Analysis for filtered neutron transmission

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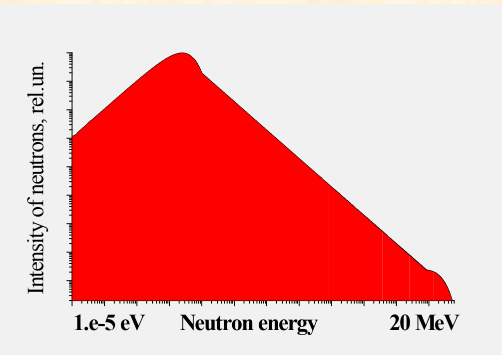
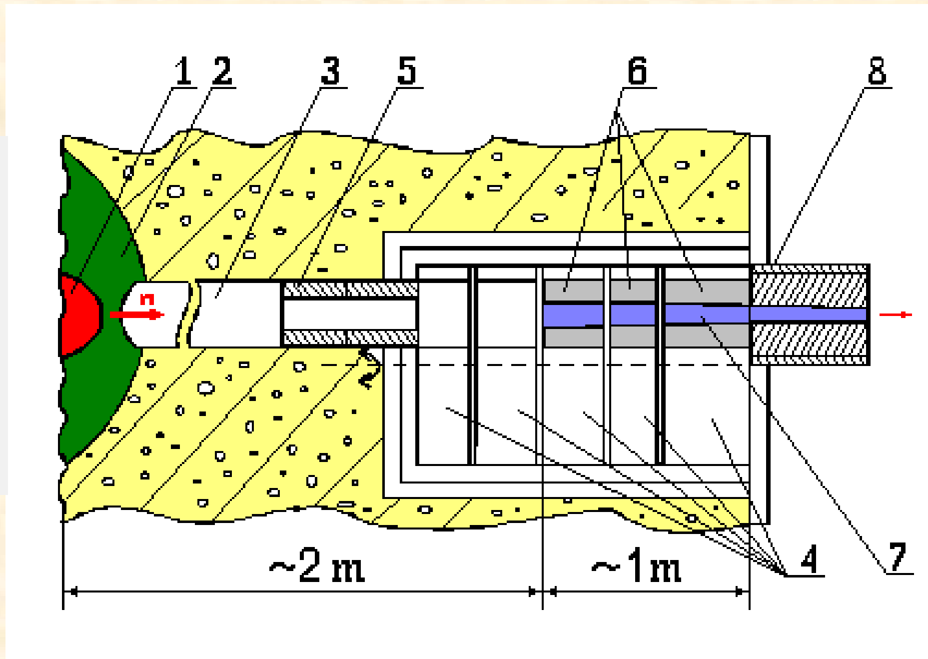
Filtered neutron beam

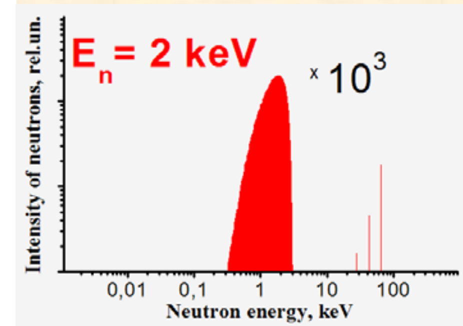
Reactor (white) spectrum



10^{14} n/cm^{2}s



Quasi-mono-energy line

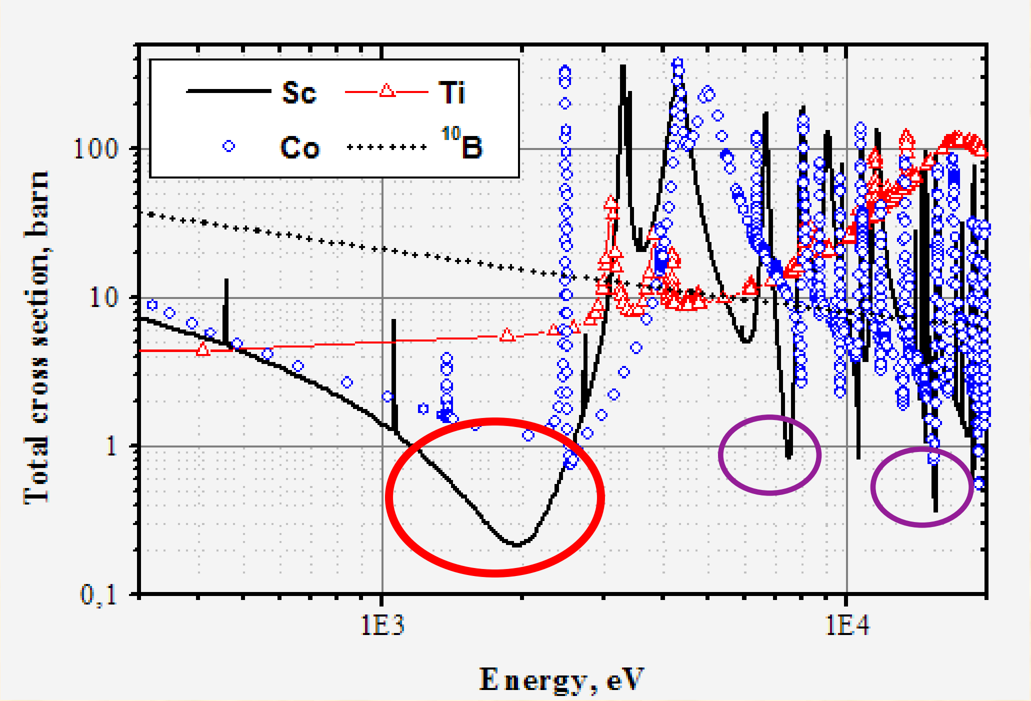


10^5-10^8 n/cm^{2}s

1 – reactor core, 2 – beryllium reflector; 3 – horizontal channel tube; 4 – beam shutter disks; 5 – preliminary collimator; 6 – filter-assembles; 7 – filter components; 8 – outside collimator.

