)

Neutron-Gamma Separation



The Unfolding Problem

$$Z(E_p) = \int_{E_{n\min}}^{E_{n\max}} \varphi(E_n) z(E_p, E_n) dE_n$$

- $\varphi(E_n)$ neutron energetic spectrum (this is what we want to measure)
- $z(E_p, E_n)$ detector response function (obtained by Monte Carlo simulation)
- $Z(E_p)$ measured proton spectrum (detector output)

Maximum Likelihood Estimation

- Discrete form: $\boldsymbol{g} = \boldsymbol{Af}$,
- Assumption: neutron and proton spectra are random vectors with mutually independent, Poisson-distributed components
- Likelihood function for $\boldsymbol{f}$: $$L(\boldsymbol{f}) = \prod_{i=1}^{n} \mathrm{e}^{-\bar{g}_i} \frac{\bar{g}_i^{g_i}}{g_i!}.$$

  where $$\bar{g}_i = \sum_{j=1}^{n} a_{ij} f_j$$

- Algorithm: $$f_i^{(k+1)} = f_i^{(k)} \sum_{j=1}^{n} \frac{g_j a_{ji}}{\sum_{l=1}^{n} f_l^{(k)} a_{jl}}$$

Mathematica Code

$$f_i^{(k+1)} = f_i^{(k)} \sum_{j=1}^{n} \frac{g_j a_{ji}}{\sum_{l=1}^{n} f_l^{(k)} a_{jl}}$$

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fce = Compile[{{pL, _Real, 1}, {pTK, _Real, 2}, {ppp, _Real, 1}, {pK, _Real, 2}}, pL (pTK.(ppp/(pK.pL)))];
fce10 = Compile[{{pL, _Real, 1}, {pTK, _Real, 2}, {ppp, _Real, 1}, {pK, _Real, 2}},
                Module[{xL}, xL = pL; Do[xL = xL (pTK.(ppp/(pK.xL))),{10}]; xL]];
mnorm=Table[Sum[m[[i,j]],{i,mink,maxk}],{j,mink,maxk}];
K=Table[m1[[i,j]]/mnorm[[j]],{i,Length[spektrumM]},{j,Length[spektrumM]}];
TK=Transpose[K];