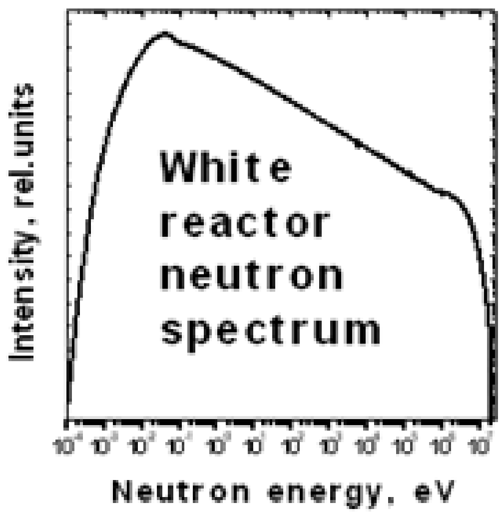
Physical basis of neutron filter

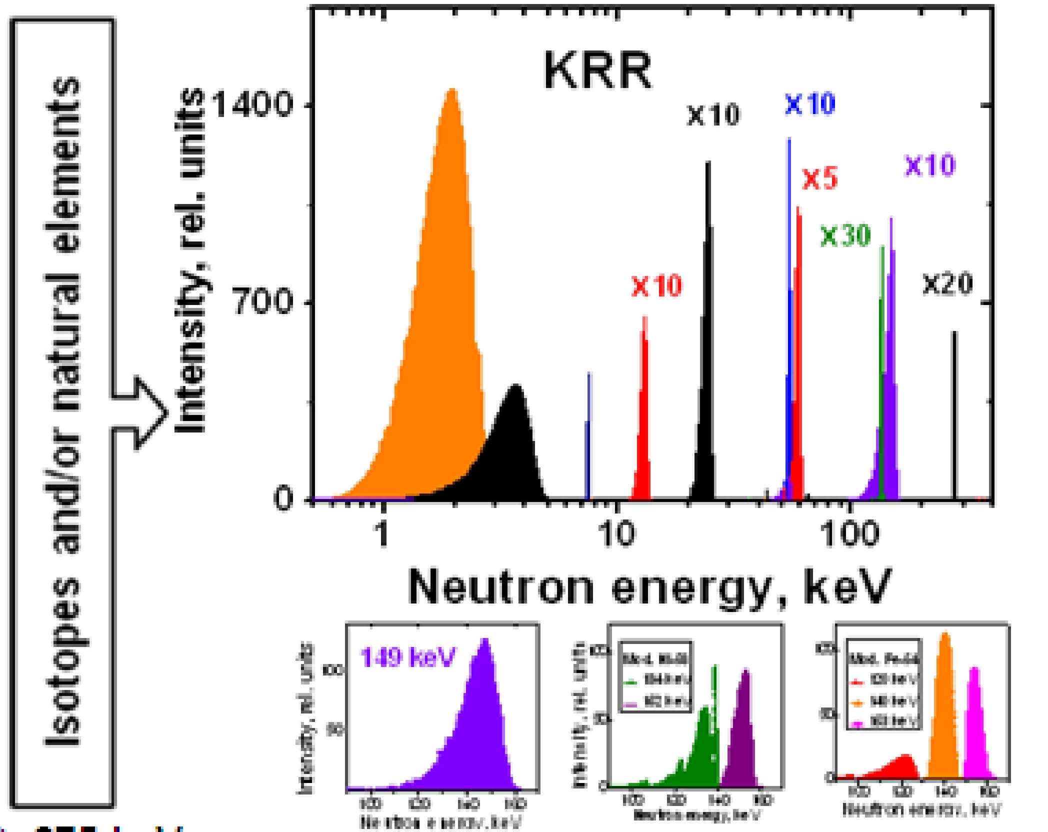
A "white" reactor spectrum is transmitted through the thick layers of materials, which nuclei have the deep interference minima in their total neutron cross sections



To remove the rest (parasitic) lines - additional materials are used. Resonance maxima for their TCS coincide with interference minima for the main filter material, excepted the most deep interference minimum.

Neutron filters used in NPD





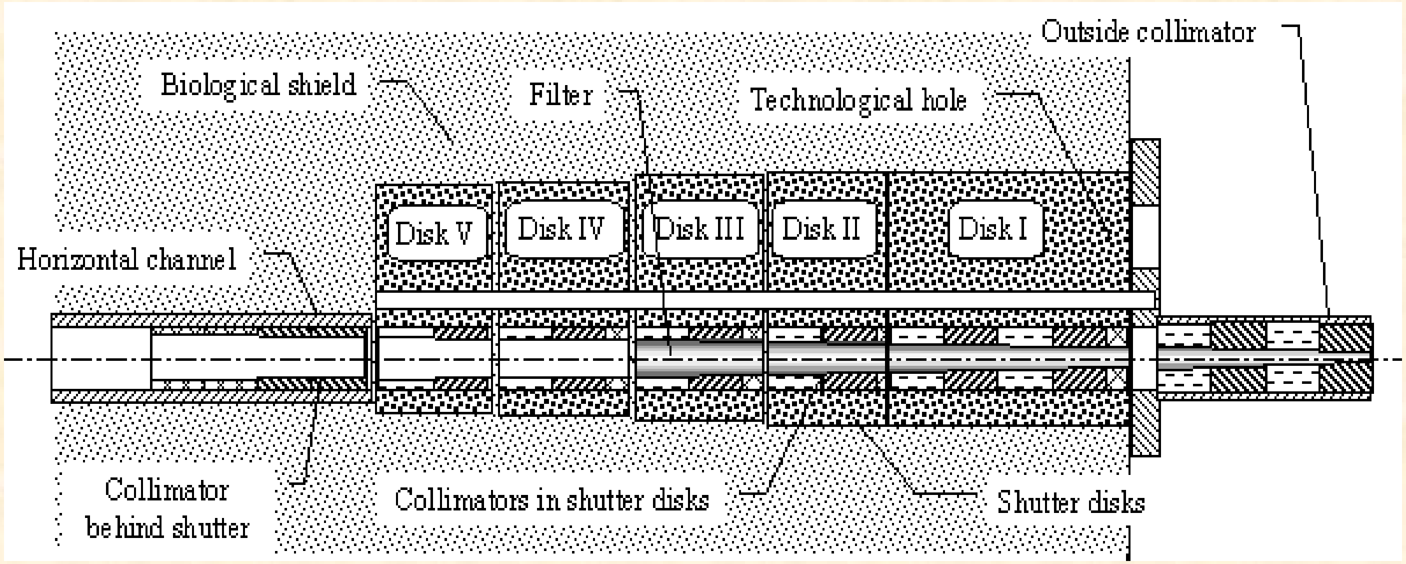
FC: Fe, Al, S, Si, V, Ni, Cr, Ti, ^{10}B, Mg, Sc, Mn, Co, Cu, Rh, Cd, Ce, ^{52}Cr, $^{54,56,57}Fe$, $^{58,60,62}Ni$, ^{80}Se, ^{10}B, ^{7}Li

E: 2, 3.5, 7.5, 13, 24, 54; 59*, 133, 148*, 275 keV
I = $10^4 \div 10^8$ $n \cdot cm^{-2} \cdot s^{-1}$, P = 99.0 ÷ 99.5%
ACS_{tot} = 0.2÷1%, $ACS_{n,\gamma}$ = 3÷5%.

FC – filter components; E, I, P – energy, intensity, purity of the filtered neutron lines,
ACS_{tot}, $ACS_{n,\gamma}$ – the best value of accuracy obtained for the total and capture cross sections,
* – a set of the neutron energies.

Forming system of filtered neutron beam

includes the elements of beam collimation & neutron filtration



- **Preliminary forming of the beam - two iron and boron carbide collimators**
- **Further forming - in the 1-st three discs of shutter & in outer collimator (in the order: lead, textolite and mixture of paraffin with H_3BO_3)**
- **The collimation system provides beam narrowing to necessary diameter**
- **The elements of neutron filtration system - in the 1-st three disks of shutter & in the outer collimator**
- **To facilitate and quicken the procedure of filter changing, special steel containers for filters were made**

Featurs of filtered neutron beams

FNBs have energies in the kilo-electron-volts region.

Intensity of them may reach 10^5-10^8 n/cm^{2}s ⟶ good statistics ⟶

⟶ high accuracy !!!

FNB is quasi-monoenergetic neutron beam ⟶ measured cross section is value averaged on spectrum of the neutron line

FNB has main neutron line and additional (parasitic) neutron lines

FNBs with the same main neutron line may have different parameters

- Purity (ratio of the main neutron line intensity to intensity of all lines)
- Width of the main neutron line
- Shape of the main neutron line
- Intensity of the main neutron line

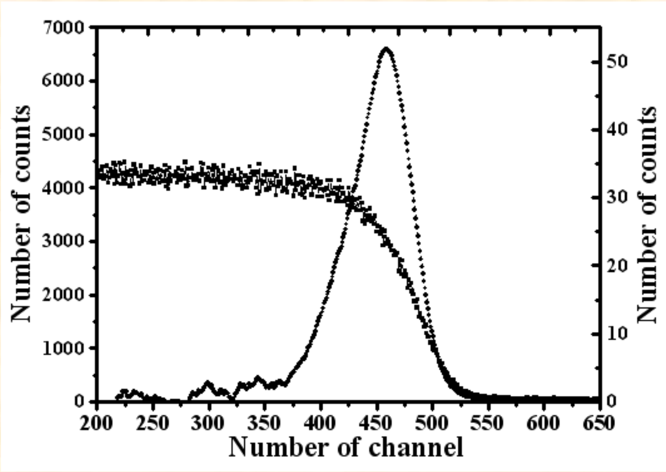
⟶ information about neutron spectrum is important!

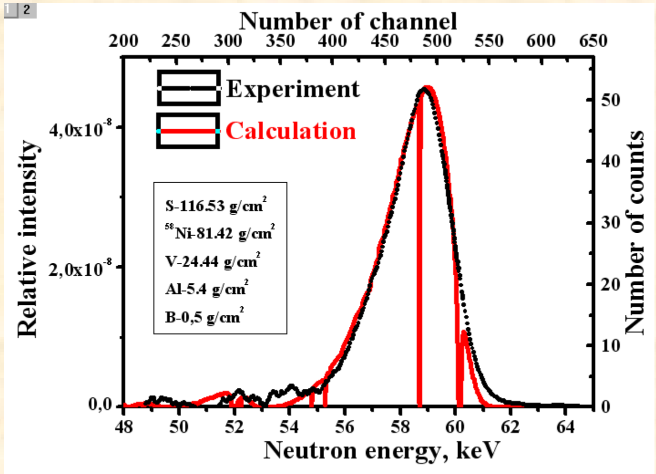
FNBs always have gamma background

What information type about neutron spectrum after filter is available?

- **Calculated neutron spectrum shape** – **for all energies**, if information about total neutron cross section for all components of this filter is presented in the ENDF/B libraries (in rel. units)

- **Experimental neutron spectrum shape** – for $E_n \geq 13$ keV, where we can use hydrogen recoil counters (in rel. units)





Influence on results

FNB has main neutron line and additional (parasitic) neutron lines

Purity

For total cross section measurements:

using hydrogen recoil counter (E_n>13 keV)

Purity is not very important as we can separate effects from different lines

using helium-3 counters (E_n<13 keV)

Purity is important as it is difficult to separate effects from different lines

For radiative capture CS measurements (using activation method):

Purity is very important as we can not separate effects from different lines

Influence on results (cont.)

Intensity of FNB may reach 10^5-10^8 n/cm^{2}s

Intensity

For total cross section measurements using transmission method:

Absolute value of intensity is not needed.

But dead time correction has to be done.

Stability of intensity during measure run (with sample and without sample) is important.

Sample position (on beam - out beam) is changed one time per minute during the measure run.

Measurements for definition of absolute value of neutron flux are carried out only periodically (as a rule after creation a new filter; using a foil activation method (Au, Mn, …))

For radiative capture CS measurements (using activation method):

Absolute value of intensity is important.

It is determined systematically, in each experiment using

1)Flux measuring by 10B(n,αγ)7Li* before and after irradiation and flux monitoring during irradiation using He-3 counter;

2)Flux measuring using a foil activation method (In, Au, …) during irradiation

Influence on results (cont.)

Width and shape of the main neutron line

For smooth cross section:

Value of measured cross section (averaged on spectrum of the neutron line)

- is very weakly dependent on the shape of the line
- does not depend on the sample thickness

For cross sections with resonance in the neutron line width:

Value of measured (observed) CS (averaged on spectrum of the neutron line)

- may depend strongly on the shape of the line
- depends on the thickness of the sample (through self-shielding resonance).

Necessary to carry out the extrapolation to zero thickness.

TNCS using transmission method

The total neutron cross section (averaged on spectrum of quasi-monoenergetic neutron line) **for a sample with nuclear density *n_x* is determined as**

$$<\sigma_x> = -\frac{1}{n_x}\ln <T>$$

Total uncertainty $\Delta<\sigma_x>$ includes the statistical inaccuracy of measurements, sample weight and dimensions inaccuracies:

$$\Delta <\sigma_x> = \frac{1}{n_x}\sqrt{\left(\frac{\Delta <T>}{<T>}\right)^2 + (\sigma_x \Delta n_x)^2}$$

Transmission

Sample transmission is calculated with formulae:

$$T = \frac{N^{SMP} - B^{SMP}}{N^{DB} - B^{DB}} = \frac{N^{SMP} - N^{SMP+PE}}{N^{DB} - N^{DB+PE}}$$

where

N_{SMP} – beam after sample,

N_{SMP+PE} – beam after sample + polyethylene (SMP background),

N_{DB} – direct beam,

$N_{DB\ +PE}$ – direct beam + polyethylene (DB background).