Print["*** Vypocet neutronoveho spektra ***"];
    spektrum=Table[spektrumM[[j]],{j,Length[spektrumM]}];
    CilovaOdchylka=nasobek Length[spektrum];
    G=Sum[spektrum[[i]],{i,1,Length[spektrum]}];
    pp=spektrum/G;
    L = Table[1/Length[spektrum], {Length[spektrum]}];
    StaraOdchylka=(m1.(G L/mnorm)-spektrum).((m1.(G L/mnorm)-spektrum)/spektrum);
    L = fce[L,TK,pp,K];
    L = fce[L,TK,pp,K];
    NovaOdchylka=(m1.(G L/mnorm)-spektrum).((m1.(G L/mnorm)-spektrum)/spektrum);
    While[NovaOdchylka>CilovaOdchylka && Abs[(StaraOdchylka-NovaOdchylka)/StaraOdchylka]>presnost,
           L = fce10[L,TK,pp,K];
          StaraOdchylka=NovaOdchylka;
          NovaOdchylka=(m1.(G L/mnorm)-spektrum).((m1.(G L/mnorm)-spektrum)/spektrum)];
    neuit=Table[{(mink+i-1) krok - krok/2,(G L/mnorm)[[i]]/(krok^2 plocha)},{i,Length[L]}];
    zaltoky=Table[{neuit[[i,1]], neuit[[i,1]] kobrsek konstanta neuit[[i,2]]/(Ecf cas)}, {i,Length[neuit]}];
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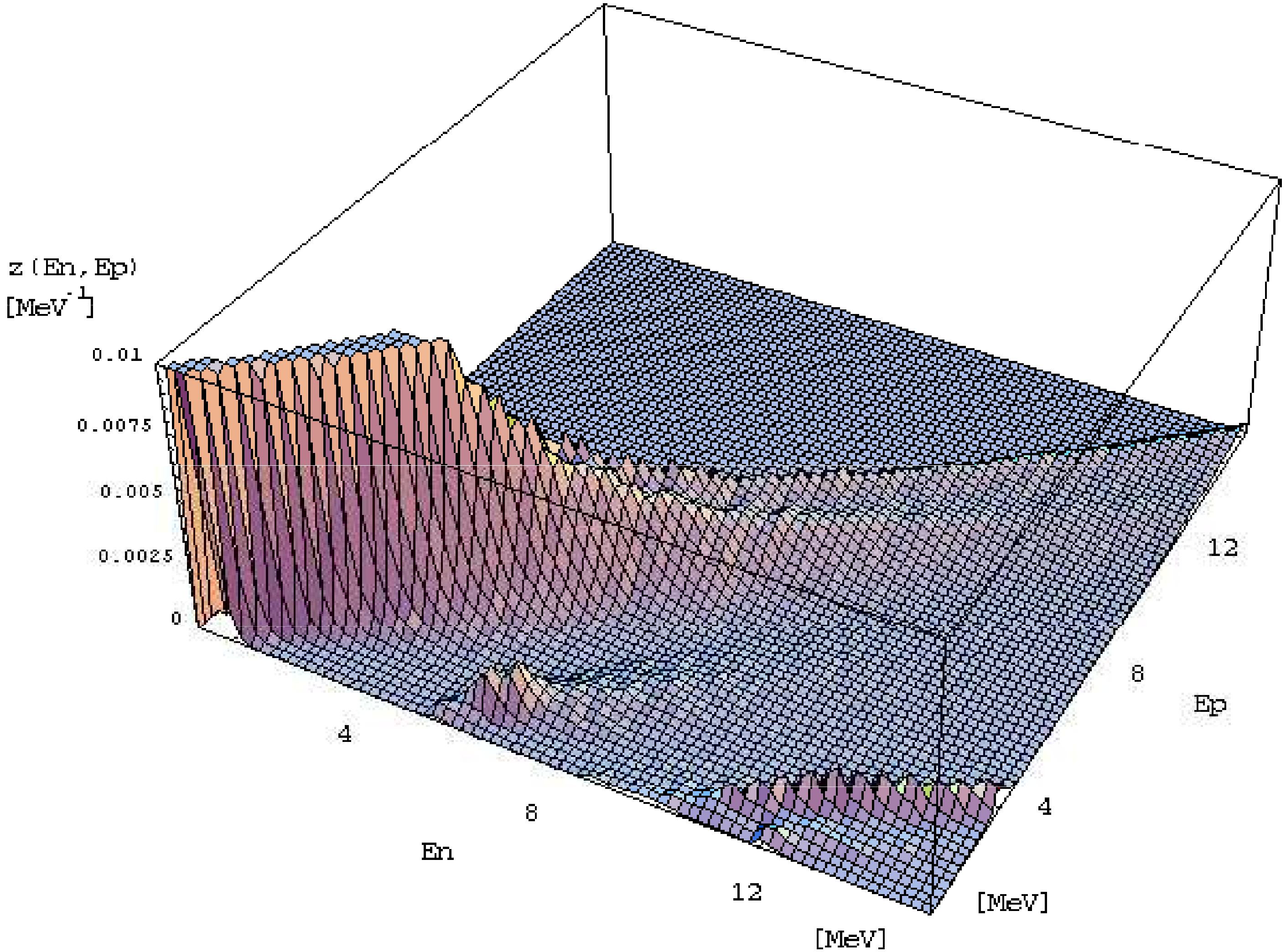
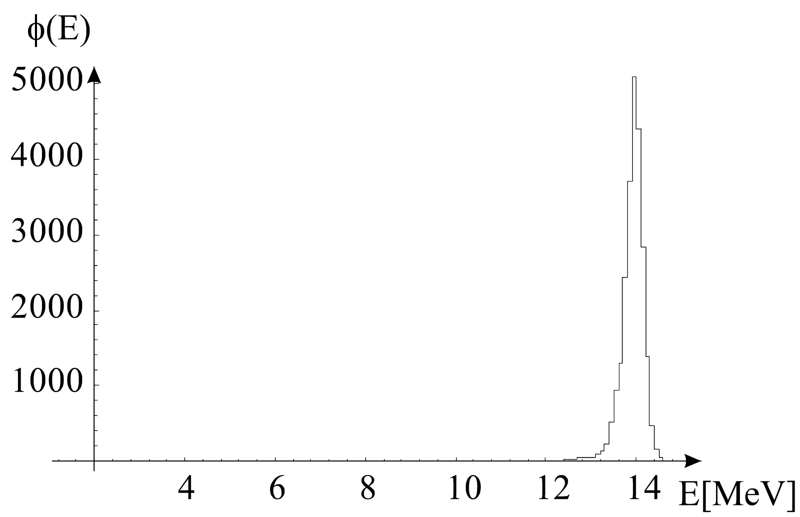
Detector Response Function

- Obtained by Monte Carlo simulation
- The interaction of the neutron with the detector is modeled.
- What must be taken into account:
  - detector geometry (cylinder)
  - chemical composition (C, H, O, B, ...)
  - different kinds of interactions (elastic and inelastic scattering, capture)
  - library data (describe stochastic properties of interactions)
  - user settings (energetic step, desired output format, etc.)