Dead time correction

Calculation of true value of accounts in the i-th channel of analyzer is <u>the first and mandatory step</u> in spectrum treatment. It is connected with necessity to take into account the dead time corrections.
This true value N_i^r **is calculated with formula:**

$$N_i^r = \frac{N_i}{1 - \tau_0 \sum_{j=1}^{1024} N_j - \Delta\tau \sum_{j=1}^{1024} \left(N_j \cdot j\right)}$$

τ_0 – time at which electron spectrometer tract loses sensitivity to signals;
$\Delta\tau$ – uncertainty of time by frequency channel ADC path; N_i – account in the *i-th* channel of analyzer.
τ_0 and $\Delta\tau$ were determined experimentally: τ_0 = 6,67 μs, a $\Delta\tau$ = 0.02 μs

$$\Delta N_i^r = \sqrt{\left(\frac{1 - \tau_0 \sum_{j=1}^{1024} N_j - \Delta\tau \sum_{j=1}^{1024}(N_j \cdot j) + N_i \cdot (\tau_0 + \Delta\tau \cdot i)}{\left(1 - \tau_0 \sum_{j=1}^{1024} N_j - \Delta\tau \sum_{j=1}^{1024}(N_j \cdot j)\right)^2} \cdot \Delta N_i\right)^2 + \sum_{\substack{j=1, \\ j \neq i}}^{1024} \left(\frac{-N_i(\tau_0 + \Delta\tau \cdot j)}{\left(1 - \tau_0 \sum_{k=1}^{1024} N_k - \sum_{k=1}^{1024} N_k\right)^2} \cdot \Delta N_j\right)^2}$$

Transmission (cont.)

PROPORTIONAL HYDROGEN RECOIL COUNTER	HELIUM-3 DETECTOR
FOR ONE RUN AND ONE SAMPLE	
Taking into account the dead time corrections (see above).	
Taking into account absorption of gamma-rays by polyethylene $N_i^{SMP+PE}/T_\gamma \Rightarrow B_i^{SMP}$; $N_i^{DB+PE}/T_\gamma \Rightarrow B_i^{DB}$	Determination of treatment region in each spectrum k and n – the first and last channel of treatment region in spectrum
Calculation of transmission for each channel (subtraction of background) $T_i = \frac{N_i^{SMP} - B_i^{SMP}}{N_i^{DB} - B_i^{DB}}$. To shorten expression for $\frac{\Delta T_i}{T_i}$ let $(N_i^{SMP}-B_i^{SMP})=\Delta SMP_i$ and $(N_i^{DB}-B_i^{DB})=\Delta DB_i$, then $\frac{\Delta T_i}{T_i} = \sqrt{\frac{N_i^{SMP}}{(\Delta SMP_i)^2} + \frac{B_i^{SMP}}{(\Delta SMP_i)^2} + \frac{N_i^{DB}}{(\Delta DB_i)^2} + \frac{B_i^{DB}}{(\Delta DB_i)^2}}$	Calculation of sum $N^{SMP} = \sum_{i=k}^{n} N_i^{SMP}$; $N^{SMP+PE} = \sum_{i=k}^{n} N_i^{SMP+PE}$; $N^{DB} = \sum_{i=k}^{n} N_i^{DB}$; $N^{DB+PE} = \sum_{i=k}^{n} N_i^{DB+PE}$ $dN^{SMP} = \sqrt{N^{SMP}}$; $dN^{SMP+PE} = \sqrt{N^{SMP+PE}}$; $dN^{DB} = \sqrt{N^{DB+PE}}$; $dN^{DB+PE} = \sqrt{N^{DB+PE}}$
Determination of transmission treatment region k and n – the first and last channel of this chosen region	Calculation of transmission (subtraction of background) $T = \frac{N^{SMP} - N^{SMP+PE}}{N^{DB} - N^{DB+PE}}$. Let $(N^{SMP}-N^{SMP+PE}) = \Delta SMP$; $(N^{DB}-N^{DB+PE}) = \Delta DB$, then $\frac{\Delta T}{T} = \sqrt{\frac{N^{SMP}}{(\Delta SMP)^2} + \frac{N^{SMP+PE}}{(\Delta SMP)^2} + \frac{N^{DB}}{(\Delta DB)^2} + \frac{N^{DB+PE}}{(\Delta DB)^2}}$
Average of transmission on chosen region $T = \frac{\sum_{i=k}^{n} \frac{T_i}{\Delta T_i^2}}{\sum_{i=k}^{n} \frac{1}{\Delta T_i^2}}$; $\Delta T = \sqrt{\frac{\sum_{i=k}^{n} \frac{(T_i - T)^2}{\Delta T_i^2}}{\sum_{i=k}^{n} \frac{(N-1)}{\Delta T_i^2}}}$	

Transmission (cont.)

FOR R RUNs AND ONE SAMPLE

Average of the transmissions on R runs. T_j and ΔT_j are transmission and its absolute error, obtained for *j-th* run.

$$\langle T \rangle_R = \frac{\sum_{j=1}^{R} \frac{T_j}{\Delta T_j^2}}{\sum_{j=1}^{R} \frac{1}{\Delta T_j^2}} \; ; \qquad \Delta \langle T \rangle_R = \sqrt{\frac{\sum_{j=1}^{R} \frac{\left(T_j - \langle T \rangle_R\right)^2}{\Delta T_j^2}}{\sum_{j=1}^{R} \frac{(R-1)}{\Delta T_j^2}}}$$

Calculation of total neutron cross section for a sample

$$\sigma_x = -\frac{\ln \langle T \rangle_R}{n_x}, \qquad \Delta \sigma_x = \frac{1}{n_x} \sqrt{\left(\frac{\Delta \langle T \rangle_R}{\langle T \rangle_R}\right)^2 + \left(\sigma_x \times \Delta n_x\right)^2}$$

for powder sample:

$$n_x = \frac{4 I_x \times P_{SMP} \times N_A}{\pi D^2 \times A_x} \quad \frac{\Delta n_x}{n_x} = \sqrt{\left(\frac{\Delta I_x}{I_x}\right)^2 + \left(\frac{\Delta P_{SMP}}{P_{SMP}}\right)^2 + 4 \times \left(\frac{\Delta D}{D}\right)^2} \; ;$$

for solid sample:

$$n_x = \frac{I_x \times \rho \times L \times N_A}{A_x} \quad \frac{\Delta n_x}{n_x} = \sqrt{\left(\frac{\Delta I_x}{I_x}\right)^2 + \left(\frac{\Delta \rho}{\rho}\right)^2 + 4 \times \left(\frac{\Delta L}{L}\right)^2}$$

.

N_A – Avogadro constant; A_x – mass number of nuclide, I_x – purity; P_{SMP} – weight of the sample;
D – diameter of the sample container; ρ – density; L – sample thickness.

Transmission (cont.)

FOR M SAMPLES

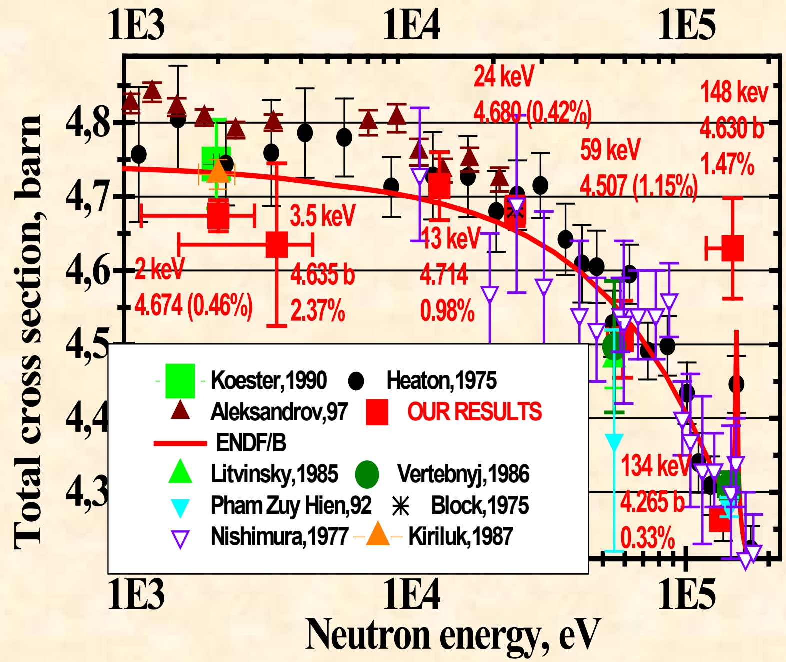
Average of the transmissions on M samples. T_j and ΔT_j are transmission and its absolute error, obtained for m-*th* sample.

$$\langle T \rangle_M = \frac{\sum_{m=1}^{M} \frac{T_m}{\Delta T_m^2}}{\sum_{m=1}^{M} \frac{1}{\Delta T_m^2}}$$

$$\Delta \langle T \rangle_M = \text{ maximum from } \sqrt{\frac{\sum_{m=1}^{M} \frac{\left(T_m - \langle T \rangle_M\right)^2}{\Delta T_m^2}}{\sum_{m=1}^{M} \frac{(M-1)}{\Delta T_m^2}}} \quad \text{and}$$

$$\sqrt{\sum_{m=1}^{M} \frac{1}{\Delta T_m^2}}$$

^{13}C (abundance 1.1%) p-wave resonance
E=152.9 ±1.4 keV, Γn=3.7 ± 0.7 keV, Γγ=4.0 ± 1.6 eV
148 keV filter: 118.71 - 157.01 keV



Strong resonance for isotope ^{12}C

Canton L., Amos K., Karataglidis S., et al.
«Particle-unstable light nuclei with a Sturmian approach that preserves the Pauli principle»

Experimental results on the 149 keV filter.

# smp	Concentration (C), atoms/barn	Type of sample	σ_{tot}, barn	$\Delta\sigma_{tot}$, barn	$\Delta\sigma_{tot}/\sigma_{tot}$, %	$T=\exp(-n\sigma_{tot})$
1	0,008880(12)	disk	4,660*	0,270	5,79	0.9594
2	0.01302	powder	4,580	0,050	1,09	0.9421
3	0.01917	powder	4,610	0,050	1,08	0.9154
4	0.02661	three disks	4,310*	0,150	3,48	0.8916
5	0.04097	powder	4,224	0,230	5,45	0.8411
6	0.04209	solid	4,568	0,030	0,66	0.8251
7	0.04379	solid	4,509	0,013	0,29	0.8208
8	0.08711	solid	4,424	0,010	0,23	0.6784
9	0.18707	powder	4,362	0,010	0,23	0.4422
10	0.24788	powder	4,364	0,010	0,23	0,3390

Uncertainty $<\sigma_x>$

Total uncertainty $\Delta<\sigma_x>$ includes the statistical accuracy of measurements and nuclear density accuracies:

$$\Delta < \sigma_x > = \frac{1}{n_x}\sqrt{\left(\frac{\Delta < T >}{< T >}\right)^2 + (\sigma_x \Delta n_x)^2}$$

Relative error $<\sigma_x>$

$$\frac{\Delta < \sigma_x >}{< \sigma_x >} = \sqrt{\left(\frac{\Delta < T >}{< T >}\right)^2 \bullet \left(\frac{1}{\ln < T >}\right)^2 + \left(\frac{\Delta n_x}{n_x}\right)^2}$$