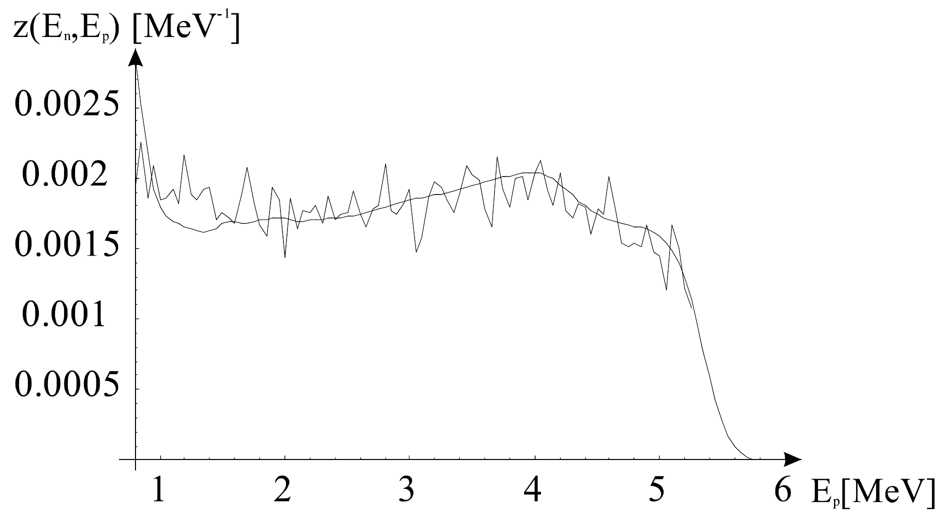
Sample Response Matrix



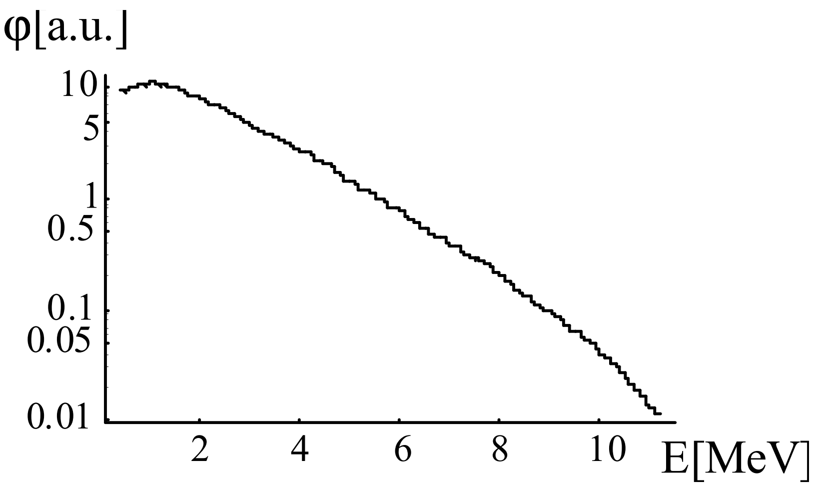
Verification of Results



Neutron line 13.9 MeV (stilbene Φ=1cm, H=1cm, coaxial impact)



Measured and calculated response E_n=5 MeV, perpendicular impact



Neutron spectrum from spontaneous fission of a ^{252}Cf source

Neutron spectrum from a ^{239}Pu-Be source

Further Work

- In frame of TA ČR no. TA01011383
  - replace analog part with digital equipment
  - develop software for controlling and processing
  - improve current methods
  - incorporate new detectors
- My main responsibility: software part
  - neutron-gamma discrimination
  - lead software development (evaluation procedures and response functions)
  - increase level of automation
  - improve propagation of uncertainties

Publications

- Determination of AKR-2 beam and verification at iron and water arrangements
  Košťál, Michal - Cvachovec, František - Cvachovec, Jiří - Ošmera, Bohumil - Hansen, Wolfgang. *Annals of Nuclear Energy*, Volume 38, Issue 1, 8 s. ISSN 0306-4549. 2011.
- Maximum Likelihood Estimation of a Neutron Spectrum and Associated Uncertainties
  Cvachovec, Jiří - Cvachovec, František. *Advances in Military Technology*, Brno : Univerzita obrany, Vol. 3, No. 2, 14 s. ISSN 1802-2308. 2008.
- Neutron Response Function for BC-523A Scintillation Detector in the Energy Range 0.5 to 20 MeV
  Cvachovec, Jiří - Cvachovec, František - Pošta, Severin - Ošmera, Bohumil. *Journal of ASTM International*, Vol. 5, No. 5, 4 s. ISSN 1546-962X. 2008.
- Výpočet funkce odezvy pro detektory s dopovanými scintilátory (II)
  Cvachovec, Jiří - Cvachovec, František - Pošta, Severin - Ošmera, Bohumil. ÚJV Řež, 2004. 12107-R,D.
- Multiparameter multichannel analyser system for characterisation of mixed neutron-gamma field in the experimental reactor LR-0
  Bureš, Zbyněk - Cvachovec, Jiří - Cvachovec, František - Čeleda, Pavel - Ošmera, Bohumil. In *Reactor Dosimetry in the 21st Century: Proceedings of the 11th International Symposium on Reactor Dosimetry Brussels, Belgium 18 - 23 August 2002*. Brussels : World Scientific Publishing Company, 2003. od s. 194-201, 8 s. ISBN 9812384480.
- Anisotropy of light output in response function of stilbene detectors
  Cvachovec, F. - Cvachovec, J. - Tajovský, P. *Nuclear Instruments & Methods in Physics Research A*, Elsevier Science Publishers, 476, 1-2, od s. 200-202. ISSN 0168-9002. 2002.

Q & A