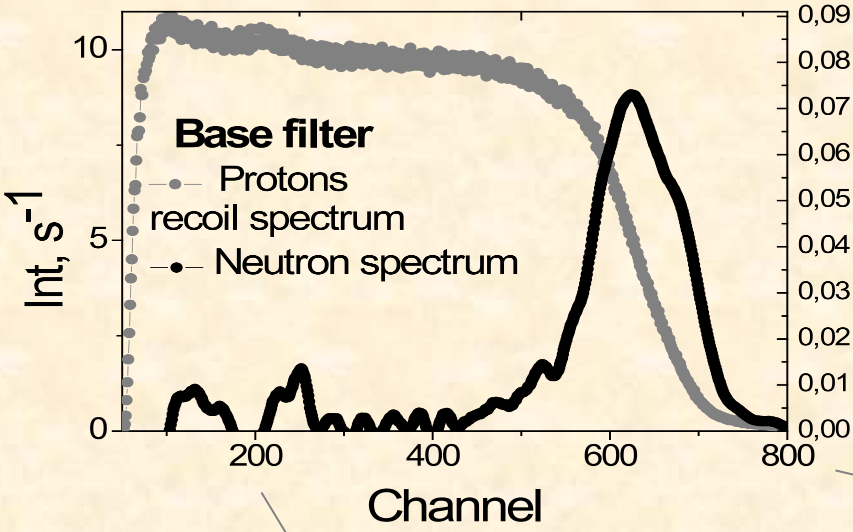
$$\frac{\Delta n_x}{n_x} \to 0$$

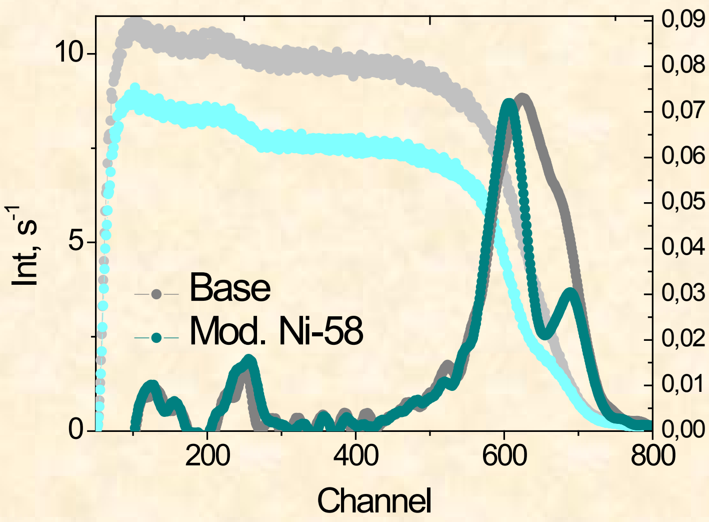
$$\frac{\Delta < \sigma_x >}{< \sigma_x >} \approx \frac{\Delta < T >}{< T >} \bullet \frac{1}{\ln < T >}$$

T	0.99	0.95	0.8	0.5	0.4	0.3	0.2	0.1
1/lnT	99.5	19.5	4.48	1.44	1.09	0.83	0.62	0.43

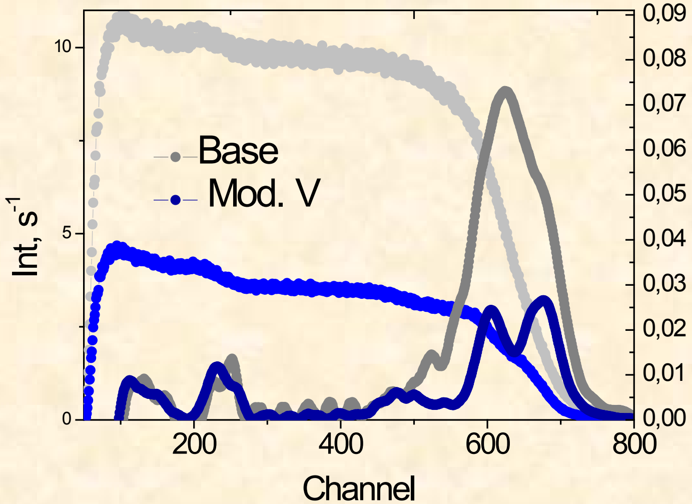
Modified neutron filtered beams

We used the modified neutron filtered beams where the main line of the base filter was splitted into a few lines





At first just these filtered beams were used in measurement in 2010



Modified neutron filtered beams (cont.)

Name of filter	Number of lines, (E_c, E_{min}- E_{max}, keV)	Components (g/cm^2)						
		^{10}B	Si_{nat}	Ti_{nat}	V_{nat}	^{58}Ni	^{54}Fe	Al
Base	1(146.5, 90.9-171.2)	0.2	213.43	11.49	-	-	-	-
Mod. V	3(107.3, 87.0-127.5) (131.6, 123.2-140.1) (147.5, 135.7-159.2)	0.2	184.07	7.66	24.44	-	-	-
Mod. Ni	2(132.7, 88.1-148.8) (150.9, 139.6-162.2)	0.2	184.07	7.66	-	20.49	-	-
Mod. Fe	**3(122.1, 75.3-136.2) (138.3, 128.8-147.8) (153.5, 145.0-161.9)**	0.2	184.07	-	-	-	77.45	-
Mod. Al	1(131.8, 91.7-166.2)	0.2	213.43	-	-	-	-	10.00

Modified neutron filtered beams (cont.)

A new approach consists of the following steps:

1. **<u>Calculation of a neutron spectrum</u>** after the given modified filter by the FILTER-7.1 code using the ENDF/B libraries. A thickness of the filter components are taken just the same as in reality.

2. **Reconstruction of the proton recoil spectrum** from the calculated neutron spectrum. It is performed by formula:

$$Q_i = \sum_{j=i}^{N-1} \frac{(I_{j+1} + I_j) \cdot (E_{j+1} - E_j)}{(E_{j+1} + E_j)},$$

Q_i – number of counts in i-th channel (energy of this channel is E_i) in the proton recoil spectrum; I_{j+1}, I_j – number of counts (j+1)-th and j-th channels in the calculated neutron spectrum at the relevant energies E_{j+1} and E_j.

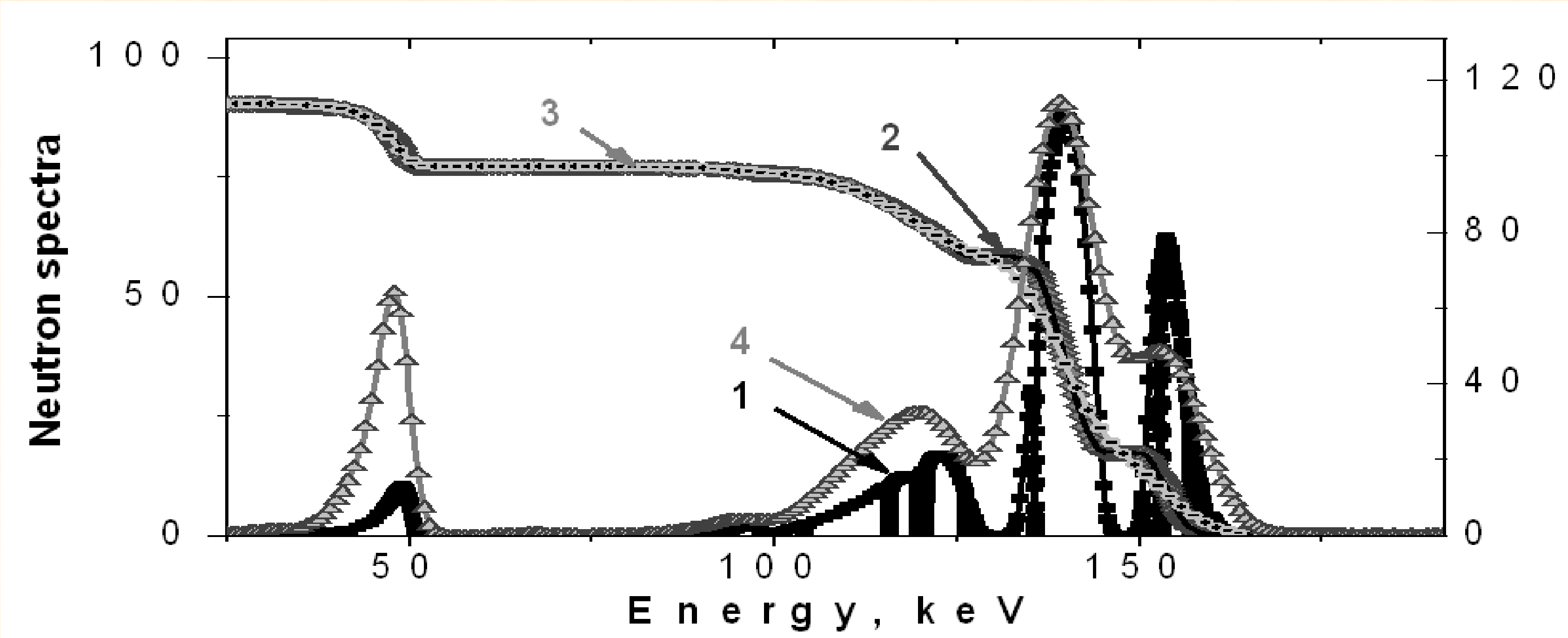
3. **<u>Blurring the reconstructed spectrum</u>** to take into account the energy resolution of the detector system. It is performed by formula:

$$R_i = \sum_{j=1}^{N} Q_j \cdot \frac{\exp\left(-\frac{(E_i + E_j)^2}{2\sigma^2}\right)}{\sigma\sqrt{2\pi}},$$

R_i – number of counts in i-th channel (energy of this channel E_i) in the blurred proton recoil spectrum; Q_j – number of counts in i-th channel (energy of this channel E_j) in the reconstructed proton recoil spectrum; σ – an energy-dependent resolution parameter. It was estimated from experiment and was taken $\sigma = 0{,}075 \cdot E$.

Modified neutron filtered beams (cont.)

4. **Differentiation** of the blurred spectrum



Output calculated spectra. 1 – neutron spectrum; 2 – reconstructed proton recoil spectrum; 3 – blurred proton recoil spectrum; 4 – differentiated proton recoil spectrum, i.e. reconstructed neutron spectrum.

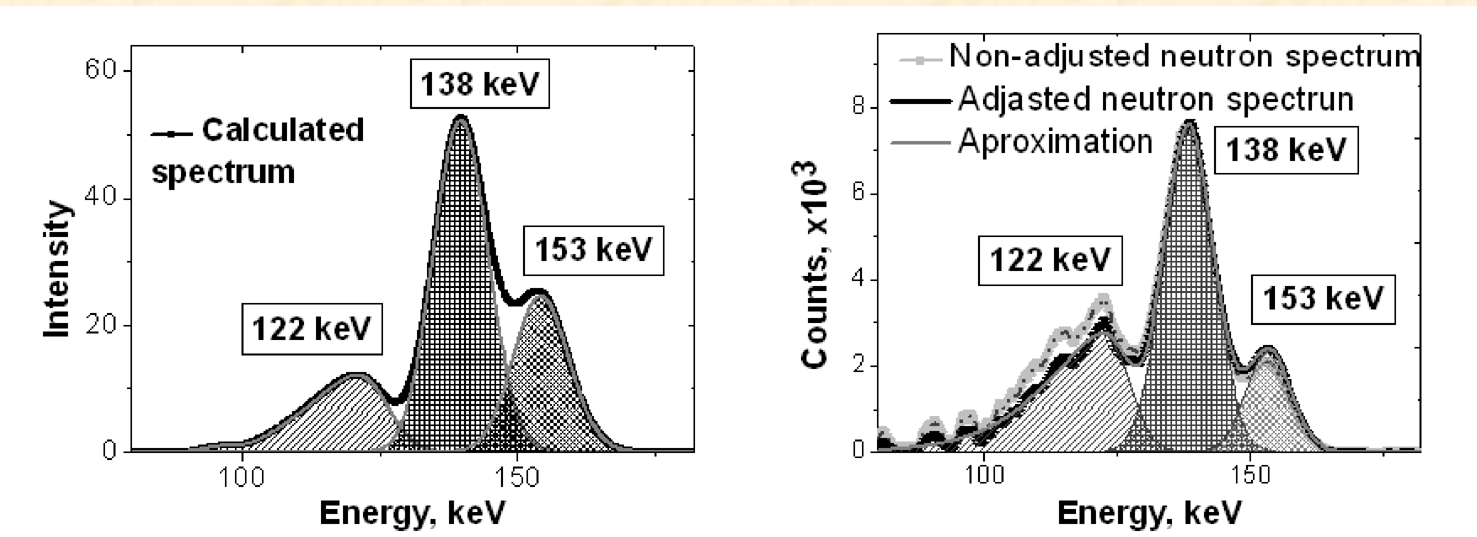
Modified neutron filtered beams (cont.)

5a. The reconstructed neutron spectrum is fitted by the function

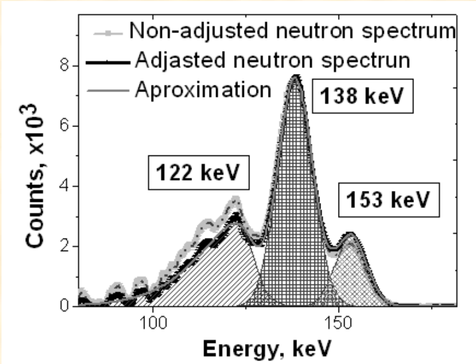
$$F(x)=\sum_{i=1}^{M} A_i \frac{1}{1+e^{-\frac{x-Xc_i+\frac{W_{1i}}{2}}{W_{2i}}}}\left(1-\frac{1}{1+e^{-\frac{x-Xc_i-W_{1i}/2}{W_{3i}}}}\right)+\sum_{j=1}^{N}\frac{A_j}{W_j\sqrt{\frac{\pi}{2}}}e^{-2\frac{(x-Xc_j)^2}{W_j^2}},$$

the first sum describes non-symmetrical lines, the second one describes symmetrical lines (A_i, A_j – amplitudes, Xc_i, Xc_j – energy parameters, which correspond to coordinate position of maximum for *i*-th and *j*-th lines, W_{1i}, W_{2i}, W_{3i} , W_j – width parameters, M – number of non-symmetrical lines, N – number of symmetrical lines). This fitting was carried out using the OriginLab OriginPro ver.8 software.

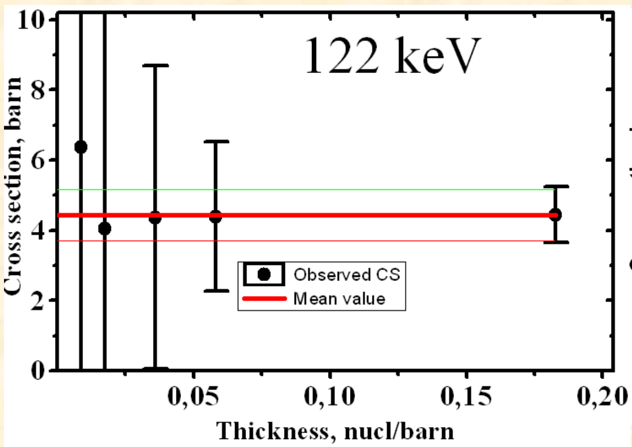
5b. Similar procedure is performed with the **non-adjusted neutron spectrum (experimental).**

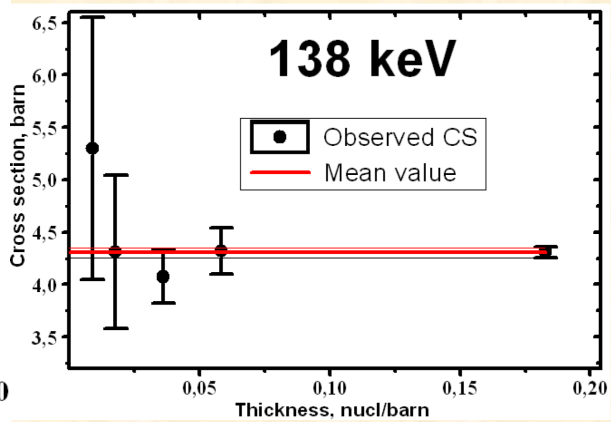


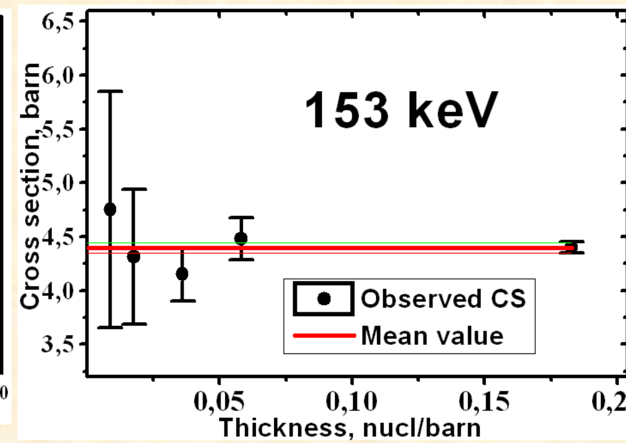
Modified neutron filtered beams (cont.)



$$\Delta<\sigma_x>=\frac{1}{n_x}\sqrt{\left(\frac{\Delta<T>}{<T>}\right)^2+(\sigma_x\Delta n_x)^2}$$



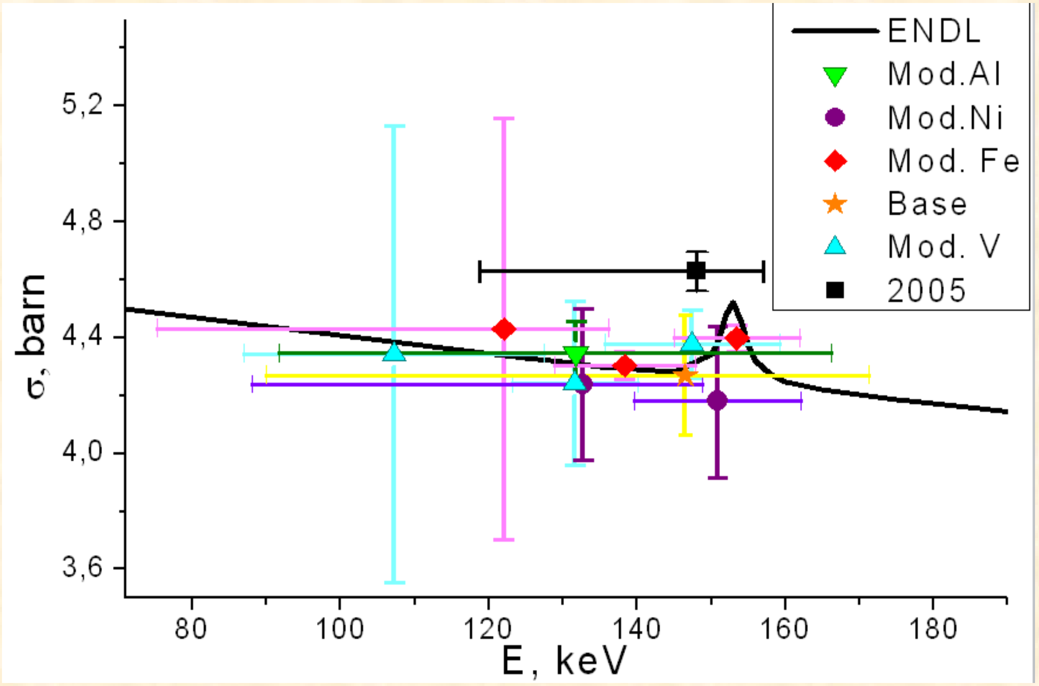




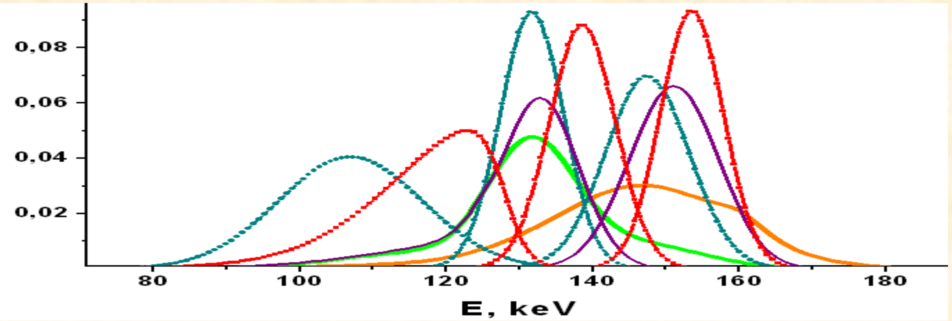
$$\frac{\Delta n_x}{n_x}=0.07\%\div0.10\%$$

$\Delta<T>$ **consists of statistical error + error connected with fitting procedure (it depends on statistics indirect)**

Experimental averaged total cross-sections



Weight spectra



Preliminary conclusion - resonance is absent in the energy region 130-160 keV

Thank You

for your attention!

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